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Volume 23, Part 2—July 1976

CONTENTS

Paleontology and Depositional Environments: Cambrian of Western North America

A symposium

Contributors of Papers

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Extended presentations of some papers presented at a Paleontological Society symposium held in Salt Lake City, Utah, on October 20, 1975.

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EDITORIAL PREFACE

Prior to the last decade, the large majority of Cambrian studies in western North America were concerned with either stratigraphy or systematics of trilobites. A new phase of Cambrian investigations commenced about a decade ago with expanded interest in not only stratigraphy and trilobites, but many other types of organisms, depositional environments, facies relationships, paleoecology, evolution, and other topics. Of particular significance is a marked increase in cooperation between paleontologists and sedimentologists to better present an integrated analysis of Cambrian faunas and their environments. Because favorable climate and structure interact to provide excellent outcrops in numerous mountain ranges, much of this new work has been concentrated in the Great Basin of eastern and southern Nevada, western Utah, and parts of adjacent California and Idaho.

The idea of a symposium to summarize this new Cambrian work was first discussed by A. R. Palmer, R. A. Robison, and M. E. Taylor during 1972 and resulted in a Paleontological Society symposium that was convened in Salt Lake City, Utah, on October 20, 1975. Limits of a one-day session allowed for presentations by probably less than half of those qualified to participate. However, the program is judged to be representative of the problems being investigated and the results being obtained.

This volume contains 14 of the 22 papers read at the symposium. Some of the papers that were read are being published elsewhere. For a variety of other reasons, some of the symposium participants were unable to contribute to this volume. The reader is referred to volume 7, number 7, of the 1975 Geological Society of America Abstracts with Programs for a complete list of symposium topics (p. 922-923) and abstracts. One short paper, "Trilobites in Utah Folklore," although not read at the symposium, has been added here because it concerns *Elrathia kingii*, which is probably the most widely known of all Cambrian fossils. The diversity of subject matter covered in the total of 15 papers is obvious, and it is hoped that from the seemingly autonomous approaches, the reader will gain a general feeling of the new era of Cambrian investigation.

Several of the papers in this volume are concerned with areas in western Utah that are covered by a series of excellent geologic maps and stratigraphic columns that have been prepared by L. F. Hintze. Readers may well benefit by reference to these 15-minute quadrangle maps, which were published in 1974 as U. S. Geological Survey Miscellaneous Field Studies Maps MF-633 to 637. Professor Hintze has additional maps in preparation.

We acknowledge with gratitude the aid of J. K. Rigby and W. K. Hamblin in arranging for publication of these symposium papers. Funds for much of the miscellaneous cost of organizing this volume were provided by the Department of Geology, University of Kansas. Finally, we appreciate the cordial and prompt cooperation we received, without exception, from each of the contributors.

Lawrence, Kansas
March 1976

R. A. Robison
A. J. Rowell

Trilobites in Utah Folklore

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INTRODUCTION

Well-preserved specimens of *Elrathia kingii* (Meek) are found in the Wheeler Formation of Middle Cambrian age east of Antelope Spring in the Wheeler Amphitheater, House Range, Millard County, Utah (Text-fig. 1). The species is common in western Utah (Robison, 1964), but the locality at Antelope Spring is unique in yielding articulated, dark-colored dorsal exoskeletons having thick deposits of fibrous calcite on the under surfaces (Bright, 1959). The secondary calcite strengthens the fossil so that specimens weather free or are easily extricated from the rock matrix.

Great abundance, fine degree of preservation, and ease of removing specimens from the matrix have resulted in *Elrathia kingii* becoming popular among both professional and amateur fossil collectors. Photographs of *Elrathia kingii* from the Wheeler Amphitheater have been widely published in textbooks, and commercial demands are currently sufficient to support a small private quarrying operation. The trilobite is popular among rockhounds, a situation undoubtedly stimulated by several popular articles on fossil collecting at the Wheeler Amphitheater (for example, Beckwith, 1931; Robison, 1970; Dickerson and Dickerson, 1972).

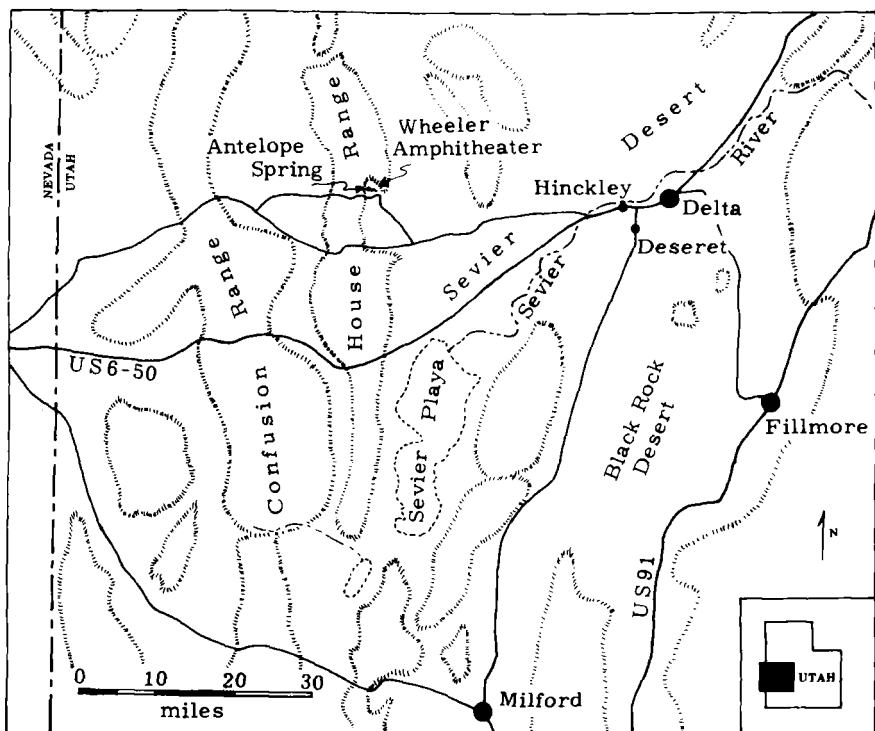
Some historical records suggest that *Elrathia kingii* was collected at the Wheeler Amphitheater and fabricated into amulets by the Pahvant Ute Indians from Sevier Valley, Utah. The story provides an interesting sidelight to studies of Cambrian trilobites from the Great Basin.

BECKWITH'S NECKLACE

Frank Asahel Beckwith lived in Delta, Utah, from 1913 until his death in 1951. Mr. Beckwith, a banker, later the editor of the *Millard County Chronicle*, spent much of his free time roaming the desert regions of western Utah studying the geology and history of the local Indians—the Pahvant Utes. Despite a lack of college training, he was an accomplished natural historian.

Beckwith was familiar with the more common local fossils, having served as guide for Charles E. Resser, Teiichi Kobayashi, Riuji Endo, and other geologists who occasionally visited western Utah on collecting trips. Out of respect for Beckwith's prowess as a fossil collector, Charles E. Resser, Smithsonian Institution, named the Middle Cambrian merostome *Beckwithia typa* after him in 1931.

Upon his death, Beckwith left a substantial personal library, a large collection of fossils, Indian artifacts, photographs, and voluminous notes on observations made during his travels. The narrative that follows is based largely upon information from an unpublished manuscript by Beckwith (1934) and a brief account that was published in a now rare book (Beckwith, 1947). A second manuscript by Beckwith, containing a slightly modified version of the story, was published in 1975.



TEXT-FIG. 1.—Map showing location of places in western Utah that are discussed in the text. Black rectangle in inset shows area of larger map.

During a collecting trip in the early 1900s near Deseret, Utah, Frank Beckwith excavated an Indian burial site and found a single trilobite within the rib cage of an Indian skeleton. Beckwith recognized the trilobite as being *Elrathia kingii* (Meek) from Middle Cambrian rocks that crop out in Wheeler Amphitheater in the northern House Range.

The trilobite from the burial had been drilled through the cephalon and was apparently carried on a thong around the Indian's neck. Beckwith was greatly intrigued by the Indian's use of a trilobite and asked a young Pahvant friend, Joseph J. Pickyavit, if he knew anything about them. Joseph Pickyavit recognized the trilobite by the name *limpe khamitza pachavee*. The name refers specifically to a trilobite in the matrix and means, according to Beckwith, "little water bug like stone house in." On another occasion, Joseph Pickyavit's brother Tedford N. Pickyavit visited Beckwith and was asked the same question, except that Beckwith offered Tedford the drilled trilobite that had been recovered from the Indian burial. Tedford recognized the matrix-free specimen by the name *shugi-pits napa t'schoy*, meaning "lizard foot bead things."

Beckwith asked Joseph Pickyavit what the *weenoonse*, or older Indians, used the trilobites for. Pickyavit replied, "Body defendancies, Beckwith; help diphtheria, sore throat, lots of sickness. Old timers wore 'em in necklace—no get shot while have 'em on—at least it work for a time."

Some pioneer settlers in western Utah apparently also knew of the Pahvants' association with trilobites. In an interview between Beckwith and Thomas W. Cropper of Hinckley, Utah, Cropper reported that in the late 1800s a group of Indians from Sevier Valley intercepted an immigrant family from Tooele, took their horses, and left the family on foot a few miles from the pioneer settlement of Deseret. Then, as the story goes, fearing reprisals from the settlers, the Indians retired to Antelope Spring to gather trilobites "to keep them from being hurt by the white man's bullets." The validity of the Cropper story is uncertain, particularly because the Indians apparently left the area soon after the altercation without being followed by any of the settlers. However, the story does show that an association between the Pahvant Utes and trilobites was established in local tradition.

At Beckwith's request, Tedford Pikyavit agreed to make a necklace following the Pahvant's tradition and did so in 1931 at a reported cost of \$2.50 to Beckwith. The necklace (Text-fig. 2) consists of 13 specimens of *Elrathia kingii*, each drilled through the cephalon and tied on a rawhide thong. Interspaced between the trilobites are hand-formed clay beads dyed either red, dark brown, or green. The two tassels are horse hair. Tedford Pikyavit told Beckwith that the old tradition was to make the beads from polished stones that were drilled for threading on a thong.

In an attempt to verify the association of trilobites and prehistoric Indians, we contacted archaeologists familiar with Great Basin prehistory at the University of Utah, the Antiquities Section of the Division of State History of Utah, and the Smithsonian Institution. None of the specialists knew of scientific data that would corroborate Beckwith's story. Nevertheless, Beckwith's writings show him to be a person of high intellectual integrity, and there is no reason to doubt the accuracy of his report of a drilled trilobite in the rib cage of an Indian exhumed near Deseret. Unfortunately however, the antiquity of the Indian burial is unknown.

Trilobites were discovered at Antelope Spring by members of the King Survey during the late 1860s (Meek, 1870). This date is probably the earliest time at which white men could have introduced trilobites to the Pahvant Utes. Whether the Indians knew about the Antelope Spring trilobite locality before the 1860s is not known, although the reports by the Pikyavit brothers may indicate that they did, and Beckwith himself believed that an association between Indians and trilobites was hundreds of years old.

Prehistoric association of trilobites with the Pahvant Utes would be interesting if verified. The Pahvants' name for trilobites in matrix, *timpe khanitza pachavee*, suggests that the Indians recognized the organic origin of the fossils. The Sevier Valley, ancestral home of the Pahvants, was near a low-lying swampy area around the delta of the Sevier River until a land reclamation project in the early 1900s diverted the water for irrigation and drained much of the land for farming. Until then, the Pahvants gathered roots and hunted water birds in and around the sloughs. A life style at least partially keyed to the slough habitat would have given the Pahvants ample opportunity to observe aquatic insects. General similarity of some aquatic insects and *Elrathia kingii* could have been the impetus for the name *timpe khanitza pachavee*.

A specialty gift catalogue recently advertised a necklace with a silver-mounted *Elrathia kingii* as "a natural beauty from the ancient past styled for your future" (American Express Company, 1974, p. 23). Little did the adver-



TEXT-FIG. 2.—Trilobite necklace made for Frank A. Beckwith by Tedford N. Pickyavit in 1931.

tiser realize that "your future" would include protection against sickness and getting shot! "At least it work for a time."

ACKNOWLEDGMENTS

The Beckwith trilobite necklace shown in Text-figure 2 is owned by Mrs. Athena B. Cook. Mrs. Susan B. Dutson is thanked for allowing us to photograph the necklace and for stimulating discussions about her grandfather, Frank A. Beckwith. The assistance of Mrs. Martha Stewart, Research Librarian, Utah State Historical Society, is also greatly appreciated.

REFERENCES

- American Express Company, 1974, First Choice (an advertising catalogue): Amer. Express Co., Minneapolis, Minn., 41 p.
- Beckwith, Frank, Sr. [Frank Asahel Beckwith], 1931, A field of small fossils in western Utah: Utah Historical Quart., vol. 4 (1) p. 25-29.
- , 1934, Just jaunting 'round 1914 to 1934: Unpub. manuscript, Utah State Historical Soc. Lib., Salt Lake City.
- , 1947, Trips to points of interest in Millard [County] and nearby: Art City Publ. Co., Springville, Utah, 140 p.
- , 1975 [1939], Indian Joe in person and in background: DuWil Publ. Co., Delta, Utah, 206 p.
- Bright, R. C., 1959, A paleoecologic and biometric study of the Middle Cambrian trilobite *Elrathia kingii* (Meek): J. Paleont., vol. 33 (1), p. 83-98.
- Dickerson, Pat, and Dickerson, Flo, 1972, From Utah's treasure chest: Lapidary J. vol. 26 (9), p. 1342-48.
- Meek, F. B., 1870, Descriptions of fossils collected by the U.S. Geological Survey under the charge of Clarence King, Esq.: Acad. Nat. Sci., Philadelphia, Proc. 14 (2nd ser.), p. 56-64.
- Resser, C. E., 1931, A new Middle Cambrian merostome crustacean: U.S. Nat. Mus., Proc. 79 (art. 33), p. 1-4.
- Robison, Joleen, 1970, Tracking the trilobites: Desert Mag., Oct., p. 28-30.
- Robison, R. A., 1964, Late Middle Cambrian faunas from western Utah: J. Paleont., vol. 38 (3), p. 510-66.

Lower Cambrian Stratigraphy, Mackenzie Mountains, Northwestern Canada

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ABSTRACT.—Lower Cambrian strata deposited on a carbonate shelf, unstable slope, and deep basin are described from four stratigraphic sections in eastern Yukon Territory and western Northwest Territories. Underlying the sections are predominantly barren Upper Precambrian(?) and Lower Cambrian quartzite and siltstone that were deposited under shallow subtidal and intertidal conditions. The base of each section is believed to be near the top of the *Fallotaspis* Zone. Near the close of *Fallotaspis* Zone time a carbonate shelf began forming in the east. Shallow subtidal siltstone was deposited contemporaneously at the outer margin of the shelf. Shortly thereafter a basin formed to the west in early *Nevadella* Zone time. Dark limestone in thin, platy beds covered a wide area in the basin and extended eastward to the outer margin of the carbonate shelf. Silt then poured into the basin near the basin-shelf contact and formed an unstable slope. Shelf carbonates prograded over the shallow portion of the slope, extending the shelf westward. Carbonate sedimentation ceased on the shelf near the end of *Nevadella* Zone time, completing grand cycle A, which consisted of Upper Precambrian(?) and Lower Cambrian clastics (lower half-cycle, A1) and shelf carbonates (upper half-cycle, A2).

In the late *Nevadella* and earliest *Bonnia-Olenellus* zone times clastics from the inner detrital belt blanketed the shelf and poured into the basin to form a second, unstable siltstone slope. This clastic blanket on the shelf constitutes the lower half (B1) of the second grand cycle (B). The upper half-cycle (B2) began over the former shelf and shallow slope with deposition of shelf limestone in thin and medium beds that continued until the end of the second grand cycle. In part of this area, medium- and thick-bedded dolomite was deposited until it attained a great thickness within the upper half-cycle.

In the basin dark, platy limestone continued to accumulate beyond the margin of the second unstable slope during the lower half-cycle (B1) and part of the upper half-cycle (B2). Then in late middle and early late *Bonnia-Olenellus* Zone time, shale and thin-bedded limestone were deposited on a third unstable slope. This was covered by shallow-water limestone and, in latest(?) *Bonnia-Olenellus* Zone time, by dark siltstone that initiated a major, regional transgression. Deposition of the same dark siltstone unit over the shelf ended the second grand cycle there during late medial to late *Bonnia-Olenellus* Zone time.

A regional facies analysis that includes facies data from seven other nearby sections shows that the basin protruded eastward, forming a reentrant into the carbonate shelf. I suggest that the thick succession of dolomite in the upper half of the second grand cycle was deposited on the down-current side of this reentrant. Here clear shallow waters may have provided optimum conditions for the rapid deposition of carbonate.

INTRODUCTION

The present study illustrates a lateral change in Lower Cambrian strata from a carbonate shelf to a slope and basin environment. Four stratigraphic sections (Text-fig. 1) positioned across the depositional strike are used to demonstrate this facies change. Additional regional data are provided in Text-figure 2 by integrating the facies information from these four sections with that known from seven other sections in the area. This Text-figure shows the localities of the sections; their map coordinates are given in Table 1. Two or three sets of coordinates listed for one section indicate a composite section measured on two or three adjacent mountains.

Most of these Lower Cambrian strata are within the Sekwi Formation, the type section of which was originally described by Handfield (1968). I also

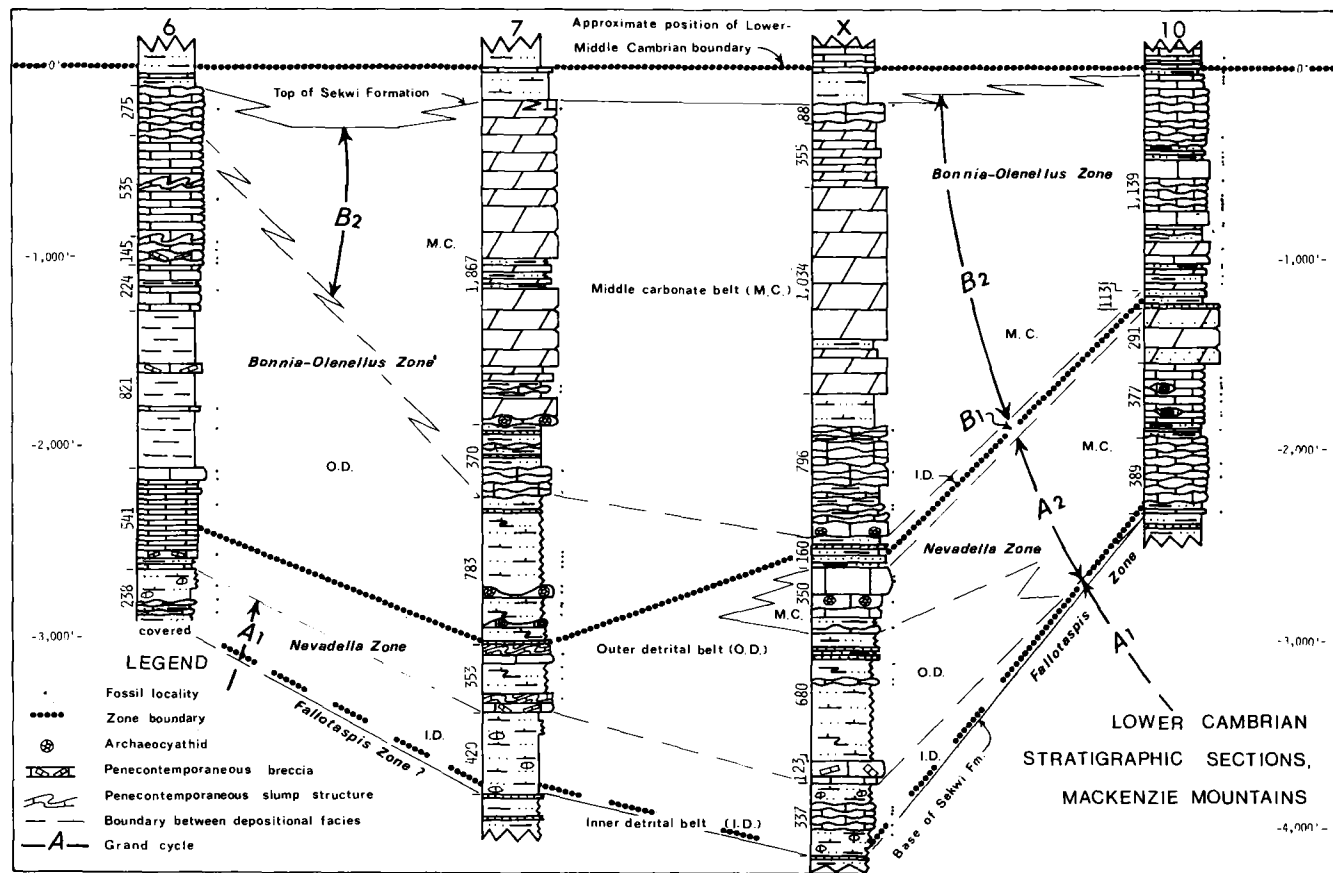
TABLE 1
MAP COORDINATES FOR STRATIGRAPHIC SECTIONS

Section	Thickness of Sekwi Fm. (0' = Base)	Latitude	Longitude
1	3,802'	64° 49½' - 50'	131° 58¾' - 132°
2	3,434'	64° 37' - 37¾'	131° 43' - 45'
3	3,381'	64° 26' - 27½'	131° 22' - 24'
4	2,552' +	64° 22¾'	129° 43' - 44'
5	0' - 3,355'	63° 42¾' - 43'	129° 27¾' - 29¼'
	3,355' - 3,435'	63° 42¼'	129° 29¼'
6	0' - 292'	63° 53¾'	130° 26¼'
	292' - 1,824'	63° 53½'	130° 25¼'
	1,824' - 2,779'	63° 51½' - 52'	130° 26' - 27'
7	0' - 1,975'	63° 26¾' - 26¾'	129° 21' - 23'
	1,975' - 3,802'	63° 28½'	129° 27'
8	2,322' +	63° 16¾'	128° 50½' - 51½'
9	2,202'	63° 15¾'	128° 35½' - 37'
10	2,309'	63° 31¾'	128° 41¾'
X	0' - 460'	63° 29¾'	129° 9' - 10'
	460' - 3,923'	63° 28¾' - 29'	129° 11½' - 13'

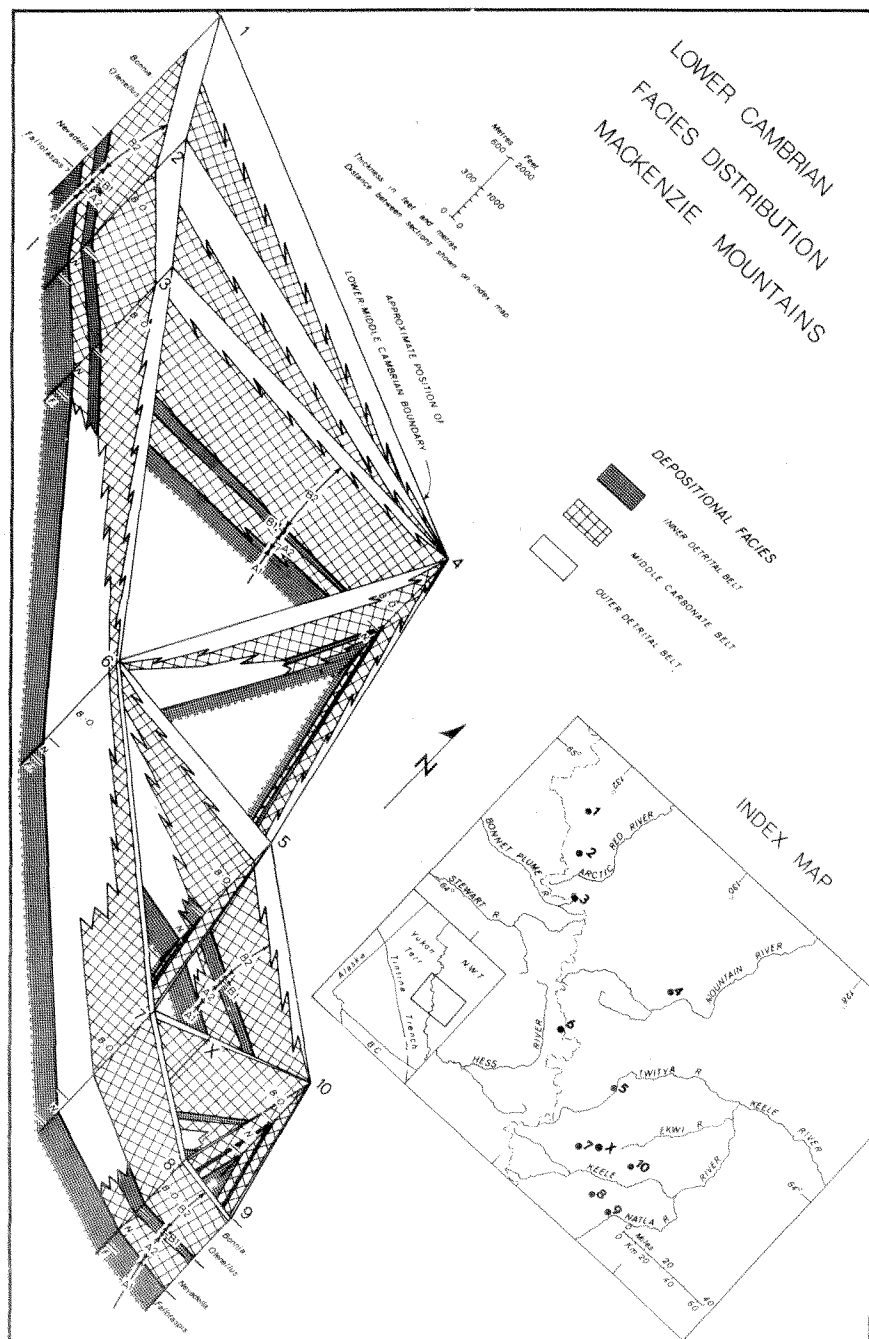
studied that section (Text-fig. 1, sec. 10), and used the fossils collected there to establish a Lower Cambrian trilobite zonation for the North American Faunal Province (Fritz, 1972). A map showing the geology in the vicinity of this and five other sections has been prepared by Blusson (1972).

Lower Cambrian strata considered here have been assigned to three depositional belts (Text-figs. 1, 2) following the procedure initiated in Great Basin Cambrian studies by Palmer (1960) and Robison (1960). In the Mackenzie Mountains, strata assigned to the outer detrital belt consist of medium brownish gray-weathering shale and siltstone, and dark gray, platy limestone. In the middle carbonate belt the strata are, as the name suggests, mainly carbonate. The limestone is in thin, wavy beds that commonly weather medium gray. A subordinate amount of limestone is in thick beds that weather medium or light gray. Some of the dolomite is in thin and medium beds that weather light yellowish orange. In the thick dolomite units, where the bedding is between four and sixteen inches, the predominant weathering colors are medium light gray and medium brownish gray. In large to small units containing thick-bedded to massive dolomite, the weathering color is cream to light orange. Most of the strata in the inner detrital belt consist of thin- and medium-bedded dolomite that is platy and weathers light yellowish orange, quartzite that weathers light brown, and siltstone that weathers yellowish orange, light green, maroon, or light brown.

In addition to depositional belts, some of the strata described in this paper are assigned to grand cycles as defined by Aitken (1966) in Cambrian and Lower Ordovician strata of the Canadian Rocky Mountains. Aitken states (p. 405) that grand cycles are "depositional cycles . . . , each comprising 300 to 2,000 feet of strata and two or more fossil zones. . . . Each . . . commences at an abrupt basal contact, and consists of a lower, shaly half-cycle gradationally overlain by a carbonate half-cycle." I have suggested (1975, p. 538) that three grand cycles may be present in Lower Cambrian strata of the North American



TEXT-FIGURE 1.—Lower Cambrian stratigraphic sections from the Mackenzie Mountains. The geographic location of the sections is given on an index map in Text-figure 2.



TEXT-FIG. 2.—Fence diagram showing Lower Cambrian facies distribution in the Mackenzie Mountains.

Cordillera, but only two cycles can be recognized in the Mackenzie Mountains. In the present paper, grand cycle A and the lower half-cycle of grand cycle B in the Mackenzie Mountains are considered to be equivalent to strata given those designations farther south. The upper half-cycle of grand cycle B in the Mackenzie Mountains is considered to include the half-cycle to the south and part (perhaps all, locally) of grand cycle C to the south. The recognition of grand cycle C, and a subsequent restriction of the upper half-cycle of B in the Mackenzie Mountains, is dependent upon the future recognition of a regional clastic unit that is equivalent to the lower half-cycle of C to the south.

In the following discussion the strata will be described in ascending order as they occur in each of the four sections shown in Text-figure 1. It can be assumed that strata assigned to the lower (clastic) half-cycles belong to the inner detrital belt, and that strata assigned to the upper (carbonate) half-cycles belong to the middle carbonate belt. Grand cycles cannot be easily traced into the outer detrital belt; hence the use of the heading "outer detrital strata" for these rocks.

SECTION 10 (TYPE SEKWI)

Grand cycle A, lower half-cycle (A1)

Underlying the Sekwi Formation at the type section and at section X are two unnamed formations that Blusson (1971, 1972) called map units 12 and 13. These formations are here assigned to the lower half-cycle of grand cycle A. Map unit 12 consists of buff-weathering, fine-grained sandstone that Blusson (1971, p. 9) assigned to the "Cambrian and/or Precambrian." Map unit 13, composed of brown-weathering siltstone and very fine-grained sandstone, is 500 feet thick below section 10. Handfield (1968, p. 5) found an olenellid trilobite 30 feet below the top of this unit, and Blusson assigned the unit to the Lower Cambrian. Blusson's map (1972) shows that these two clastic units grade westward into a dark gray or brown slate unit (map-unit 10a) that underlies section 7. None of these older units were seen by the writer below the base (covered) of the Sekwi at section 6.

Grand cycle A, upper half-cycle (A2)

At section 10 the boundary between the lower and upper half-cycle of grand cycle A is situated at the boundary between the Sekwi Formation and map unit 13. The upper, carbonate half-cycle consists of a basal 389-foot unit of mainly thin, wavy-bedded limestone, a 377-foot unit of platy, dark gray limestone, and a 291-foot unit of orange-weathering, thick-bedded dolomite. No penecontemporaneous breccias or slump features were seen in strata assigned to the upper half-cycle. An abundance of pagetiid trilobites, a predominance of dark, platy limestone, and the presence of archaeocyathid bioherms at two horizons suggest that strata in the 377-foot interval may be close to or within the outer detrital belt. The assignment of these last-mentioned strata to the middle carbonate belt (Text-fig. 1) is therefore tentative until further work is accomplished near the section.

Fossils belonging to the *Fallotaspis* Zone were collected 6 feet above the base of the Sekwi Formation. A collection 155 feet above the base and all of the other collections from this half-cycle belong to the *Nevadella* Zone. The 291 feet of barren dolomite at the top of the half-cycle could not be dated directly, but a fossil collection above this unit in section 8 belongs to the *Nevadella* Zone.

Grand cycle B, lower half-cycle (B1)

Above the dolomite unit in section 10 are 113 feet of light brown quartzite, light brown dirt weathering from siltstone(?), and orange-weathering, thin- to thick-bedded dolomite, all of which are assigned to the lower half-cycle. Numerous intervals within the quartzite contain distinctive quartz grains that are poorly sorted, well rounded, and have frosted surfaces. Similar grains were found scattered ("floating") throughout the dolomite matrix in the 291-foot dolomite unit in the underlying half-cycle.

Fossil collections in section 3 and 8 prove that the boundary between the *Nevadella* Zone and the *Bonnia-Olenellus* Zone lies within the lower half-cycle in those sections. This half-cycle, or immediately overlying strata in sections 1 through 5 and 8 through 10, contains fossils belonging to the lower portion of the *Bonnia-Olenellus* Zone. Taken together with the *Nevadella* occurrences, this suggests that the lower half-cycle is approximately the same age over the study area.

Grand cycle B, upper half-cycle (B2)

Medium gray-weathering limestone in thin, wavy beds predominates in the 1,139-foot succession constituting this half-cycle at section 10. Fossils from the uppermost beds are assigned to a high position in the *Bonnia-Olenellus* Zone. The species *Bonnia columbensis* Resser, *Piaziella pia* (Walcott), and *Olenellus pueyoblancoensis* (Lochman) from this horizon are also present in the Peyto Limestone of Alberta and British Columbia.

Post-Sekwi dark siltstone and limestone

Above the Sekwi formation in section 10 is a covered interval 67 feet thick. Float suggests that the underlying strata consist of black siltstone and inter-bedded limestone in dark gray, platy beds. Local float from 10 feet above the base of the interval contains fossils from the *Bonnia-Olenellus* Zone. An unmeasured succession of dark, platy limestone overlies the covered interval. A faunule belonging to the upper Middle Cambrian was found 3 feet above the base of the platy limestone and 70 feet above the top of the Sekwi Formation.

SECTION X

Grand cycle A, lower half-cycle (A1)

At section X (Pl. 1, fig. 1) this half-cycle consists of the same map units (12, 13) that are present at section 10, plus an informal stratigraphic unit that Green and Roddick (1961) have called the "Swiss cheese limestone." The latter unit in section X is comprised of medium gray, light brownish gray-weathering limy siltstone (Pl. 1, fig. 4). Within the siltstone are dispersed limestone nodules that are locally recessive weathering. Dark gray burrows (?) one-eighth inch wide are common. At section X the "Swiss cheese" siltstone is 337 feet thick, and the base of the Sekwi Formation is placed between the limy siltstone of this unit and the nonlimy siltstone and very fine-grained quartzite of underlying map unit 13.

Fossils found in the "Swiss cheese" siltstone belong to the *Nevadella* Zone. As the lowest locality (72 feet above the base) contains an undescribed trilobite known to be near the base of the zone, it is possible that additional fossil finds will locate the *Fallotaspis-Nevadella* Zone boundary in the lower beds of this unit.

Outer detrital strata

Two units of outer detrital strata overlie the "Swiss cheese" siltstone in section X. The lower is a 123-foot unit composed of dark, platy limestone in thin beds, and thick beds of penecontemporaneous breccia (Pl. 1, figs. 1, 2). Some "exotic" blocks of light gray, thick-bedded limestone, orange dolomite, and quartzite are present in the breccia beds. The upper unit consists of 680 feet of dark gray, limy siltstone that weathers to medium brown flakes. Sparse interbeds of light brown, very fine-grained quartzite outline medium- and large-scale penecontemporaneous slump structures that might be overlooked in a more uniform siltstone. Three localities in the siltstone unit contain *Judomia*(?) sp., a *Nevadella* Zone genus that is common in outer detrital strata in the area but rare elsewhere.

Grand cycle A, upper half-cycle (A2)

Only a portion (350 ft.) of this half-cycle is represented in the western segment of section X, the remainder having been displaced by the two outer detrital units just mentioned. This portion is comprised of thin- to very thick-bedded limestone that weathers medium to light gray and is finely crystalline (Pl. 1, fig. 3). At various horizons in the western segment the limestone has been replaced by orange-weathering dolomite. Above the eastern segment of section X (one mile to the east) 255 feet of equivalent strata are composed of fine-grained limestone in medium beds that exhibit cross bedding. Fossils from this limestone unit at both localities belong to the *Nevadella* Zone.

Grand cycle B, lower half-cycle (B1)

The 160-foot interval containing this half-cycle is occupied by light brown-weathering quartzite and siltstone that weathers light brown and light greenish gray. *Skolithos* sp. was the only fossil found but, from regional data given earlier, it is assumed that the boundary between the *Nevadella* Zone and the *Bonnia-Olenellus* Zone lies within the half-cycle. In the eastern segment of section X, a fossil locality containing a *Nevadella* Zone faunule was located 33 feet below the half-cycle. In the western segment a locality belonging to the *Bonnia-Olenellus* Zone was found 132 feet above the half-cycle.

Grand cycle B, upper half-cycle (B2)

Four units in which carbonate predominates are present in this half-cycle. The lower unit (796 ft.) contains mainly gray-weathering limestone in thin, wavy beds. Also present are olive-gray shale, and light greenish gray siltstone that weathers light yellowish orange. Strata in the next overlying unit (1,034 ft.) consists mainly of medium-light gray and medium- to medium-dark brownish gray dolomite in medium and thick beds. Medium and light gray dolomite in the following unit (355 ft.) resembles that in the unit below, but is mainly thin and medium bedded. At the top of the half-cycle is 88 feet of medium gray-weathering limestone in thin, wavy beds. At all localities strata within this half-cycle belong to the *Bonnia-Olenellus* Zone. The uppermost fossil locality, located 15 feet below the top, contains *Bonnia* sp., *Olenellus paraoculus* Fritz, and *Wanneria logani* (Walcott), and is considered to occupy a position high in the medial portion of the zone.

Post-Sekwi dark siltstone and limestone

Overlying the Sekwi Formation is at least 167 feet (faulted?) of black siltstone that weathers rust to black. This in turn is overlain by thin-bedded, platy limestone that weathers dark gray and light orange. *Protospongia* sp., a sponge that is locally common in the Middle Cambrian, was found in float 286, 457, and 485 feet above the top of the Sekwi Formation.

SECTION 7

Grand cycle A, lower half-cycle (A1)

Map unit 10A and an overlying 429 feet of "Swiss cheese" siltstone constitute this half-cycle at section 7. Fossils collected from the medial portion of the latter unit belong to the *Nevadella* Zone (Fritz, 1973). Until fossils are found in the lower "Swiss cheese" beds, it is assumed that they belong to either the *Falloiaspis* or *Nevadella* Zone.

Outer detrital strata

Two units of outer detrital strata in section 7 have laterally displaced the upper half-cycle of grand cycle A and the lower half-cycle of grand cycle B. The lower unit (353 ft.) contains two subunits of dark-gray, platy, laminated limestone (Pl. 2, fig. 4) and a medial subunit (162 ft.) of brown-weathering, limy siltstone. The limestone contains penecontemporaneous slump structures and breccias, and also contains some "exotic" blocks of light gray-weathering limestone. Medium gray, limy siltstone predominates in the upper unit (783 ft.) Sparse interbeds of very fine-grained sandstone outline medium and large penecontemporaneous slump folds (Pl. 2, fig. 2). Small (1 ft.) limestone bioherms containing archaeocyathids are involved in some of the slumping, and near the base of the unit are two horizons of archaeocyathid bioherms that attain a maximum thickness of 33 and 94 feet. The boundary between the *Nevadella* Zone and the *Bonnia-Olenellus* Zone is tentatively placed just below 15 feet of quartzite at the base of this unit. Fossils belonging to the *Nevadella*

EXPLANATION OF PLATE 1

- FIG. 1.—View looking south toward lower segment of section X; "a" is contact between map-unit 12 and map-unit 13, "b" is contact between map-unit 13 and Sekwi Formation, "c" is base of 123-foot dark, platy limestone unit, "d" is top of 680-foot siltstone unit measured one mile to the west in upper segment of section X. GSC photo. no. 202887-C.
- FIG. 2.—Close-up of 123-foot dark, platy limestone unit in section X. At right of center is 31-foot bed of penecontemporaneous breccia. GSC photo no. 202887-G.
- FIG. 3.—Upper beds of 350-foot limestone unit in section X. Medium and medium-gray limestone shown change laterally at various horizons in nearby outcrops to orange-weathering dolomite. Resistant beds of finely crystalline limestone shown are in western segment of section X. They contrast with equivalent fine-grained limestone beds cropping out in moderate relief immediately above "d" in figure 1. The distance between the two outcrops is 1 mile. Assistant with five-foot staff is located by arrow in center of figure. GSC photo no. 202887-E.
- FIG. 4.—Medium brownish gray-weathering siltstone in "Swiss cheese" siltstone, section 8. Note light blue gray weathering limestone nodules scattered through siltstone matrix. GSC photo no. 201829-J.



Zone were found 53 feet below this horizon, and fossils belonging to the *Bonnia-Olenellus* Zone were found 135 feet above.

Grand cycle B, upper half-cycle (B2)

The lower, 370-foot unit in this half-cycle consists of fine-grained, cross-bedded limestone with *Girvanella* sp. 80 feet above the base, and of burrowed siltstone that weathers light brown and orange. Interbedded with the siltstone is some (10 percent) fine-grained sandstone. In the upper unit (1,867 ft.) medium light gray and medium light brownish gray dolomite predominates. Within the lower 650 feet of the dolomite succession are numerous beds containing oolite- and pisolite-sized carbonate grains. Most of the dolomite is thick and medium bedded. A limestone interbed near the top of the unit contains *Bonnia* sp., *Labradoria*(?) sp., and *Salterella* sp., which are assigned to the late medial or upper third of the *Bonnia-Olenellus* Zone.

Post-Sekwi dark siltstone and limestone

Overlying the Sekwi Formation at section 7 is a succession of unfossiliferous dark gray siltstone interbedded with medium light brown, limy siltstone. Fossils were not found above the Sekwi Formation.

SECTION 6

Grand cycle A, lower half-cycle (A1)

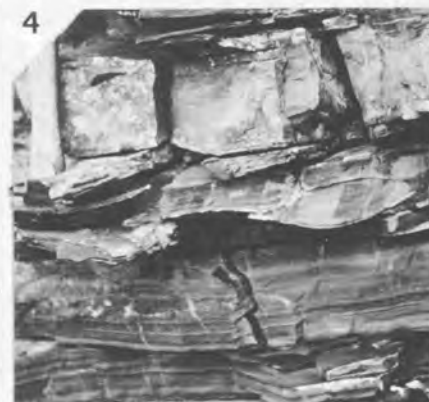
Only a small portion of this half-cycle, consisting of 238 feet of "Swiss cheese" siltstone, is exposed at section 6. Here the "Swiss cheese" unit closely resembles the same unit at sections 7 and X, and contains fossils of the same age.

Outer detrital strata

In section 6 (Pl. 2, fig. 3) the upper half-cycle of grand cycle A, the lower half-cycle of grand cycle B, and most of the upper half-cycle of grand cycle B are displaced by outer detrital strata. The lowest detrital unit consists of 541 feet of mainly dark gray, platy limestone similar to the limestone overlying the "Swiss cheese" siltstone in sections X and 7. In section 6, the boundary between the *Nevadella* Zone and the *Bonnia-Olenellus* Zone lies between fossil horizons located 92 and 470 feet above the base of the platy limestone unit. An intermediate collection of *Bonnia-Olenellus* Zone fossils found 353 feet above the

EXPLANATION OF PLATE 2

- FIG. 1.—View looking southeast toward lower segment of section 7. Base of Sekwi Formation is at "a," top of 353-foot platy limestone and siltstone unit is at "b," top of 783-foot siltstone unit is at "c." GSC photo no. 202887-F.
- FIG. 2.—Penecontemporaneous folds in sandstone and siltstone of 783-foot siltstone unit of section 7. Outcrop is near section 7 at lat. $63^{\circ}27'$, long $129^{\circ}27'$ GSC photo no. 202887-H.
- FIG. 3.—View looking south toward middle segment of section 6. Base and top of 821-foot shale unit in Kekwi Formation are at "a" and "b" KSC photo no. 201829-K.
- FIG. 4.—Dark platy limestone near top of 353-foot unit in lower segment of section 7. GSC photo. no. 202887-J.



base is in float, and therefore is of questionable use in restricting the boundary interval.

Above the platy limestone is a 821-foot unit in which shale predominates (Pl. 2, fig. 3). The lower 630 feet consists of brownish gray-weathering, limy shale with two intervals containing dark, platy limestone; penecontemporaneous limestone breccia is present in the upper interval. The upper 191 feet of the shale unit weathers silvery light yellow.

At the top of the outer detrital succession are three limestone units totaling 904 feet in thickness. In ascending order, they consist of an argillaceous limestone that weathers orange and medium gray (224 ft.), a thin, wavy-bedded limestone that weathers dark blue gray and contains some penecontemporaneous breccias and slump structures (145 ft.), and a thin-bedded, platy limestone that weathers dark gray and exhibits penecontemporaneous folds at several horizons (535 ft.). Numerous trilobite exoskeletons are preserved intact in the upper limestone unit.

Grand cycle B, upper half-cycle (B2)

The platy limestone just mentioned grades upward into this half-cycle, which consists of 275 feet of thin, wavy-bedded limestone with disarticulated trilobite exoskeletons and burrows. The limestone is medium dark gray and weathers medium gray. A fossil locality 135 feet from the top contains *Olenellus puertoblancoensis* (?) (Lochman), which is tentatively assigned to the upper portion of the *Bonnina-Olenellus* Zone.

Post-Sekwi dark siltstone and limestone

Overlying the Sekwi Formation at section 6 is 385 feet of medium brownish gray-weathering, dark gray siltstone that contains some (5 percent) interbeds of bright orange-weathering limestone. Fossils were not found in this unit. The next overlying unit, which is composed of black, brittle shale, contains Lower Ordovician graptolites 55 feet above the base.

INTERPRETATION OF STRATIGRAPHIC SECTIONS

The light-colored quartzite in map unit 12, the thin-bedded, burrowed sandstone and siltstone in map unit 13, and the siltstone and slate equivalent of these two map units to the west (map unit 10a) are considered to have been deposited under intertidal and shallow subtidal conditions at the sites of the eleven sections studied. The following discussion will bear mainly on Lower Cambrian strata above these map-units.

In section 10, one of the thinnest of the eleven sections measured, there is an abundance of thin, wavy-bedded limestone and numerous fossil horizons, suggesting that here deposition took place at a relatively slow, even rate under shallow subtidal conditions. Shallower intertidal conditions may have prevailed during the deposition of the medial 291-foot dolomite unit and the overlying 113-foot unit containing quartzite, siltstone, and orange-weathering dolomite. At the top of the Lower Cambrian succession, the 67-foot interval covered by dark platy silty siltstone and dark silty limestone may contain strata representing an increase in water depth. The overlying dark, platy limestone, bearing a late Middle Cambrian faunule (including agnostids) provides a more definite indication of the deeper conditions. If a deeper water environment is accepted for both units, it seems reasonable to assume an extremely slow rate of sedi-

mentation to account for the close proximity of the upper Lower Cambrian fossils (local float) 10 feet above the base of the covered interval and the upper Middle Cambrian fossils 60 feet higher.

At section X deposition of the 337-foot "Swiss cheese" siltstone is believed to have taken place under quiet, shallow, subtidal conditions. The overlying 123 feet of platy limestone may represent deposition under deeper conditions at a time when clastics were being held in check eastward by a carbonate reef between sections X and 10. A thick dolomite unit that may be part of this reef is present at section 8. Rapid filling of the proposed "off-reef deep" is suggested in section X by the 680 feet of overlying siltstone with penecontemporaneous slump structures. These strata are interpreted as having accumulated on an unstable slope. Once shallower depths were attained, the proposed reef (Pl. 1, fig. 3) to the east may have prograded basinward over the slope deposits, as is suggested by the overlying 350-feet of thin- to thick-bedded, archaeocyathid-bearing limestone. The close of carbonate deposition at the top of this interval and at the top of the 291-foot dolomite unit in section 10 marks the end of grand cycle A in both sections. The overlying 160 feet of quartzite and siltstone in section X is but part of the widespread clastic unit that maintains its relatively thin, uniform thickness (Text-fig. 2, B1) wherever it overlies strata of the middle carbonate belt. It is believed that this unit represents a regional regression caused by a pause, or at least a great reduction, in the rate of subsidence. Thin, wavy-bedded limestone and interbedded siltstone in the succeeding 796-foot unit probably represent a return to the former rate of subsidence and a resumption of shallow subtidal deposition. Dolomite in the overlying 1,034-foot and 355-foot intervals may have accumulated at an equivalent rate, but under very shallow, restricted conditions. Later, during medial *Bonnia-Olenellus* Zone time, normal-marine seas transgressed over the dolomite to deposit 88 feet of thin, wavy-bedded limestone under shallow subtidal conditions. At the location of section X, and probably concurrently at section 7 as well, the seas then deepened to mark the close of grand cycle B, while at section 10 the cycle continued with shallow subtidal deposition until almost the end of *Bonnia-Olenellus* Zone time.

At section 7, the environmental history is nearly the same as at section X for the closing phase of the lower half-cycle of grand cycle A and the following early deposition in the outer detrital belt. Deposition of the "Swiss cheese" siltstone (429 ft.) represents the closing phase under shallow, subtidal conditions, and the overlying platy limestone marks an abrupt change to deeper water (outer detrital) conditions. The reader will recall that the next two events interpreted at section X were siltstone accumulation on an unstable shelf and progradation of a carbonate reef. At section 7 medial siltstone of the 353-foot unit, equivalent to the 680-foot unit at section X, is only 162 feet thick. Dark platy limestone (deep-slope deposits) 97 feet thick in the upper part of the 353-foot unit at section 7 is thought to be the lateral equivalent of the 350-foot carbonate reef at section X. The difference in thickness between the mentioned siltstone and limestone pair at section X and the equivalent pair at section 7 is 771 feet. Although this figure cannot be taken as the exact difference in water depth between section X and 7 after the pairs were deposited (because of compaction, etc.), it gives a general idea of the local relief between the sections and adds weight to the next interpretation—that the overlying 783 feet of siltstone in section 7 were deposited on an unstable slope.

Fossils date most (lower 135 feet barren) of the 783-foot siltstone unit of

section 7 as belonging to the *Bonnia-Olenellus* Zone. Because this 783-foot siltstone unit seems to be separated from the 680-foot siltstone unit in section X by a deep- to shallow-water limestone, and as the 680-foot siltstone unit can be dated as being well within the *Nevadella* Zone, the two units are considered to be the product of two discrete events. The event that triggered deposition of the 680-foot siltstone unit is unknown. Deposition of the 783-foot siltstone unit took place during a period when inner detrital clastics were being deposited at sections X, 10 (Text-fig. 1, B1) and elsewhere (Text-fig. 2, B1). It therefore seems likely that the 783-foot siltstone unit is composed of that fraction of the clastics that bypassed the carbonate platform during the proposed regression and formed a thick unstable prism just oceanward of the middle carbonate belt.

The succession of Lower Cambrian strata (370 ft.) overlying the 783-foot siltstone unit in section 7 is similar to the 796-foot unit exposed in section X. However, it contains a considerable amount of cross-bedded, fine-grained limestone and siltstone that may have been deposited under intertidal, as well as the shallow subtidal, conditions suggested for the 796-foot equivalent unit in section X. The 1,867 feet of overlying dolomite recall the same restricted environment as proposed for the dolomites at section X, and the overlying dark siltstone and platy limestone suggest the same rapid transgression and rapid change to deeper water conditions.

At section 6, the 238 feet of "Swiss cheese" siltstone above the covered base of the Sekwi Formation and the overlying 541 feet of dark platy limestone are believed to represent a shallow subtidal environment abruptly followed by a much deeper environment, which is the same interpretation given for those lithologies near the base of the Sekwi Formation at sections 7 and X. Fossils from the platy limestone unit in section 6 indicate that it belongs not only to the *Nevadella* Zone, but to the lower half of the *Bonnia-Olenellus* Zone as well. Except for rare beds of penecontemporaneous breccia, all other evidence indicates that the 541-foot unit was deposited at a point within the deep basin that was beyond the outer margin of the unstable slope. Overlying the 541-foot unit are 821 feet of shale and a minor amount of limestone with penecontemporaneous breccia. In general, resistant interbeds are lacking, and it was not possible to confirm the presence or absence of penecontemporaneous slump structures. The 821-foot shale unit and the three overlying limestone units (224 ft., 145 ft., 535 ft.) are tentatively considered to be part of a third generation of unstable slope deposits, the other two having been described at sections X and 7. Penecontemporaneous slump structures and breccias in the limestone units suggest the slope environment, and fine planar laminae and trilobite exoskeletons found intact indicate deposition below wave base. The 275-foot limestone unit above the three limestone units and at the top of the Sekwi Formation contains burrows, disarticulated trilobite exoskeletons, and wavy bedding surfaces indicative of a shallow subtidal environment. No evidence (granule-sized limestone clasts, algal mounds, etc.) was found to suggest the near proximity of a limestone bank. It is uncertain whether the 275-foot limestone unit represents an extension of the middle carbonate belt or simply an area of isolated shoaling. *Olenellus puertoblancoensis*(?) found near the top of this unit, suggests a high position in the *Bonnia-Olenellus* Zone that is younger than the localities at the top of grand cycle B in section 7 and X. The overlying 385 feet of dark, limy, post-Sekwi siltstone probably indicates an increase in water depth, although a thin bed of oolite and some burrows

were found 40 feet above the base. The upper Lower Cambrian age is tentatively assigned the immediately underlying limestone, and the presence of Lower Ordovician graptolites 55 feet above the siltstone unit suggests either slow deposition or an unconformity at the top of the unit.

REGIONAL INTERPRETATION OF SECTIONS

In Text-figure 2, eleven sections distributed over nearly 200 miles are placed in a regional facies fence diagram. The diagram shows a large reentrant of outer detrital strata centered near section 6 and extending eastward into the middle carbonate belt. Near the margin of the reentrant the thickness of upper half-cycle A2 and lower half-cycle B1 remains relatively constant. Strata assigned to upper half-cycle B2 and the post-Sekwi Lower Cambrian dark siltstone and platy limestone are thicker northwest of the reentrant. There, sections 1 through 3 contain a higher proportion of siltstone in half-cycles A2 and B2 than do section 8 through 10 on the southeast side of the reentrant. The Sekwi Formation in the sections mentioned on the northwest and southeast sides of the reentrant is comprised predominantly of thin, wavy-bedded limestone that is thought to have been deposited under shallow subtidal conditions. The medium- and thick-bedded dolomite present in half-cycle B2 at sections 7 and X is not present elsewhere, except for some dolomite of this type and age in section 4.

The following tentative explanation for the distribution of Lower Cambrian strata in the study area is based on an assumption that the Lower Cambrian longshore current ran from what is now north to south along the present eastern margin of the Cordillera. Allowing for regional curvature in the Cordillera, the current in the study area should have flowed southeast (following the present depositional strike) and parallel to a line drawn through sections 1 through 3 and 6 through 8. Along this line, and upcurrent from the previously mentioned reentrant, the rate of deposition at the sites of sections 1 through 3 was high, being half again the rate to the south at the sites of sections 8 through 10. Within the reentrant, subsidence was equal to that upcurrent, but the "normal" rate of sedimentation was less because the main detrital load had already been deposited. Here the tendency was toward a relative deepening of waters because of sediment starvation, but this was interrupted by brief periods of rapid sedimentation on unstable slopes. Downcurrent from the reentrant, where subsidence was slower (sections 8-10), shallow-water deposition took place at an even rate. Because detritus was dropped upcurrent at the sites of sections 1 through 3 during "normal" periods of deposition, and in the reentrant (section 6, part of sections 5, 7, X) during "abnormal" periods of deposition, the longshore current carried very little detritus to the sites of sections 8 through 10. Some clastics undoubtedly reached these sections after traveling around the landward margin of the reentrant, while others probably moved across the carbonate shelf from the east. The clearest shallow waters in the area were upcurrent from sections 8 through 10, at the southeastern margin of the reentrant. This is the deposition site of relatively rare carbonates that are clean and thick bedded (section X: 350 ft., 1,034 ft., and 355 ft. units; section 7: 1,867 ft. unit).

REFERENCES

- Aitken, J. D., 1966, Middle Cambrian to Middle Ordovician cyclic sedimentation, southern Rocky Mountains of Alberta: *Canadian Petrol. Geol. Bull.*, v. 14, 405-41.

- Blusson, S. L., 1971, Sekwi Mountain map-area, Yukon Territory and District of Mackenzie: Geol. Surv. Can. Paper 71-22, 17 p.
- , 1972, Sekwi Mountain, Northwest Territories-Yukon Territory: Geol. Surv. Can. map 1333A.
- Fritz, W. H., 1972, Lower Cambrian trilobites from the Sekwi Formation type section, Mackenzie Mountains, northwestern Canada: Geol. Surv. Can. Bull. 212, 58 p.
- , 1973, Medial Lower Cambrian trilobites from the Mackenzie Mountains, northwestern Canada: Geol. Surv. Can. Paper 73-24, 43 p.
- , 1975, Broad correlations of some Lower and Middle Cambrian strata in the North American Cordillera: Geol. Surv. Can. Paper 75-1, Part A, p. 533-40.
- Green, L. H., and Roddick, J. A., 1961, Nahanni, Yukon Territory and District of Mackenzie: Geol. Surv. Can. map 14-1961.
- Handfield, R. C., 1968, Sekwi Formation, a new Lower Cambrian formation in the southern Mackenzie Mountains, District of Mackenzie: Geol. Surv. Can. Paper 68-47, 23 p.
- Palmer, A. R., 1960, Some aspects of the early Upper Cambrian stratigraphy of White Pine County, Nevada and vicinity: Intermountain Assoc. Petrol. Geol., Eleventh Ann. Field Conf., p. 53-62.
- Robison, R. A., 1960, Lower and Middle Cambrian stratigraphy of the eastern Great Basin: Intermountain Assoc. Petrol. Geol., Eleventh Ann. Field Conf., p. 43-52.

Depositional Environments of the Lower Cambrian Poleta Formation and Its Stratigraphic Equivalents, California and Nevada

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ABSTRACT.—The Poleta Formation contains distinct members and subunits identifiable over a large portion of the western Great Basin (14,000 km²). Lower member deposition took place in a carbonate-bank complex where environments ranged from restricted behind shoal to outer margin. Terrigenous sedimentation in tidal-flat to offshore environments dominated the middle member. The upper member marks a return to carbonate bank deposition but in a transitional back-bank to shoal environment.

Carbonate deposition took place in bank systems which were elongate northeast-southwest with currents approximately paralleling this trend. Terrigenous sediment was derived from a southeastern source and deposited in a basin with loci of active subsidence.

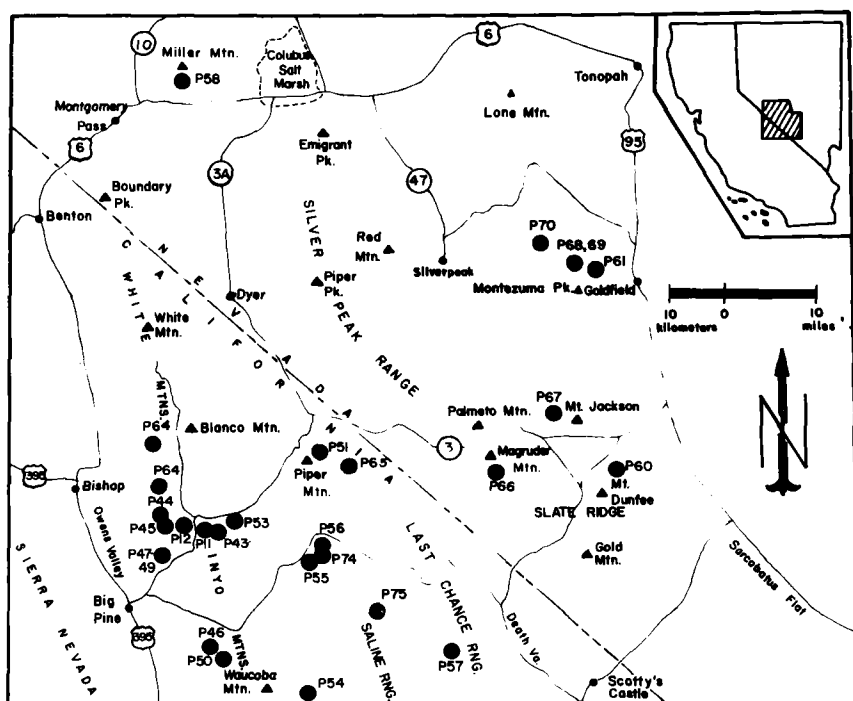
INTRODUCTION AND STRATIGRAPHY

The Poleta Formation is a distinctive Lower Cambrian marine carbonate and terrigenous sequence exposed throughout eastern California and western Nevada. Nelson (1962) named the formation for exposures in the western White Mountains, Inyo County, California. He (Nelson 1966a, b; 1971) divided the Poleta into two members but McKee and Moiola (1962) and Stewart (1970) preferred a three member subdivision. The three member nomenclature is followed in this report.

In the area studied, approximately 14,000 km² (Text-fig. 1), the Poleta Formation ranges in thickness from about 180 m (locality P56) to nearly 330 m (P75); Stewart (1970) measured a much thicker section (576 m) of the Poleta in the Weepah Hills, Esmeralda County, Nevada, but that section is not included in this investigation. The Poleta Formation is correlative with carbonates of the upper member of the Wood Canyon Formation in the Death Valley region (Stewart, 1970), which further correlates with a portion of unit 3 of the Prospect Mountain Quartzite in central Nevada (Stewart, 1974). Because of the similarity and sequence of lithologies, the Poleta is here considered correlative to the sequence of marble, hornfels, and quartzite described by Wilson (1961) at Miller Mountain, Nevada. This correlation is supported by the trilobite fauna within this sequence (Nelson, personal communication) and the occurrence of archeocyathids in the upper limestone.

Conformably underlying the Poleta is a dominantly siltstone and shale unit, the Montenegro Member of the Campito Formation. The Harkless Formation, containing siltstone, shale, and minor limestone and sandstone, conformably overlies the Poleta.

The fauna of the Poleta Formation is characterized by an abundance of archeocyathids (McKee and Gangloff, 1969), trilobites (Nelson, 1975), and by the occurrence of *Helicoplacus* (Durham and Caster, 1963). Trilobites from the terrigenous units within the Poleta have been used by Nelson (1975) to establish zones within the area of exposure, and the Poleta contains the boundary between the *Nevadella* and *Bonnia-Olenellus* zones. This boundary's



TEXT-FIGURE 1.—Index map showing location of measured sections.

widespread occurrence at about the same horizon within the middle member suggests that Poleta member boundaries approximate time lines. This contention is supported by Stewart's (1970) observation that near time-equivalence of major lithologic subdivisions, Precambrian-Cambrian sequence, exists in the western Great Basin. Internal stratigraphy and regional changes in depositional environments within the Poleta also suggest near time-equivalence of each member.

REGIONAL STRATIGRAPHIC VARIATION AND DEPOSITIONAL ENVIRONMENTS

General Statement

Textures, associated faunas, and sedimentary structures within each unit of the Poleta are detailed in Text-fig. 2. Comparison with modern analogues is used to reconstruct the environments of deposition for each member, and differences between southern (central Inyo Mountains and Last Chance Range) and northern localities (White-Inyo Mountains and Esmeralda County) are described.

Throughout the area studied, the upper part of the Montenegro Member contains lithologies, bedding forms, and primary sedimentary structures, characteristic of a tidal flat as described by Klein (1970), Reineck (1972), and Reineck and Singh (1973). In the northern exposures, archeocyathid bioherms

are present but limited in extent, and represent deposition in a shallow subtidal environment.

The Harkless Formation also displays characteristics typical of a tidal flat. However, the lower few meters may have been deposited in a subtidal environment, for the beds are characterized by trilobite fragments and abundant horizontal trace fossils. Sandstone and limestone marker beds in the Harkless were deposited in environments varying from intertidal to very shallow subtidal; they possibly accumulated in sand flats or sand bars and shoals (Barnes and Klein, 1975). Some beds grade laterally into archeocyathid bioclastic limestone which was deposited subtidally as local banks and mounds.

POLETA LOWER MEMBER ENVIRONMENTS

The limestone-dominated lower member ranges in thickness from 35 m in the Last Chance Range to about 140 m in the White Mountains, where interbedded shale adds to the thickness. The limestone contains abundant archeocyathids. Five major lithofacies make up the lower member: 1) archeocyathid-bearing bioclastic limestone, 2) archeocyathid-bearing biohermal limestone, 3) oolitic limestone, 4) bioclastic and oolitic limestone, 5) shale, (Text-figs. 2 and 3).

Oolitic-Shoal Lithofacies

This lithofacies separates bioclastic and oolitic limestone of northern areas from archeocyathid-bearing bioclastic limestone in southern localities (Text-fig. 3a). The lower member oolitic limestone represents deposition in a shoal environment at or near the bank margin. The textures and scale of cross laminae in this unit suggest deposition in an environment analogous to the tidal-bar belt of Ball (1967) in the Great Bahama Bank. The absence of large-scale cross strata suggests no extensive development of tidal deltas or spill-over lobes typical of the marginal marine belt of Ball (1967).

Back-Shoal Archeocyathid-bearing Bioclastic Limestone

Southward of the oolitic-shoal lithofacies, the lower member represents deposition in a fairly turbulent environment which was occasionally restricted and near a terrigenous source. These features could easily be formed behind an oolitic shoal. Such an area would be somewhat isolated from the open marine environment but could also be subject to active tidal currents. The bryozoan facies of the Pleistocene Miami Limestone contains similar characteristics and is an analogue of the Poleta. Hoffmeister, et al. (1967) described this facies as forming shoreward of an oolitic-shoal facies. The archeocyathid-bearing bioclastic limestone formed shoreward of the oolitic-limestone lithofacies but was transitional to tidal flats to the southeast (uppermost Wood Canyon Formation) from which the terrigenous sediment was derived. The irregular archeocyathids of this unit are analogous to the bryozoans of the Miami Limestone. The minor associated oolitic limestone probably formed on local shoals.

Archeocyathid Bioherms

Although only forming a minor part of the lower member, this lithology is very distinct. It was deposited as local bioherms within the carbonate bank in areas with subdued current activity. Analogous deposits are forming today

in the Abu Dhabi Complex, where irregular patch reefs are established on shallower portions of the inner shelf (Bathurst, 1975). Lower member "patch reefs" are not biologically bound reef limestones. In southern localities they are dolomitic, contain quartz silt, and represent deposition behind the major shoal complex with some terrigenous influx. In contrast, the terrigenous-free limestone of the bioherms in northern localities represents deposition seaward of or within the marginal complex.

Shelf Margin Bioclastic-Oolitic Limestone

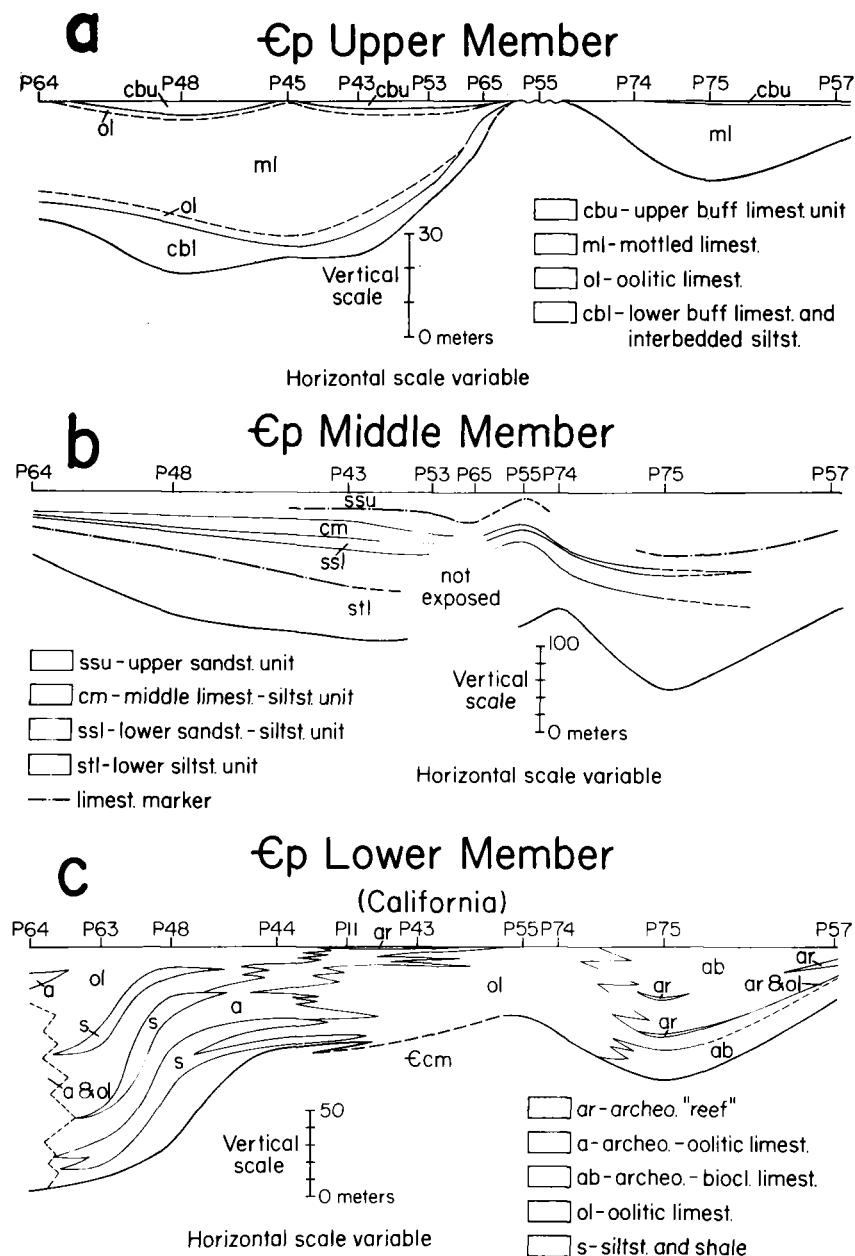
In the White-Inyo Mountains the oolitic limestone of the lower member is transitional to an archeocyathid-bearing, bioclastic, and oolitic limestone. This is the major lithology of the lower member in Esmeralda County, Nevada, as well as in the White Mountains. It represents deposition on the bank edge or upper outer slope, just seaward of the oolitic-shoal complex. Tidal current activity is indicated by the presence of lenses of intraclastic limestone which probably formed in tidal channels within the marginal complex. This unit ranges from nearly pure bioclastic limestone to oolitic limestone, but always contains a large amount of archeocyathid debris. It differs from the bioclastic limestone in the southern localities, deposited in the back-shoal environment, in containing only a minor amount of silty-dolomitic limestone, and by being much finer grained and more oolitic.

Offshore Shale

Dark greenish gray shale is present within the lower member in northern localities of the White Mountains (Text-fig. 3a). The lithology, bedding types, and fauna indicate terrigenous subtidal deposition (Emery, 1960). Archeocyathid-trilobite bioclastic limestone lenses in the shale were probably deposited in channels formed by tidal currents, indicating that deposition occurred in a shallow subtidal environment. The occurrence of these terrigenous muds seaward of the carbonate-bank shoal complex suggests they were deposited in the offshore environment. During deposition of the lower member, terrigenous mud from the southeast was transported across the bank. Some mud accumulated on the outer bank margin; however, the bulk of the sediment was deposited seaward of the bank.

TEXT-FIGURE 2.—General stratigraphic column comparing characteristics of northern and southern localities. *Texture*: xl—crystalline limestone; o—oolitic limestone; p—pelletal limestone; bc—bioclastic limestone; stly—silty limestone; f ss—fine and very fine grained sandstone; m ss—medium grained sandstone; ic—intraclastic limestone; sh—shale and siltstone; sdm—silty-dolomitic limestone interlayers. *Bedding*: i—indistinct; t—thin (1 to 10 cm); m—medium (10 to 60 cm); tk—thick (60 to 150 cm). *Laminae*: tr—trough cross laminae; ir—irregular laminae; h—horizontal laminae; hb—herringbone cross laminae; la—low angle cross laminae; fl—flaser bedding; ln—lenticular bedding; rs—reactivation surface; w—wedge cross laminae; p—planar cross laminae. *Ripple Marks*: sw—straight-crested, wave; ip—interference, two perpendicular crests; r—Runzelmarken; if—interference, flat-topped; ii—interference, irregular; sc—straight-crested, current. *Burrows*: bm—burrow mottling; v—vertical burrows; h—horizontal trails and burrows; vb—burrows changing from vertical to horizontal. *Other*: es—escape structures; mc—mud cracks. *Fauna*: T—trilobites; A—archeocyathids; B—brachiopods; H—Helicopacrus.

NORTHERN LOCALITIES									SOUTHERN LOCALITIES								
UNIT (Fig. 3)	LITHOLOGY	TEXTURE	BEDDING	LAMINAE	IRIPPLE MK.	BURROWS	OTHER	FOSSILS	FOSSILS	OTHER	BURROWS	IRIPPLE MK.	LAMINAE	BEDDING	TEXTURE	LITHOLOGY	
ol		o	m	tr	—	—	—	—	—	—	—	—	—	—	—		
mi		o, bc, sdm	t-m	ir	—	bm	—	A	—	—	bm	—	ir	t	p, xl sdm		
ol		o	m	tr	—	—	—	A	—	—	—	—	—	—	—		
cbl		xl, sty	t	ir	—	—	—	A	—	es,	v,	sw, li,	hb, h,	m-tk	msa, fss		
ssu		f-m ss	m-tk	h, la	sw, ip	v, h, bm	lc, mc	T	—	mc	h	ac r	la	—	—		
cm		e, p, sh	t-m	tr, h, ir	—	bm	—	T, A	—	—	—	—	—	—	—		
ssi		fss	m	h, la	r	h	lc	T	—	—	—	ip r	rs tr	t	fss sh		
sti		sh	t	fl, ln,	r, ip, if, il	h	rs	T	—	—	—	li,	fl,	—	—		
		o, lc	m-t	la	—	—	—	A	T	mc	h	ip, if, r	ln, tr	t	fss st		
ol, a, s		o, bc, ic	t-m	tr, w, p	—	vh	—	A, B	A	—	—	—	tr	—	bc, o		
		sh	t	h, ln, tr	—	—	—	B, A, T	—	—	—	—	ir, tr	—	—		
		sh	t	h, ln, tr	—	—	—	B, A, T	—	—	—	—	tr	—	—		



TEXT-FIGURE 3.—Generalized cross sections of the Poleta members from the Last Chance Range to the White Mountains. See Text-figure 1 for locality numbers.

POLETA MIDDLE MEMBER DEPOSITIONAL ENVIRONMENTS

The middle member represents a return to terrigenous sedimentation after a major stage of carbonate-bank deposition. It ranges in thickness from about 70 m in the northern White Mountains to 230 m in the northern Saline Range. Two major geographic subdivisions of the member are apparent from the detailed internal stratigraphy. In northern localities four subunits are easily distinguished (Text-fig. 3b), representing deposition in intertidal to shallow subtidal environments along an open coast. In southern areas the subunits are less distinct, generally contain more sandstone and display sedimentary structures and lithologies typical of an intertidal environment. Although the majority of sedimentation was terrigenous, there was a brief return to carbonate deposition to form the persistent limestone unit within the middle member.

Southern Tidal-Flat Lithofacies

Lithologies and sedimentary structures in the middle member reflect deposition in the tidal-flat environment, ranging from mud flat to lower sand flat (Reineck and Singh, 1973). Flat-topped interference ripple marks present in the lower part of the member are analogous to those found on modern tidal flats, and the abundance of siltstone with Runzelmarken and mudcracks indicates deposition on mud flats, the highest portion of the tidal flat where current activity is at a minimum. Higher in the section, sandstone beds become dominant and thicker, signifying evolution to a dominantly mixed flat and lower flat environment where deposition took place in sand flats and bars. Although sandstone is generally evenly laminated, *Skolithos* is very common, the burrows forming distinct escape structures (Reineck and Singh, 1973). These are common features on modern tidal flats (Reineck, 1972) where large amounts of sand are being deposited in the lower flat. The presence of herringbone cross laminae is further evidence of lower tidal-flat or intertidal-bar deposition (Klein, 1967, 1970; Hays, 1971).

Northern Localities

Lower Siltstone Unit.—This unit forms about two-thirds of the middle member in most White-Inyo Mountains localities. The unit is divided into an upper and lower part by a continuous limestone marker bed. In the White-Inyo Mountains the lower siltstone unit (Text-fig. 3b) represents deposition in mud-flat and shallow subtidal environments separated locally by a carbonate-sandbar complex, the limestone marker bed. Sedimentary structures and the associated fauna indicate subtidal deposition below the marker. Interbedded sandstone and intraclastic and bioclastic limestone lenses were formed in channels; locally their sinuous pattern on bedding planes suggests deposition as tidal channels.

Above these subtidal muds, the limestone marker bed was deposited in a much more energetic environment. Sedimentary structures suggest it was deposited in longshore bars or a foreshore environment (McKee, 1957) or in tidally dominated subtidal bars (Reineck and Singh, 1973). Above the marker, the upper part of the lower siltstone unit contains structures and lithologies similar to those seen in southern localities representing mud-flat deposition. However, here there is less sand, and deposition occurred totally in a mud flat with interbedded sandstone and limestone lenses possibly de-

posited in subtidal or lower intertidal channels, as indicated by their shape and coarser grain size.

The lower siltstone member in Esmeralda County contains features typical of subtidal deposition only. Lithologies and sedimentary structures are similar to those of the lower part in the White-Inyo sections and trilobite fragments are common throughout the unit. Also the increase in channel sands and carbonates containing trilobite fragments and archeocyathids supports shallow subtidal deposition with no associated tidal-flat environments.

Lower Sandstone-siltstone Unit.—Above the lower siltstone unit an extensive but thin unit (generally about 20 m) represents deposition in a wave-dominated bar complex. This unit's lithologies and associated sedimentary structures are common in the shoreface-offshore transition (McKee, 1957; Howard, 1972). The presence of Runzelmarken, interference ripple marks, and mudcracks indicates the sand was locally emergent. Characteristics of the unit as a whole indicate deposition in a shoreface-offshore transition, but with bars locally extending into the foreshore.

This unit contains more limestone and calcareous sandstone in the Esmeralda sections, suggesting deposition was mainly within the shoreface-offshore transition. Intermixing of terrigenous and carbonate sands in the Esmeralda sections represents the beginning of the return to local carbonate deposition in the overlying unit.

Middle Limestone-siltstone Unit.—This unit is composed of gray and light brown, mottled limestone with subordinate interbedded shale and is from 10 to over 30 m thick. It represents a brief return to carbonate-bank deposition. Basal coarse calcarenite containing cross laminae and megaripple marks suggests strong tidal currents. The remainder of the unit is burrow-mottled limestone typical of back bank environments in modern carbonate banks (Newell et al., 1960; Purdy, 1963). Within the unit, shale containing abundant trilobites indicates a return to offshore conditions. The unit as a whole represents deposition in a somewhat protected subtidal carbonate-bank complex with occasional influx of terrigenous sediment in the offshore.

Upper Sandstone Unit.—This unit represents the largest accumulation of sandstone in the Poleta Formation and forms one-quarter to one-third of the middle member in northern localities. The major lithology is thick-bedded sandstone containing the ubiquitous and abundant vertical burrow *Skolithos*. Locally the sandstone is nearly homogenized by burrowing and displays a faintly mottled appearance.

These sands were deposited in a bar complex mainly within the foreshore but ranging into the uppermost offshore. The thick quartz arenite of this unit was deposited in the foreshore. Interference ripple marks, Runzelmarken, and mudcracks indicate local and periodic emergence with some tidal influence. However, most of the current activity was due to wave action in a typical beach and nearshore environment similar to those forming today along low-gradient coastlines (McKee, 1957; Reineck and Singh, 1973). Bioturbated and silty sandstone and mottled limestone concentrated in the center of the unit represent upper shoreface deposition. The upper and lower thick beds and associated widespread vertical burrows, escape structures, and load structures in Esmeralda County sections suggest very rapid deposition.

POLETA UPPER MEMBER DEPOSITIONAL ENVIRONMENTS

Two major geographic subdivisions of the upper member are discernible on the basis of stratigraphy. The boundary between them occurs in the southern White-Inyo Mountains (Text-fig. 3c), where the member was not deposited (P 55 Text-fig. 3c). North of this boundary, in the White-Inyo Mountains and in Esmeralda County, the member contains four major lithologies indicative of different depositional environments: 1) buff limestone and interbedded siltstone deposited in a terrigenous to carbonate transition, 2) oolitic limestone deposited in a shoaling bank environment, 3) mottled oolitic-bioclastic or micritic-pelletal (?) limestone deposited in back-bank to shoal transitional environments, 4) structureless crystalline limestone probably formed by local exposure of the carbonate-bank complex. South of the area of nondeposition, the member is composed almost entirely of mottled, micritic, and pelletal (?) limestone deposited in a back-bank environment. Locally, crystalline limestone identical to that in the northern localities is also present.

The upper member represents reestablishment of carbonate-bank deposition of a more restricted nature than that of the lower member. Carbonate sedimentation ended abruptly with the inception of extensive terrigenous tidal-flat deposition of the overlying Harkless Formation.

Back-Bank Lithofacies of Southern Localities

In the northern Last Chance and Saline ranges, the upper member is composed of mottled limestone deposited in a somewhat restricted back-bank environment. These lithologies are similar to the pellet mud facies in the interior of the Great Bahama Bank (Newell, et al., 1960; Purdy, 1963). Abundant burrowing, which would lead to mottling, is typical of interior platform sand blankets (Ball, 1967; Bathurst, 1975) in which local exposure followed by lithification results in local unconformities. At the top of the upper member a thin (1 to 2 m) buff, finely crystalline limestone is present locally (Text-fig. 3c). The localized occurrence of this unit and its complete recrystallization, compared to the minor recrystallization of surrounding rocks, suggest it is the result of local exposure. A minor amount of oolitic limestone is also present in the more northern sections (P 74, P 75) and was probably deposited on local shoals within the interior platform. Silty and dolomitic limestone in the member suggests that the back-bank was somewhat restricted and there was a significant influx of terrigenous sediment from a southeastern source area.

The area of nondeposition of the member lies just northward of the back-bank lithofacies. Here the uppermost Poleta is replaced by interbedded calcareous sandstone and limestone. The area was tidally dominated as evidenced by the common reactivation surfaces and herringbone cross laminae (Klein, 1970). This represents an areally limited, terrigenous sand shoal upon which there was no appreciable carbonate sedimentation. South of this shoal back-bank carbonate was deposited with minor current activity and a significant terrigenous influx.

Terrigenous-Carbonate Transition

Northwest of the area of nondeposition in the White-Inyo Mountains and northward in Esmeralda County, the upper member thickens and is more

varied (Text-fig. 3c). At the base of the member a buff limestone and siltstone unit represents the transition from terrigenous sedimentation of the upper sandstone unit of the middle member to carbonate sedimentation of the upper member.

This unit is from 3 to 14 m thick and forms a conspicuous light brown band at the base of the member. Locally it contains limestone breccia and interbedded sandstone similar to the upper sandstone unit of the middle member. Archeocyathids in the unit suggest subtidal deposition and large clasts indicate strong current action in the shallow subtidal. However, this is inconsistent with the fine grain size, dominantly micrite, of the limestones and the interlayered siltstone. In general, the unit was deposited in the shallow subtidal and certainly represents a transition from terrigenous sedimentation to carbonate-bank deposition.

Oolitic-Shoal Lithofacies

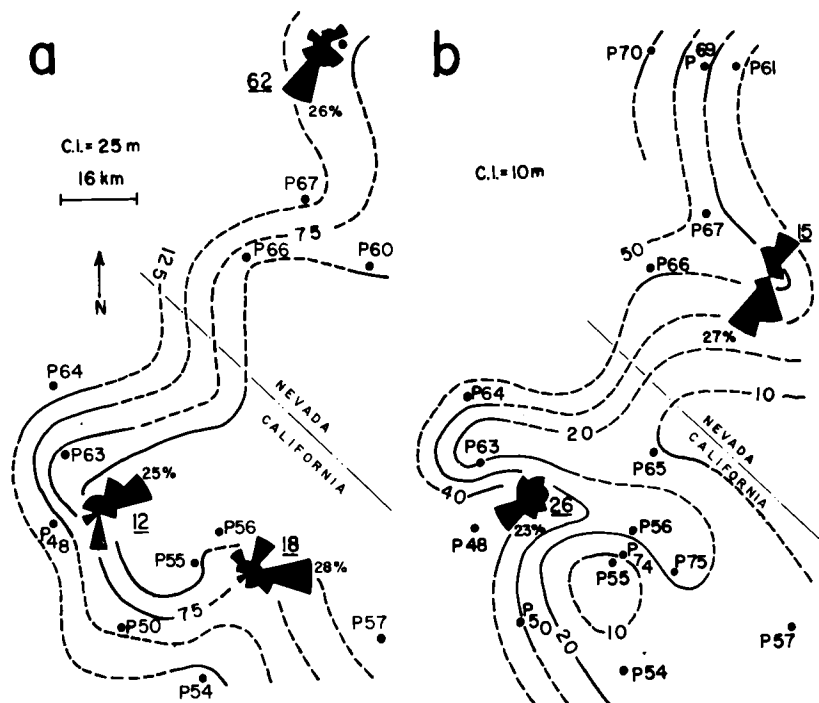
In northern sections in the White-Inyo Mountains the major upper member lithology, mottled limestone, is bounded above and below by oolitic limestone (Text-fig. 3c). This limestone is from 1 to 2 m thick and represents deposition in a turbulent marginal-shoal complex similar to that described for the oolitic limestone of the lower member. In Esmeralda County sections, oolith deposition was supplemented by biogenic constituents and the current activity was quite high, such as would occur in tidal channels.

In most northern sections the top of the upper member is marked by the presence of a light brown to white crystalline limestone. This unit also possibly resulted from local exposure, which caused recrystallization and lithification at the carbonate bank surface, as postulated for similar rocks in the southern sections.

Back-Bank-Oolitic-Shoal Lithofacies.—The bulk of the upper member is composed of mottled limestone deposited in an open back-bank environment. This lithology is similar to the open interior platform sands (Ball, 1967) or a combination of the oolitic and grapestone lithofacies (Purdy, 1963) of the Great Bahama Bank. Mottling in this unit is definitely due to burrowing and distinct burrow systems are common on bedding planes.

The unit differs from mottled limestone of the back bank in southern sections by containing much less silty limestone and by the prevalence of ooliths and bioclastic grains. This suggests the unit was deposited near the bank margin and probably received ooliths from the shoal, together with bioclastic material from just behind the shoal. Current activity was low enough, however, to allow abundant burrowing, and terrigenous influx was significantly reduced.

In the Esmeralda sections, where no area of nondeposition divides the member, the unit contains more silty interlayers southward, but they are much less dolomitic than those in the Last Chance and Saline Ranges. The lack of the barrier prevented the formation of a more restricted environment. The unit retains its dominantly bioclastic nature with a larger input of terrigenous sediment, but without the influx of ooliths from the bank margin.

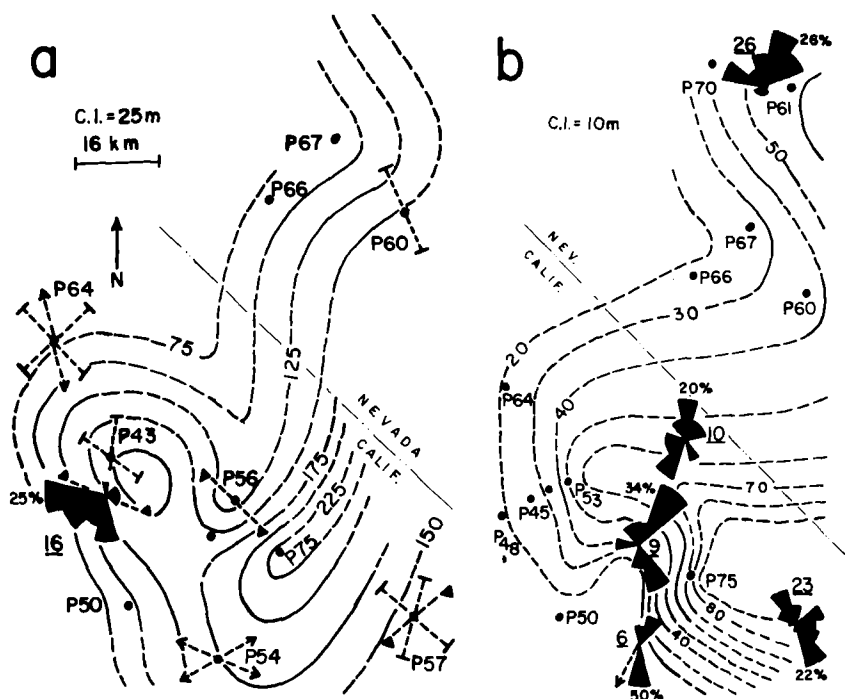


TEXT-FIGURE 4.—Isopach maps for (a) lower and (b) upper members. Plotted on palynostratigraphic locality map, reconstruction based on published geologic maps and Stewart's (1967) interpretation of the Furnace Creek Fault Zone. Current roses from rotated cross laminae, underlined number next to rose is number of measurements; percent of measurements in the largest class is indicated.

BASIN PALEOGEOGRAPHY

Lower Member

Isopach trends for the lower member are consistent with a carbonate-bank system elongate in a northeast-southwest direction (Text-fig. 3a). Cross laminae orientation data in the outer margins (left-upper roses, Text-fig. 4a) of the bank suggest that currents approximately paralleled the elongate trend. The crest of bars at the margin of the present-day Great Bahama Bank generally preserve across-bank tidal currents (Ball, 1967). However, along-bank currents are also significant and in the outer margins longshore currents would probably predominate. Because most of the lower member current data are from the outer shoal or outer margin complex, these along-bank trends are prominent. Poleta current directions behind the shoal were probably more varied. The resulting analogous cross strata for the Poleta lower rose (Text-fig. 4a) show that current directions were a combination of across-bank and along-bank trends. Morphology of the bank definitely affected current directions because the roses parallel or are perpendicular to isopachs. Although sediment was transported across the bank, along-bank currents were important and were probably longshore currents



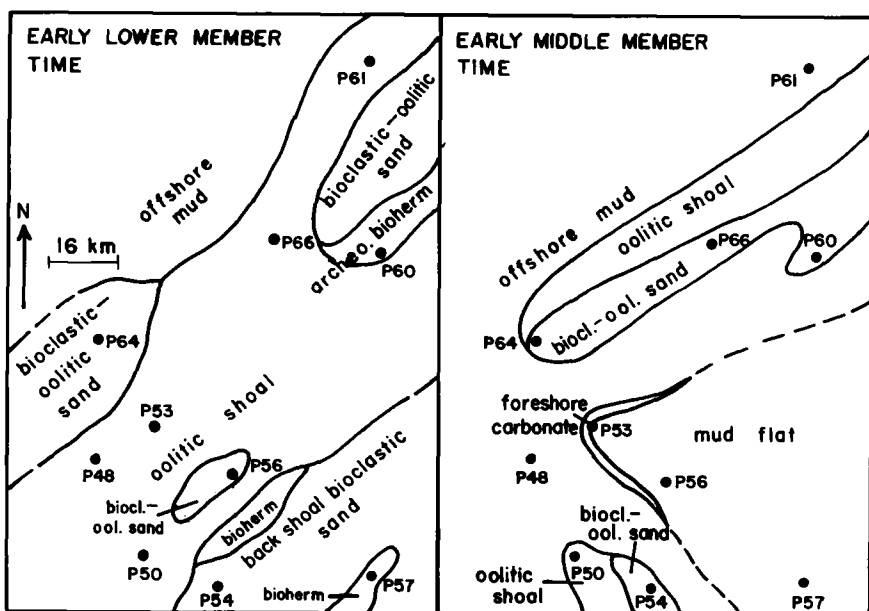
TEXT-FIGURE 5.—Isopach maps for (a) middle member and (b) upper sandstone unit of the middle member. Plotted on palinspastic base. Dashed lines are trend of ripple mark crests. Barred ends signify irregular ripple marks, arrowed ends signify straight crested wave ripple marks, and solid triangles on ends point in the direction of steep face on straight crested current ripple marks.

parallel to the bank edge. Similar patterns are common at the margins of terrigenous tidal bars (Evans, 1965).

Middle Member

Middle member isopachs show more varied basin subsidence (Text-fig. 5a). An elongate center of subsidence in the southeast is separated from another in the northwest by an area of reduced sedimentation. However, the member generally thins northward. Ripple marks oriented normal to and parallel to isopachs represent tidal and longshore currents respectively. The southeastward thickening and the increase in sandstone indicate a south-eastern source. During middle member carbonate deposition there was a return to northeast-southwest currents (rose, Text-fig. 5a).

Isopachs for the upper sandstone unit of the middle member (Text-fig. 5b) define a southeastward thickening wedge substantiating a southeasterly source. Cross laminae directions are consistent with tidal currents normal to shore in the higher flats (southeasternmost rose, Text-fig. 5b) and long-shore dominated currents seaward (Evans, 1965).



TEXT-FIGURE 6.—Generalized paleofacies maps. Plotted on palinspastic base. Localities are for orientation and do not represent the only data points used to construct the maps. See isopach maps for complete distribution of data points.

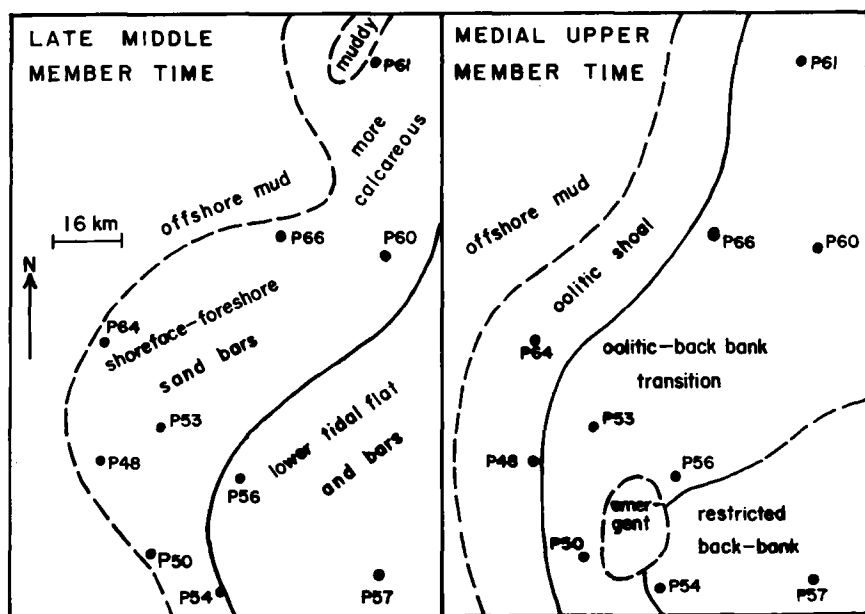
Upper Member

Thickness trends and current data for the upper member suggest a return to deposition in a carbonate bank elongate in the northeast-southwest direction (Text-fig. 4b). Basin morphology is more akin to that of the middle member with the area of reduced deposition replaced by an area of very little or no deposition (closed 10 m isopach), and is more irregular in character. However, currents in the more seaward portions of the bank paralleled the bank. The back-bank environment was restricted behind the depositional high, but was not a center of subsidence and deposition as in the middle member.

CONCLUSIONS

From the foregoing discussion the following generalizations for deposition of the Poleta Formation are made:

- 1) Deposition was along a low-gradient marine coastline subject to both near-shore and tidally dominated currents.
- 2) The area was generally stable with the rate of deposition increasing seaward (northwestward).
- 3) Local areas of more or less subsidence indicate some basins were areally restricted.
- 4) During carbonate deposition northeast-southwest trending currents dominated, paralleling an elongate bank system.



TEXT-FIGURE 7.—Generalized paleofacies maps. Plotted on palinspastic base.

- 5) Terrigenous sedimentation spread northwestward from a southeasterly source area and was characterized by both tidally dominated (northwest-southeast trending), and longshore currents (northeast-southwest trending).
- 6) Lithologic changes within the grossly time-equivalent members resulted from a combination of minor transgressions and regressions across depositional environments.
- 7) The changes from dominantly carbonate to dominantly terrigenous members and changes from dominantly siltstone to sandstone within the middle member resulted from the amount of influx of terrigenous sediment from a southeastern source area.

Although these generalities characterize Poleta deposition they do not describe the evolution of the varied environments that formed the present distribution of Poleta lithofacies. Paleoenvironments can be summarized in four generalized paleofacies maps (Text-figs. 6 and 7). Because of the approximate nature of time lines, the maps represent depositional models rather than precise paleofacies maps.

During deposition of the lower part of the lower member (early lower member time map) the inception of the broad oolitic shoal that started bank deposition is apparent. Bioclastic sand formed behind the shoal and near the outer margin of the bank. Archeocyathid bioherms were restricted and associated with bioclastic areas. Offshore mud was restricted to the seaward portion of the bank.

With an increase in terrigenous sedimentation during deposition of the lower part of the middle member (early middle member time map), tidal

flats pushed northwestward restricting carbonate-bank sedimentation. Offshore mud covered most of the bank area and was separated from the extensive southeastern tidal flats by a carbonate beach-bar complex (foreshore carbonate).

By the time the upper sandstone unit of the middle member was being deposited (late middle member time map), extensive sandbars and lower sand flats had developed. Sediments in the southeast were still tidally dominated and sand was being deposited across the entire area. The sandbars in the shoreface-foreshore were probably bounded seaward by offshore muds. The bars were muddier seaward and became more calcareous to the northeast.

Carbonate bank deposition was firmly reestablished during deposition of the middle part of the upper member (medial upper member time map). A narrow (relative to the lower member) oolitic shoal allowed extensive back-bank deposits to form. These were more restricted to the southeast behind the area of nondeposition (emergent on map). Offshore muds probably were seaward of the bank although none are seen in the sections because the outer edge of the bank is not exposed.

The Poleta sedimentary complex was ended by extensive tidal flat sedimentation of the Harkless Formation. These muds covered the entire area and the only remnants of the extensive carbonate bank deposition of the Poleta are the thin limestone marker beds in the lower Harkless.

REFERENCES

- Barnes, J. J., and Klein, G. deV., 1975, Tidal deposits in the Zabriskie Quartzite (Cambrian), eastern California and western Nevada: *in* Ginsburg, R. N. (ed.), *Tidal deposits*: 163-69.
- Ball, M. M., 1967, Carbonate sand bodies of Florida and the Bahamas. *J. Sediment. Petrol.* v. 37, p. 556-91.
- Bathurst, R. G. C., 1975, Carbonate sediments and their diagenesis. *Developments in Sedimentology*, v. 12, 658 p.
- Durham, J. W., and Caster, K. E., 1963, *Helicoplacoida*: a new class of echinoderms: *Science*, v. 140, p. 820-22.
- Emery, K. O., 1960, Basin plains and aprons off southern California: *J. Geol.* v. 68, p. 464-79.
- Evans, G., 1965, Intertidal flat sediments and their environments of deposition: *Wash. Geol. Soc. London Quart. J.* v. 121, p. 209-45.
- Hayes, M. O., 1971, Geomorphology and sedimentation of some New England estuaries: *Amer. Geol. Inst. Short Course Lecture Notes*: XII-1-XII-71.
- Hoffmeister, J. E., Stockman, K. W., and Multer, H. G., 1967, Miami Limestone of Florida and its Recent Bahamian counterpart: *Geol. Soc. Amer. Bull.*, v. 78, p. 175-90.
- Howard, J. D., 1972, Trace fossils as criteria for recognizing shorelines in stratigraphic record: *in* Rigby, J. K., and Hamblin, W. K. (eds.), *Recognition of ancient sedimentary environments*: *Soc. Econ. Paleont. Miner. Spec. Pub.* 16, p. 215-25.
- Klein, G. deV., 1967, Paleocurrent analysis in relation to modern marine sediment dispersal patterns: *Amer. Assoc. Petrol. Geol. Bull.*, v. 51, p. 366-82.
- , 1970, Depositional and dispersal dynamics of intertidal sandbars. *J. Sediment. Petrol.*, v. 40, p. 1095-127.
- McKee, E. D., 1957, Primary structures in some recent sediments: *Amer. Assoc. Petrol. Geol. Bull.*, v. 41, p. 1704-47.
- McKee, E. H., and Muiola, R. J., 1962, Precambrian and Cambrian rocks of south central Esmeralda County, Nevada: *Amer. J. Sci.*, v. 260, p. 530-38.
- , and Gangloff, R. A., 1969, Stratigraphic distribution of *Archeocyathids* in the Silver Peak Range and the White and Inyo Mountains, western Nevada and eastern California: *J. Paleont.* v. 43, p. 716-26.
- Nelson, C. A., 1962, Lower Cambrian-Precambrian succession, White-Inyo Mountains, California: *Geol. Soc. Amer. Bull.* 73, p. 139-44.

- , 1966a, Geologic map of the Waucoba Mountain quadrangle, Inyo County, California: U. S. Geol. Surv. Quad. Map GQ-528, scale 1:62500.
- , 1966b, Geologic map of the Blanco Mountain quadrangle, Inyo and Mono Counties, California: U. S. Geol. Surv. Quad. Map GQ-529, scale 1:62500.
- , 1971, Geologic map of the Waucoba Spring quadrangle, Inyo County, California. U. S. Geol. Surv. Geol. Quad. Map GQ-921, scale 1:62500.
- , 1975, Biostratigraphy of the Lower Cambrian succession, White-Inyo Range and vicinity. Geol. Soc. Amer. Abstr. with Prog. 7, p. 1211.
- Newell, N. D., Purdy, E. G., and Imbrie, J., 1960, Bahamian oolitic sand: J. Geol., v. 68, p. 481-97.
- Purdy, E. G., 1963, Recent calcium carbonate facies of the Great Bahama Bank. 2. Sedimentary facies: J. Geol., v. 71, p. 175-90.
- Reineck, H. E., 1972, Tidal flats: *in* Rigby, J. K., and Hamblin, W. K. (eds.), Recognition of ancient sedimentary environments. Soc. Econ. Paleont. Miner. Spec. Pub. 16, p. 146-59.
- , and Singh, I. B., 1973, Depositional sedimentary environments: Springer-Verlag, New York, 439 p.
- Stewart, J. H., 1967, Possible large right-lateral displacement along fault and shear zones in the Death Valley-Las Vegas area, California and Nevada: Geol. Soc. Amer. Bull., v. 78, p. 131-42.
- , 1970, Upper Precambrian and Lower Cambrian strata in the southern Great Basin, California and Nevada: U. S. Geol. Surv. Prof. Pap. 620, 206 p.
- , 1974, Correlation of uppermost Precambrian and Lower Cambrian strata from southern and east central Nevada: U. S. Geol. Surv., J. Res., v. 2, p. 609-18.
- Wilson, J. S., 1961, Cambrian paleontology and stratigraphy of the Miller Mountain area, Esmeralda County, Nevada: unpub. M.S. thesis, Univ. Calif., Los Angeles, 108 p.

Biostratigraphic Implications of Trilobite Biofacies: *Albertella* Zone, Middle Cambrian, Western United States

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ABSTRACT.—Analysis of stratigraphically controlled trilobite faunas and associated depositional environments within the *Albertella* Zone of the Carrara Formation in the southern Great Basin and the Twin Knobs Formation and the Lead Bell Shale in the northeastern Great Basin, show that three distinct biofacies are represented: 1) a restricted-shelf biofacies characterized by low species diversity and represented in most collections by species of *Mexicella* and *Albertella* s.s., and found in areas of subtidal clastics and carbonates landward of a carbonate platform margin; 2) a platform-margin biofacies characterized by high diversity and typically including a variety of zacantheidid trilobites, found along the oceanward margin of the carbonate platform; and 3) a deep-shelf biofacies characterized by lower species diversity and typically including *Ogygopsis*, oryctocephalids and agnostids, found in sediments representing deeper depositional environments oceanward of the carbonate platform.

In the Carrara Formation, trilobites of the *Albertella-Mexicella* biofacies are stratigraphically above those of the *Ogygopsis* and zacantheidid biofacies. However, in northern Utah and southeastern Idaho, trilobites of the *Albertella-Mexicella* biofacies are stratigraphically below those of the zacantheidid and *Ogygopsis* biofacies. In the two areas, sequences of beds that contain zacantheidid trilobites overlain by trilobites of the *Ogygopsis* biofacies, although sharing over a dozen species, are not of the same age. Failure to recognize the biofacies significance of these faunas could lead to serious miscorrelation of rock units.

Each of the three biofacies persists, without much evidence for evolution, throughout the *Albertella* Zone. Thus, near the oceanward margin of the Cambrian carbonate platform, trilobite biofacies must be determined before a precise regional biostratigraphy can be developed.

INTRODUCTION

The Cambrian biostratigraphy that is currently in use in North America has been developed by integration of studies of vertical changes in trilobite faunas from limited areas and limited parts of the Cambrian system. Most of these studies have not considered the possible significance of the different marine depositional environments in which the trilobites accumulated. Although the existence of contemporaneous Cambrian trilobite biofacies has been recognized for more than 17 years (Lochman and Wilson, 1958), this fact has not been incorporated into a more elaborate biostratigraphic scheme, perhaps because the earlier generalizations were adequate for most purposes. The relationships described here should serve as a stimulus towards reconsideration of the entire North American scheme for trilobite biostratigraphy during Cambrian time.

This paper is the result of exchange of information during the final stages of two independent research projects (Campbell, 1974; Palmer and Halley, in press). These studies were concerned with early Middle Cambrian trilobites in northern Utah-southeastern Idaho (Campbell) and in southern Nevada-southeastern California (Palmer).

Resser (1939a, b) described rich trilobite faunas from stratigraphic units in northern Utah and southeastern Idaho, now known as the Twin Knobs Formation, the Naomi Peak Limestone Tongue of the Twin Knobs Formation,

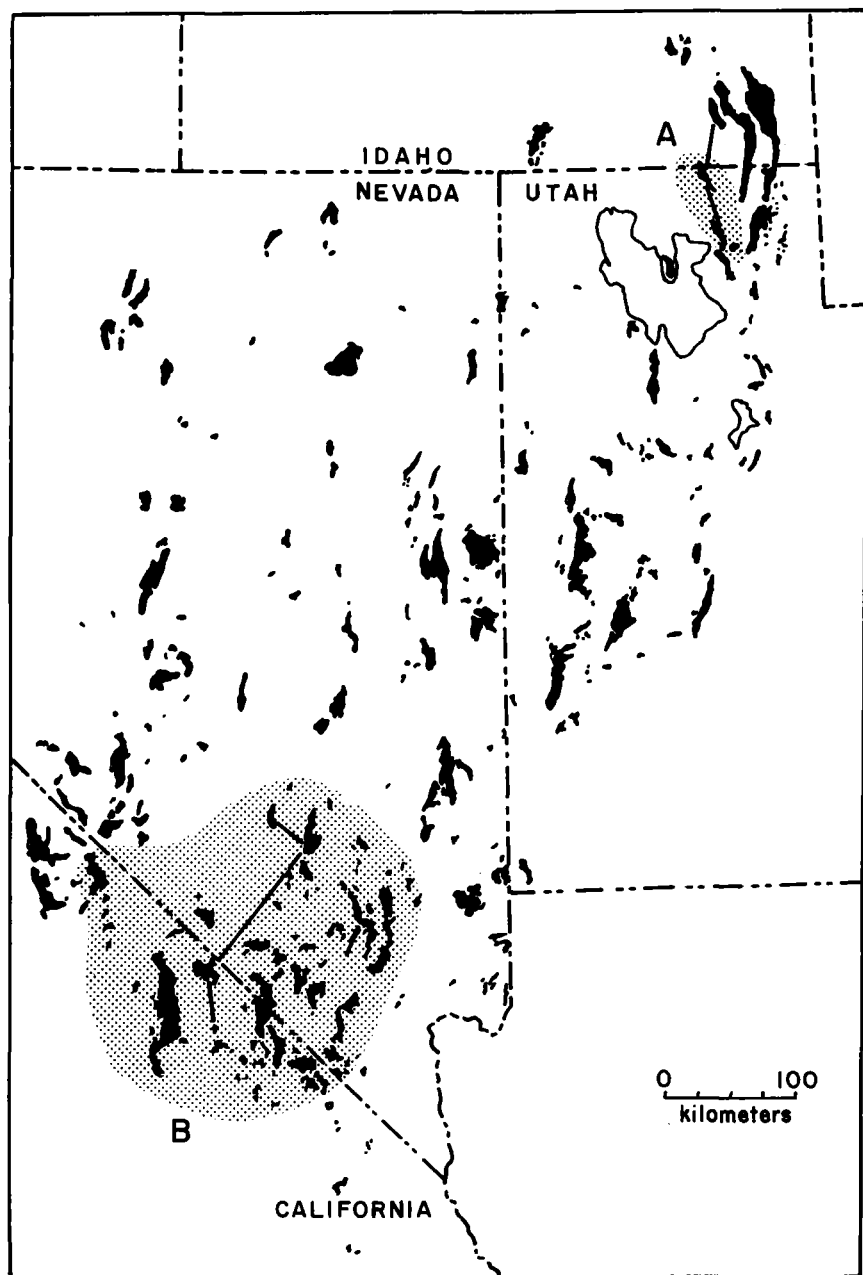
and the Spence Shale Tongue of the Lead Bell Shale (Oriol and Armstrong, 1971) (Text-figs. 1a, 2). These faunas represent parts of the *Albertella* and *Glossopleura* zones of early Middle Cambrian age. The trilobite fauna from the Naomi Peak Limestone (previously referred to as the "*Ptarmigania*" strata) was shown by Rasetti (1966) and by Fritz (*in* Oriol and Armstrong, 1971) to be a mixture of two distinct assemblages from different parts of the tongue. Campbell (1974) made a detailed biostratigraphic analysis of these lithostratigraphic units at two localities: Two Mile Canyon in the Malad Range of southeastern Idaho, and Antimony Canyon in the Wellsville Mountains of northern Utah. In the course of his study, he discovered additional trilobites of the *Albertella* Zone in beds immediately beneath the Naomi Peak Limestone Tongue in Utah and beneath a correlative limestone at the top of the Twin Knobs Formation in Idaho. These trilobites form one of the crucial elements in this paper.

Palmer began a study of the trilobite faunas of the Carrara Formation in southern Nevada and southeastern California (Text-figs. 1b, 3) in 1962. This formation ranges in age from the upper part of the Early Cambrian *Olenellus* Zone, through the lower part of the early Middle Cambrian *Glossopleura* Zone and includes faunas comparable to those studied by Campbell. In 1971, Robert Halley joined the Carrara project to make an analysis of the depositional environments of the Carrara Formation, their spatial distribution and genesis. This joint effort has resulted in an understanding of the spatial distribution of the trilobites with respect to depositional environments, as well as a description of their local biostratigraphy (Palmer and Halley, *in press*), which form the other crucial elements of this paper.

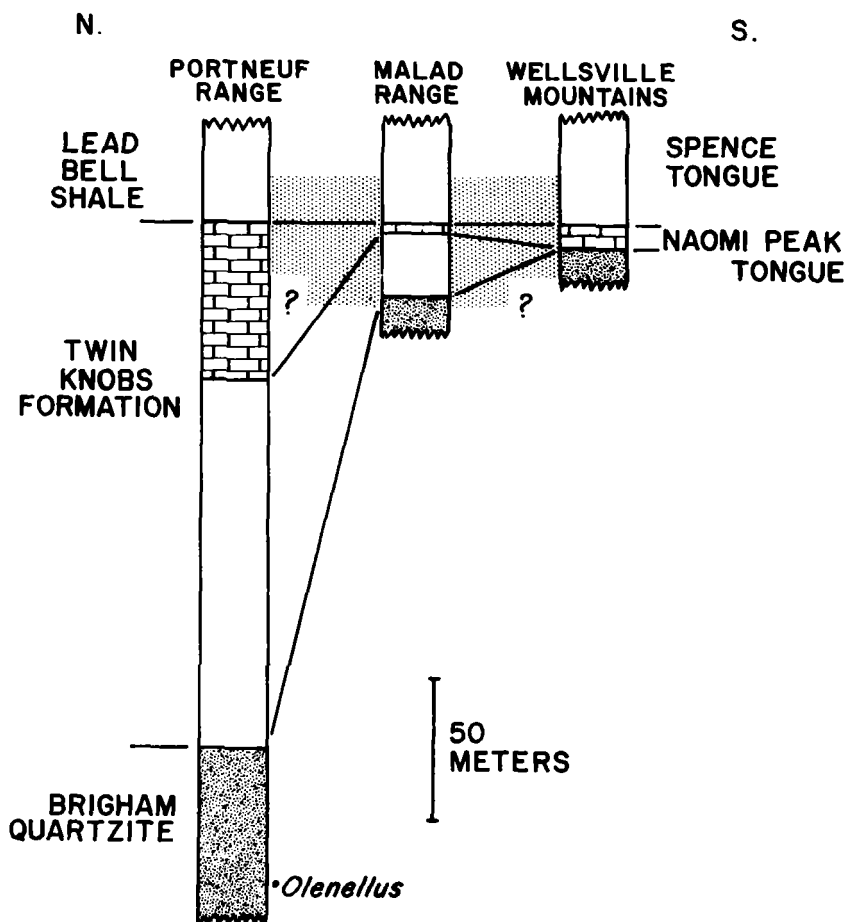
In the spring of 1974, after systematic work on the faunas of the Carrara Formation had been completed, Palmer briefly visited the University of Utah where Campbell was completing his M.S. thesis on the faunas of the *Albertella* and *Glossopleura* zones in northern Utah and southeastern Idaho. Campbell had indicated an interest in comparing some of his new forms with possibly similar forms in the Carrara Formation. This exchange of information showed that he not only had species of *Albertella* *s.s.* and *Mexicella* not previously known from the northern Utah-southeastern Idaho area, but he also had several new species and genera that were being described as new from the Carrara Formation. The most surprising information, however, was that Campbell's faunas with *Albertella* and *Mexicella* had been obtained in place from beds stratigraphically *beneath* the Naomi Peak Limestone Tongue of the Twin Knobs Formation which carries the "*Ptarmigania*" fauna; whereas, in southern Nevada and southeastern California, *Albertella* and *Mexicella* are found stratigraphically *above* beds with a fauna closely comparable to the "*Ptarmigania*" fauna! Thus, an apparently useful subzonal succession of trilobite genera in the *Albertella* Zone of the Carrara Formation does not have regional value, and the evidence indicates a potentially classical case of biostratigraphic reversal. The documentation of these faunal relationships and their implications for Cambrian biostratigraphy is presented below.

FAUNAL RELATIONSHIPS

The early Middle Cambrian rocks of northern Utah and southeastern Idaho reflect a rather rapid deepening of the sea and a concomitant eastward shift of the lithofacies that represent inner shelf clastics, a shallow carbonate

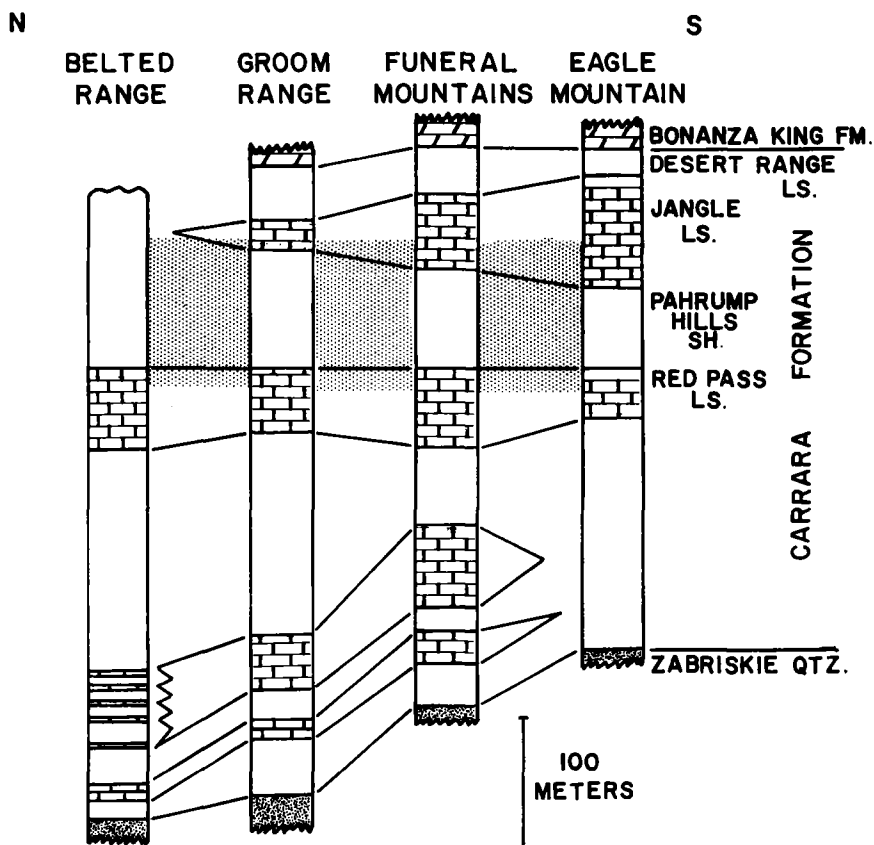


TEXT-FIGURE 1.—Index map of the Great Basin region showing the occurrences of Cambrian rocks and the areas studied by Campbell (A) and Palmer (B).



TEXT-FIGURE 2.—Stratigraphic columns for northern Utah and southeastern Idaho showing the stratigraphic nomenclature and the interval included in the *Albertella* Zone (shaded). Intervals of predominantly fine-grained clastics are shown without pattern in the stratigraphic columns.

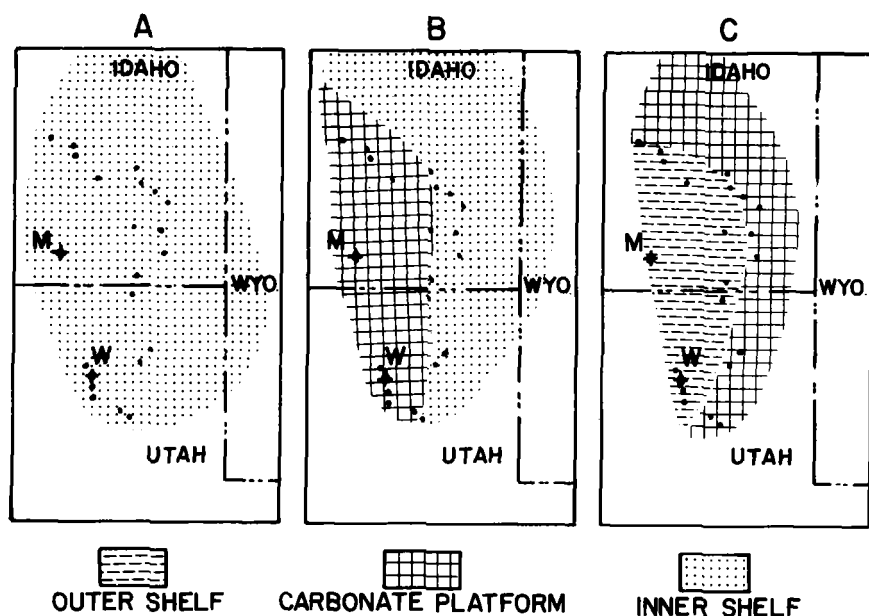
platform and outer shelf, fine clastics and carbonates. This shift took place during *Albertella* Zone time (Text-fig. 4) and is recorded in an interval 25 to 30 m thick in the sections studied by Campbell (1974) (Text-fig. 2). Between the Malad Range in Idaho and the Wellsville Mountains in Utah, the interval incorporates the upper beds of the Brigham Quartzite and the overlying shale and sandstones of the Twin Knobs Formation, which represent the inner shelf clastics; the limestones at the top of the Twin Knobs Formation and the Naomi Peak Limestone Tongue of the Twin Knobs Formation, which represent the shallow carbonate platform; and the black shale and thin-bedded black limestone of the Lead Bell Shale and the Spence Shale Tongue of the Lead Bell Shale, which represent the deeper outer shelf.



TEXT-FIGURE 3.—Representative stratigraphic columns for the Carrara Formation in southern Nevada showing the stratigraphic nomenclature referred to in the text and the interval included in the *Albertella* Zone (shaded). Intervals of predominantly fine-grained clastics or argillaceous limestone are shown without pattern on the stratigraphic columns.

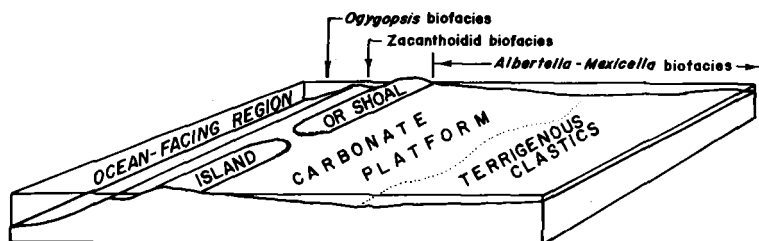
In southern Nevada and adjacent parts of California, the early Middle Cambrian sedimentary record (Text-fig. 3) reflects a more complicated series of events. During *Albertella* Zone time, a carbonate platform expanded to occupy more than 10,000 square km, disappeared, and redeveloped to a comparable size in response to differential rates of subsidence of the Cambrian shelf (Palmer and Halley, in press). These events are recorded in about 100 m of rocks that include, in upward sequence, the uppermost beds of the Red Pass Limestone Member, the Pahrump Hills Shale Member, and the lower part of the Jangle Limestone Member, all of the Carrara Formation.

Regionally, each area of carbonate sedimentation constituted a shallow subtidal carbonate platform. The carbonate sediment graded gradually shoreward (eastward) into fine clastics of the inner shelf, and more abruptly seaward (westward) into dark shale, siltstone, and thin-bedded limestone of the



TEXT-FIGURE 4.—Paleofacies maps for northern Utah and southeastern Idaho showing eastward shift of major lithofacies during the Early and early Middle Cambrian. A. Latest Early Cambrian time; B. *Albertella* Zone time; C. *Glossopleura* Zone time (after Oriol and Armstrong, 1971).

ocean-facing parts of the outer shelf (Text-fig. 5). The areas of active carbonate production ceased to exist when subsidence temporarily slowed. This happened because islands quickly developed near the outer margin of the platform and their inner margins prograded rapidly eastward, burying the shallow areas that supplied the carbonate sediment. At the same time, because input of clastic material continued unabated, the inner part of the carbonate platform was buried by westward progradation of clastics. As subsidence increased, the carbonate islands were buried by further westward progradation of clastics from the inner shelf. New carbonate platforms were regenerated as the shelf deepened and carbonate-inhibiting clastic sediments ceased to reach the outer

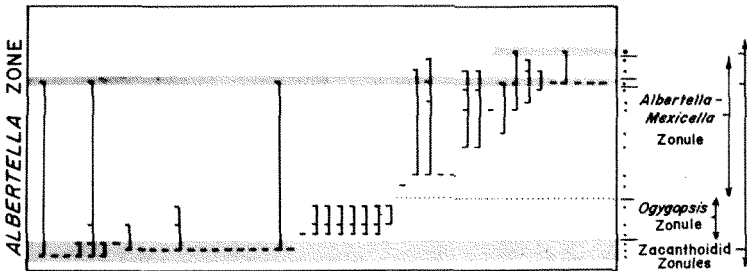


TEXT-FIGURE 5.—Model of major depositional environments and associated trilobite biofacies represented in the Carrara Formation of the southern Great Basin during *Albertella* Zone time.

parts of the shelf. Seaward from the belt of islands, the outer part of the carbonate platform was cut off from much of its sediment source and water depth increased as subsidence, even though slowed, continued. Consequently, in that area, carbonate platform sediment is succeeded by deeper water sediment.

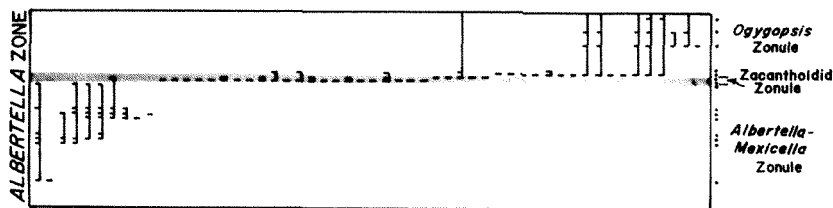
During the time represented by the *Albertella* Zone, three strongly contrasting biofacies existed across the shelf region of southern Nevada (Text-fig. 5). In the inner shelf areas, generally low-diversity trilobite faunas were characterized by *Albertella* s.s. and *Mexicella*. On the narrow outer margin of the carbonate platform was a rich and diverse fauna of trilobites, molluscs, and perhaps echinoderms. The dominant trilobites represent various genera of the Zacanthoididae. These are rare in the inner shelf region. Associated with the Zacanthoididae are eodiscids, oryctocephalids, and rare agnostids unknown in the faunas of the inner shelf. The deeper water environments just oceanward from the platform margin had faunas of somewhat lower diversity than those of the platform margin. They are characterized by *Ogygopsis* and agnostids, together with some of the eodiscids and oryctocephalids found on the outer margin of the platform. The latter three groups are believed to be part of the pelagic fauna of the Middle Cambrian Pacific Ocean because the genera and, in some cases, the species are found in similar environmental settings along Pacific-facing Cambrian platform margins from Siberia to Australia, and in western Argentina. The three biofacies are here referred to as the *Albertella-Mexicella*, Zacanthoidid, and *Ogygopsis* biofacies, respectively.

Trilobite assemblages of the Zacanthoidid biofacies have been found only in the northwestern part of the outcrop area of the Carrara Formation—at the top of the Red Pass Limestone Member, and in the transition interval between the Pahrump Hills Shale Member and the Jangle Limestone Member. Trilobites of the *Ogygopsis* biofacies are found only in the northwestern-most section of the Carrara Formation at, or just above, the top of the Red Pass Limestone Member. Trilobites of the *Albertella-Mexicella* biofacies have been found at various horizons in the Pahrump Hills Shale Member, generally in the southeastern part of the outcrop area of the Carrara Formation. There is no doubt from regional context that trilobites of the *Albertella-Mexicella* biofacies occur in beds younger than those with trilobites of the *Ogygopsis* biofacies, and the richest horizons of the Zacanthoidid biofacies (Text-fig. 6).



TEXT-FIGURE 6.—Composite observed ranges of trilobite species in the *Albertella* Zone, southern Nevada and southeastern California. Collection horizons (•) and local subzonal biostratigraphy shown on right. Shaded bands are intervals with representatives of the Zacanthoidid Zonule.

When the trilobite faunas of the Carrara Formation were being described, the faunas of the *Albertella-Mexicella* biofacies could be compared most closely with faunas described from the Grand Canyon (McKee and Reeser, 1945) and northwestern Mexico (Lochman, 1952). The trilobites of the Zacanthoidid and *Ogygopsis* biofacies are strikingly similar to those of the Naomi Peak Limestone and Spence Shale in northern Utah and southeastern Idaho described by Resser (1939 a, b). Sixteen genera and 13 species in the *Albertella-Glossopleura* faunas of the Carrara Formation are also known from the Utah-Idaho area. The stratigraphic sequence of Zacanthoidid genera and species, succeeded by *Ogygopsis* and associates, is the same in both areas. Lithologic and faunal successions at the top of the Red Pass Limestone initially suggested correlation with the Naomi Peak Limestone. However, the faunas from the clastic units above the Red Pass and Naomi Peak limestones presented problems. The *Albertella-Mexicella* faunas had not been reported from the Spence Shale, which had yielded only a diverse fauna of different trilobites including rare specimens of *Glossopleura*. There was no stratigraphic documentation of detailed relationships within the Spence Shale, however, and an explanation for the apparent differences between faunas of the clastic units above the Red Pass and Naomi Peak limestones awaited better information on details from the Utah-Idaho region. The critical information on the precise distribution of trilobites in the *Albertella* Zone in northern Utah and southeastern Idaho was provided by Campbell (1974), and is summarized in Text-figure 7. In the Malad Range, Idaho, the poorly exposed beds of the Twin Knobs Formation below its topmost ledge were exposed by trenching. Eight levels, through an interval of about 21 m, yielded trilobites. The generic assemblages in all of the collections are essentially the same as those in the *Albertella-Mexicella* biofacies of the Carrara Formation. In addition to taxa already described, they include two new genera and one new species common to both areas. As in the southern Great Basin, the number of species in each collection is small (less than 10). In contrast, a two-meter limestone ledge at the top of the Twin Knobs Formation contains 38 species of trilobites representing two distinct faunas. The lower part of the ledge contains an abundance of species of Zacanthoididae associated with ptychopariid, oryctocephalid, and eodiscid trilobites. The upper part of the ledge contains a similar fauna except that it is almost totally lacking in Zacanthoididae and is characterized by the presence of agnostids and *Ogygopsis*. Eight of the species from the limestone ledge are also found in the overlying Spence Shale; only one



TEXT-FIGURE 7.—Composite observed ranges of trilobite species in the *Albertella* Zone of northern Utah and southeastern Idaho. Collection horizons (•) and local subzonal biostratigraphy shown on right. Shaded band shows position of Zacanthoidid Zone for comparison with Text-figure 6.

of the species from the ledge is found in the underlying beds of the Twin Knobs Formation.

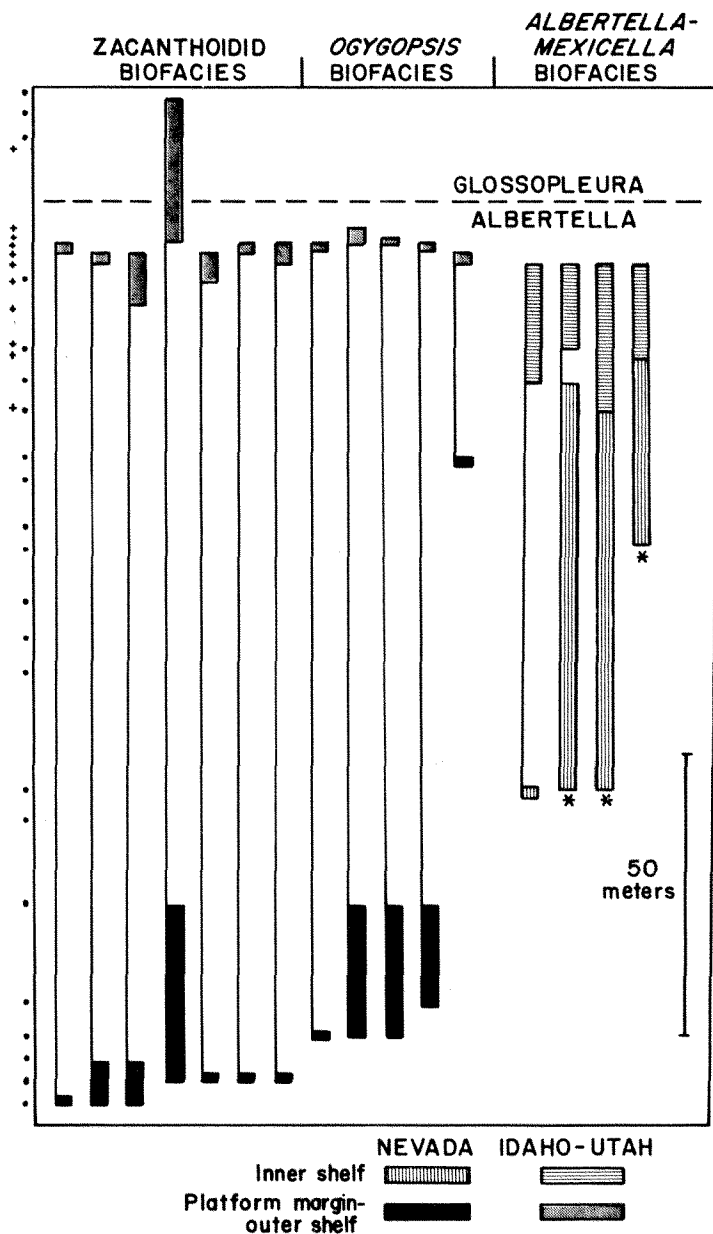
In the Wellsville Mountains, Utah, a similar sequence of faunas was collected. One collection within the upper two meters of the Brigham Quartzite yielded three species of the *Albertella-Mexicella* biofacies. The immediately overlying eight meters of the Naomi Peak Limestone yielded 21 species of trilobites including a variety of *Zacanthoididae*. Four of these species were found in the lowest meter of the overlying Spence Shale and none were found in the underlying beds. *Ogygopsis* is found at this locality only in one collection less than two meters above the base of the Spence Shale. Of the eight species associated with *Ogygopsis*, two are found in immediately underlying beds and four continue through at least 30 m of higher beds as the fauna of the Spence Shale gradually changes from assemblages conventionally assignable to the *Albertella* Zone to assemblages assignable to the *Glossopleura* Zone. *Glossopleura* first appears 20 m above the base of the Spence Shale. Regional stratigraphy and faunal data clearly show that the Naomi Peak Limestone and the uppermost limestone of the Twin Knobs Formation are correlative units and that their position is near the top of the *Albertella* Zone. Furthermore, there is no sharp boundary between the *Albertella* and *Glossopleura* zones.

In southern Nevada and southeastern California, the change from beds with assemblages referable to the *Albertella* Zone to beds with assemblages referable to the *Glossopleura* Zone takes place within the Jangle Limestone Member of the Carrara Formation. Throughout this region, thin argillaceous limestone beds of the overlying Desert Range Limestone Member yield only assemblages locally rich in specimens of *Glossopleura*, and the fossiliferous lower part of the Jangle Limestone yields assemblages containing elements of the *Albertella-Mexicella* biofacies. Inasmuch as the same trilobite assemblages bracket both the Jangle Limestone and the Naomi Peak Limestone and also bracket geographically intervening units usually referred to the Lyndon or Howell limestones, we have little doubt about the physical correlation and approximate contemporaneity of the Jangle and Naomi Peak limestones.

STRATIGRAPHY

With this correlation established, the biostratigraphic and evolutionary problems come clearly into focus. The rich assemblages including *Zacanthoididae* or *Ogygopsis* from the Red Pass Limestone member of the Carrara Formation cannot be contemporaneous with those of the Naomi Peak Limestone, even though they share over a dozen common *species* and have the same local succession in both areas! Furthermore, the time ranges of the species that represent both the *Zacanthoidid* and *Ogygopsis* biofacies are nearly coincident with, and completely overlap the time ranges of, the species of the *Albertella-Mexicella* biofacies (Text-fig. 8), proving the coexistence of these three biofacies, which was inferred from analysis of the spatial distribution of the faunas and depositional environments of the Carrara Formation (Text-fig. 5). These conclusions have important implications for the future of Cambrian biostratigraphy.

One of the great practical values of stratigraphic paleontology is its role in establishing regional and interregional correlation. Only within a reliable and reproducible time frame can many of the questions of evolutionary paleon-



TEXT-FIGURE 8.—Comparative observed ranges of the trilobites [3 genera (*) and 13 species] within the *Albertella* zone that are shared between northern Utah-southeastern Idaho and southern Nevada-southeastern California. Collection horizons are shown on left: (+) = northern Utah-southeastern Idaho; (•) = southern Nevada-southeastern California.

tology be answered. Knowledge of Cambrian faunas is now reaching the point where imprecision of correlation within the conventional assemblage zones is no longer a trivial concern. Without the data provided by Campbell's detailed study, conventional methodology would have made a very convincing case for *miscorrelation* of the Red Pass Limestone and the Naomi Peak Limestone. Because of these new insights, assertions that rich assemblages of trilobites representing the Zacanthoidid or *Ogygopsis* biofacies are of *Albertella* Zone age must be qualified, because the true time ranges of most of the trilobites within these biofacies are not yet known. We have almost no information about the platform margin and outer shelf trilobite assemblages of Middle Cambrian age that are older than the *Albertella* Zone.

We must begin to pay more attention to what the Russians call "monofacial" biostratigraphy—but what constitutes a "monofacial" region? Is it sufficient to view the inner shelf, the platform margin and the outer shelf as satisfactory "monofacial" regions for Cambrian biostratigraphic purposes? In terms of North American *Early* and *Middle* Cambrian biostratigraphy, the present answer is a qualified "yes." However, with continued expansion of the epicontinental seas in *Late* Cambrian time, the inner shelf has at least two regional biofacies contrasts. This can easily be seen by comparing the trilobites of the sandy facies of the Upper Mississippi Valley with those of the carbonates of Missouri, Texas, Utah, and the southern Canadian Rocky Mountains. Thus it may be necessary to recognize at least four "monofacial" regions in the Late Cambrian, each with its own potential biostratigraphy.

Returning to the Middle Cambrian, however, the best documented but still imperfect "monofacial" biostratigraphy is that for the inner shelf region. This can be compiled by combining the early Middle Cambrian faunal successions of the southeastern Great Basin, the Grand Canyon area, and northern Mexico—from the top of the *Olenellus* Zone through the *Glossopleura* Zone—with the late Middle Cambrian successions of Montana and parts of the northern Great Basin, from the *Glossopleura* Zone to the base of the Dresbachian Stage.

Platform margin and deep shelf "monofacial" biostratigraphies for the early Middle Cambrian for North America may not be completely resolvable. Details are lacking regarding the time ranges and evolutionary changes of faunas within the Zacanthoidid and *Ogygopsis* biofacies, which represent the platform margin and deep shelf regions, and good fossiliferous sequences through beds older than the *Albertella* Zone that include these facies regions are not yet recognized.

In the late Middle Cambrian, the fossiliferous sequences of the central and northern Great Basin have the potential for development of "monofacial" biostratigraphies for part or all of the platform margin and deep shelf regions.

Even with the present state of knowledge, the sequence of faunas in the inner shelf region during Middle Cambrian time shows faunal changes that may not be the result of simple gradual evolutionary change. Abrupt changes in trilobite faunas perhaps comparable to those defining biomes (Palmer, 1965) take place in less than a meter of stratigraphic section at the top of the *Olenellus* Zone and the top of the *Glossopleura* Zone in the Great Basin region, and between the discarded (prematurely?) younger *Bolaspis-Glyphaspis* and *Ehmania* zones (Howell and others, 1944) of Montana.

Clearly, a new Middle Cambrian biostratigraphic synthesis is needed. This must take into account as much information as possible about depositional environments of the trilobite faunas, and it should perhaps consider the evidence for possible extinctions of faunas of the inner shelf region, at least, at several different times. Because of work still in progress or needing to be done, such a synthesis now would be premature. However, it is within reach in the near future and is a goal towards which careful research should be directed.

ACKNOWLEDGMENTS

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REFERENCES

- Campbell, D. P., 1974, Biostratigraphy of the *Albestella* and *Glossopleura* zones (lower Middle Cambrian) of northern Utah and southern Idaho: unpub. M.S. thesis, Univ. Utah. 295 p.
- Howell, B. F., and others, 1944, Correlation of the Cambrian formations of North America: Geol. Soc. Amer. Bull., v. 55, p. 993-1104.
- Lochman, Christina, 1952, Trilobites: in Cooper, G. A., and others, Cambrian stratigraphy and paleontology near Caborca, northwestern Sonora, Mexico: Smithsonian. Misc. Coll. 119(1), p. 60-161.
- , and Wilson, J. L., 1958, Cambrian biostratigraphy in North America: J. Paleont., v. 40, p. 312-50.
- McKee, E. D., and Resser, C. E., 1945, Cambrian history of the Grand Canyon Region: Carnegie Inst. Washington Pub. 563, 168 p.
- Oriel, S. S., and Armstrong, F. C., 1971, Uppermost Precambrian and lowest Cambrian rocks in southeastern Idaho: U.S. Geol. Surv. Prof. Paper 394, 52 p.
- Palmer, A. R., 1965, Biome—A new kind of biostratigraphic unit: J. Paleont., v. 39, p. 149-53.
- , and Halley, R. B., in press, Physical stratigraphy and trilobite biostratigraphy of the Lower and Middle Cambrian Carrara Formation in the southern Great Basin: U.S. Geol. Surv. Prof. Paper.
- Rasetti, Franco, 1951, Middle Cambrian stratigraphy and faunas of the Canadian Rocky Mountains: Smithsonian. Misc. Coll. 116(5), 277 p.
- , 1966, Revision of North American species of the Cambrian trilobite genus *Pagetia*: J. Paleont., v. 40, p. 502-11.
- Resser, C. E., 1939a, The Spence Shale and its fauna: Smithsonian. Misc. Coll. 97 (12), 29 p.
- , 1939b, The *Ptarmigania* strata of the northern Wasatch Mountains: Smithsonian. Misc. Coll. 98(24), 72 p.

Some Observations on Occurrences of Cambrian Porifera in Western North America and Their Evolution

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ABSTRACT.—All three classes of sponges known from Early Paleozoic rocks occur in Cambrian faunas in western North America, and are perhaps best preserved in the varied Burgess Shale fauna of western Canada. Demosponges are relatively rare and do not show the great evolution and variability of either the Heteractinida or the Hexactinellida.

Heteractinid sponges show evolution during the Cambrian from early forms with spicules composed of thin-walled separate elements, which are more or less fused, to later forms which have solid, unfused spicules. One evolutionary line, leading to the *Astraeospongiidae*, became thick-walled and irregular, but another retained the geometric regularity and thin wall of that seen in Cambrian genera.

Protosponges of the Cambrian are apparently the stem family from which radiated two major groups of sponges: one developed thick walls composed of irregularly oriented spicules, and the other developed somewhat less thick walls, but retained the apparently primitive rectangular skeletal pattern. The former leads through the double-walled *Dierespongiidae* to the *Teganiidae* and to families related to the *Brachiospongiidae* and the latter leads to the Middle Paleozoic *Dictyospongiidae* and to the Cambrian *Multivasculatidae*.

INTRODUCTION

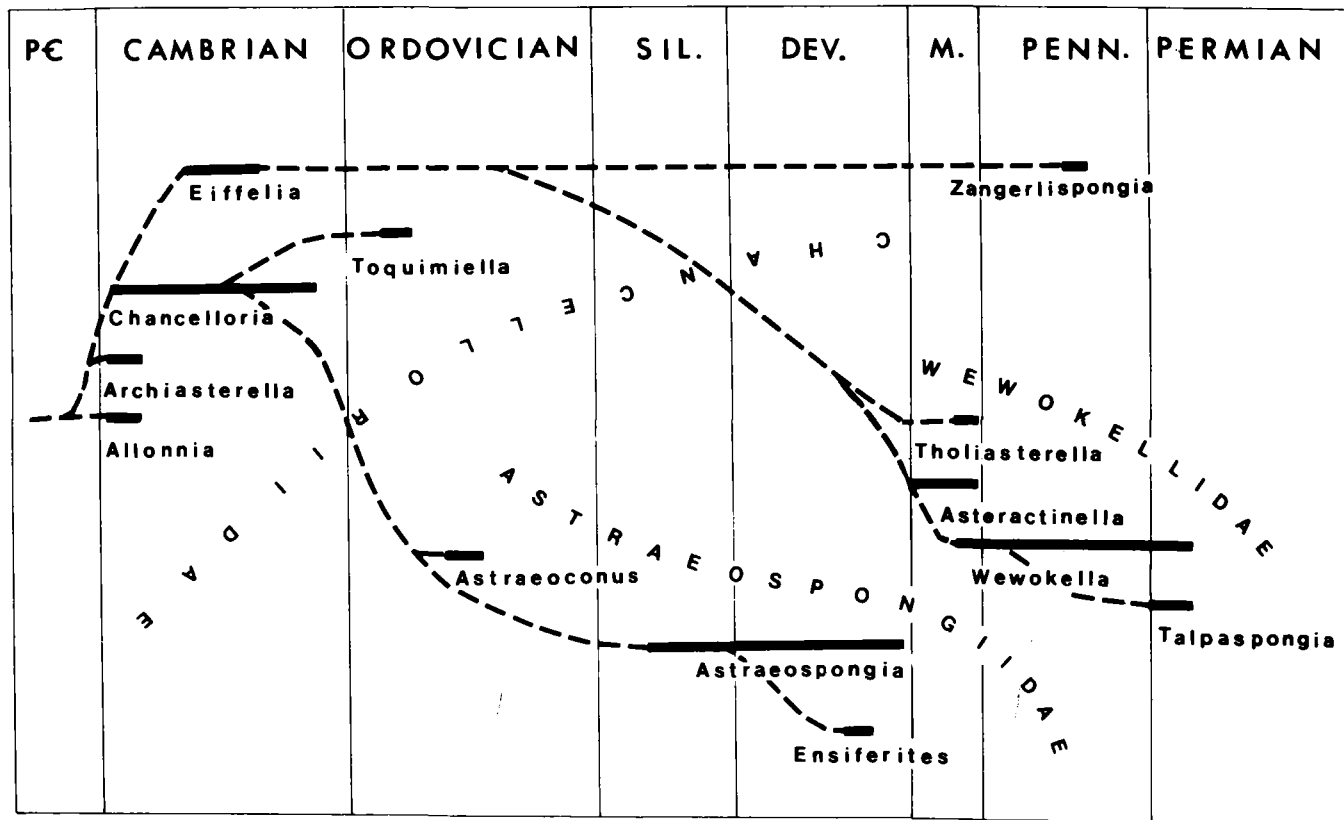
Fossil sponges have long been known from Cambrian rocks of western North America, but perhaps the most spectacular and varied, and certainly the most well known, sponge fauna is that of the Middle Cambrian Burgess Shale described by C. D. Walcott (1920) from the Canadian Rocky Mountains of British Columbia. The Burgess Shale sponges were not the first described from western North America (Walcott, 1886), nor are they the oldest (Wetzel, 1940), but certainly are among the best preserved Paleozoic sponges known. The Burgess fauna includes representatives of each of the classes of sponges known from the Cambrian and Early Paleozoic in North America. *Calcarea*, *Hexactinellida*, and *Demospongia* are all represented in the Burgess fauna, and are also represented, in varying degrees of commonness, elsewhere throughout western North America.

CALCAREA

Of the calcareous sponges known from the Paleozoic, only the Heteractinida are known from Early Paleozoic rocks. Sphinctozoan and pharetronid sponges are at present known only from Carboniferous and younger beds. DeLaubenfels (1955, p. E-96) defined the Order Solenida and listed its range as Cambrian to Recent, based apparently upon the Early Paleozoic occurrence of *Camarocladia* Ulrich and Everett in Miller (1889, p. 156). This genus is probably a trace fossil and not a calcareous sponge, and hence the known record of the order, as established by DeLaubenfels, is probably limited to the Recent.

Heteractinida

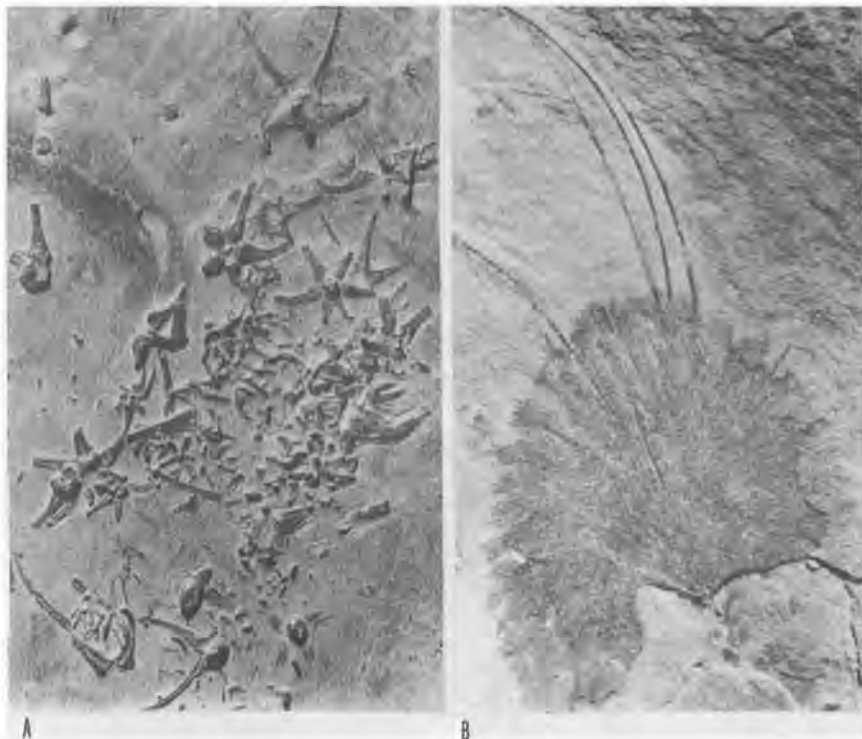
Three families (Text-fig. 1) are recognized within the heteractinid calcareous sponges (Rigby and Nitecki, 1975, p. 329-33), including the *Chancelloriidae* Walcott (1920), *Astraeospongiidae* Miller (1889), and the *Wewokellidae*



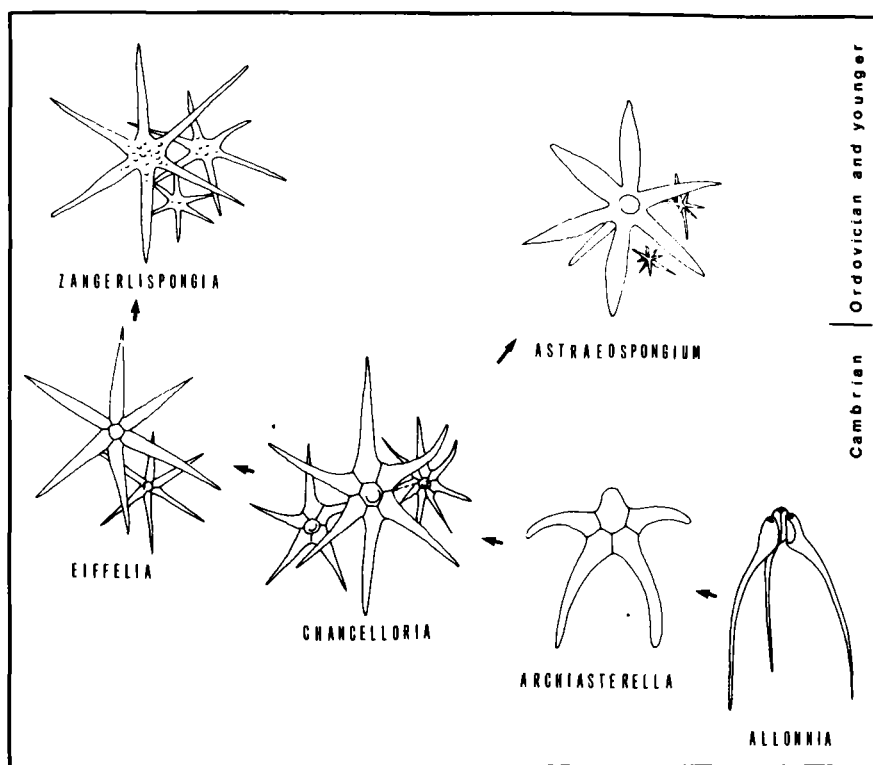
TEXT-FIGURE 1.—A possible evolutionary scheme and classification of the Heteractinida (from Rigby and Nitecki, 1975). Slightly different schemes are presented by Finks (1970) and Szduy (1969).

King (1943). Of these, only the Chancelloriidae have been recognized with certainty in Cambrian rocks. *Chancelloria* (Walcott, 1920), upon which that family is based, is relatively common throughout western North America as scattered isolated spicules or as small fragments of skeletal net (Text-fig. 2A). Only in the Burgess collections, however, are moderately complete specimens of the genus well preserved. *Eiffelia* (Walcott, 1920) is also included in the family and occurs in the Burgess collections. *Allonia* (Doré and Reid, 1965), from the Lower Cambrian of France and *Archiasterella* (Sdzuy 1969), from the Lower Cambrian of Spain, are also included in the family (Text-fig. 3), but have not been described to date from North America. *Uranosphaera* (Bedford and Bedford, 1934), from the Lower Cambrian of Australia is included within the family with less certainty. In addition, the younger sponges *Toquimiella* (Rigby, 1967) from the Ordovician of Nevada, and *Zangerli-spongia* (Rigby and Nitecki, 1975) from the Pennsylvanian of Illinois are included in the family.

As currently visualized (Rigby and Nitecki, 1975), the Chancelloriidae are thin-walled conical to globular sponges whose moderately large spicules



TEXT-FIGURE 2.—A, Photomicrograph of spicules of *Chancelloria* from the Wheeler Shale, House Range, Utah, showing the sutured nature of the spicules and the median line produced by collapse of the hollow elements (X5). B, *Choia* from the Wheeler Shale, House Range, Utah, showing the radial pattern of the central body of "thatched" spicules and larger radiating monaxial spicules (X5).



TEXT-FIGURE 3.—Spicules of Paleozoic heteractinid sponges. Early spicules are composed of separate hollow elements sutured together, but later spicules are solid. Arrows show possible evolutionary development. Spicules are all enlarged but not to the same scale.

are placed in a skeletal net with a regular geometric pattern. Spicules in primitive genera are composed of hollow, thin-walled elements, which are sutured together (Text-fig. 2A), but spicules are less obviously sutured and thicker in advanced forms (Rigby and Nitecki, 1975, p. 329-30). Evolution within the family, if the structurally most simple spicules exemplified by *Allonnia tripodophora* Doré and Reid are in reality close to the stem, appears to be toward development of a stable octactine-based spicule and toward development of solid unsutured spicules (Text-fig. 3).

The Chancelloriidae appear to be the stem family from which the *Astraeospongiidae* and the *Wewokellidae* diverged in Middle and Late Paleozoic time (Text-fig. 1), the former by loss of the regular spicule pattern in the skeletal net and development of thick walls, and the latter by development of polyactine spicules and secondary thickening or calcification of the entire skeletal net (Rigby and Nitecki, 1975, p. 335-37).

Within the Cambrian, there appears to be a structural shift from spicules composed of few elements to those with many elements (Text-fig. 3). After

some experimentation, the generalized octactine-based spicule was apparently selected as the basic structural element for other genera and families in the Heteractinida. Dominance of octactines is the pattern in Ordovician and younger genera in all but the youngest sponges of the Wewokellidae.

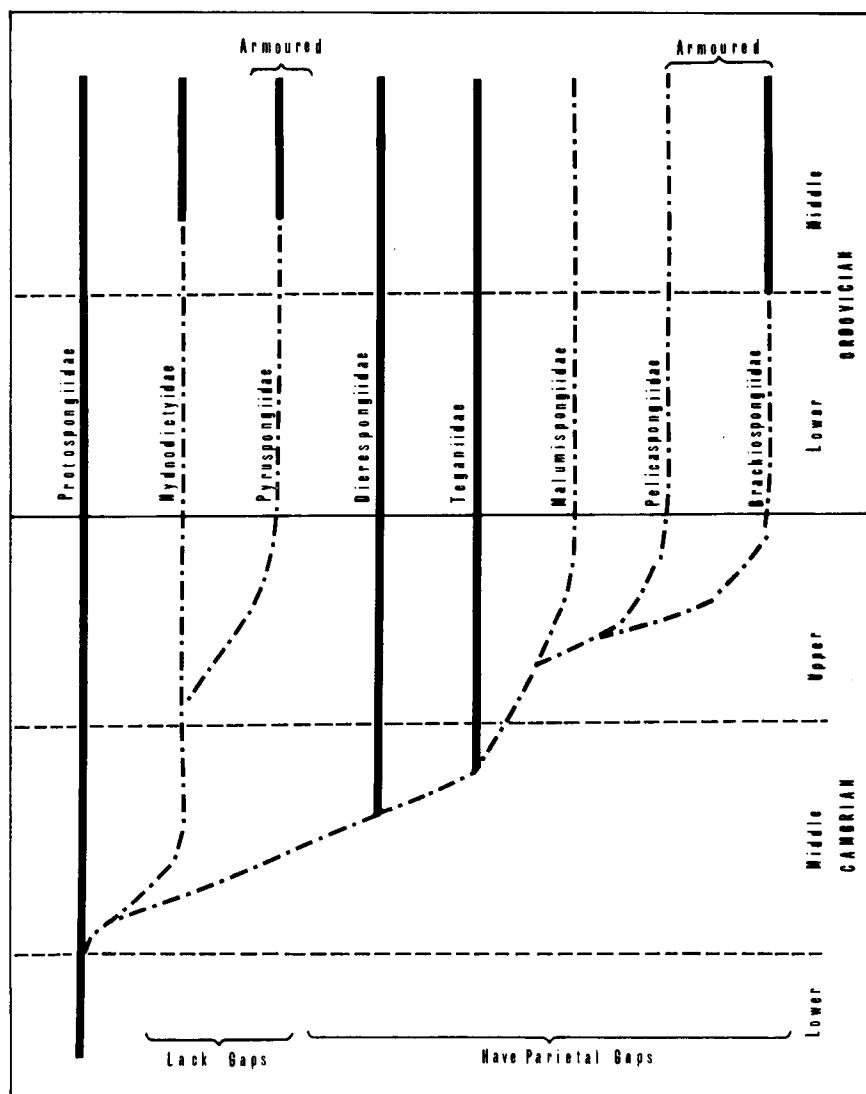
HEXACTINELLIDA

The Hexactinellida are well represented in the Cambrian by the *Lyssakida* or *Reticulosa* (Reid, 1958, p. xlv-xlvi), and show an evolutionary pattern from a relatively well organized, almost precisely geometric, skeletal pattern in early sponges (Text-fig. 4) to two thicker-walled lineages in later forms. One lineage leads to the rectangularly arranged dictyosponges in which the walls may be moderately thick and in which the regular spicule pattern is preserved. The other lineage leads through intermediate forms to the irregularly spiculed and thick-walled brachiosponges (Text-fig. 5).

Protospongia (Salter, 1864) (Text-fig. 4) and *Diagonella* (Rauff, 1894) are characteristic of early hexactinellids with geometrically arranged skeletons. They are thin-walled forms whose four-rayed stauract spicules are arranged tangential to the wall and in regular quadrangular patterns. They have several ranks of spicules which subdivide the skeletal rectangles of the net into smaller and smaller rectangles, through as many as six ranks (Salter, 1864; Sollas, 1880; Dawson and Hinde, 1890; Rauff, 1894; Walcott, 1920; Rigby,



TEXT-FIGURE 4.—Photomicrograph of *Protospongia hicksi* Hinde from the Middle Cambrian Marjum Limestone in the House Range of western Utah (X5). The regularity of spicule orientation and placement is typical of the species and characteristic of protosponges of the Cambrian and Ordovician.



TEXT-FIGURE 5.—A scheme of possible evolutionary development for some families of early Paleozoic Hexactinellida. Except for the Protospongiidae, the other families have at least one skeletal layer composed of irregularly oriented spicules. In general what is interpreted as increased specialization is shown by separation toward the right from the Protospongiidae, particularly in those sponges with parietal gaps. Solid vertical lines show known ranges and dashed lines show possible evolutionary relationships.

1966; Rushton and Phillips, 1974). Isolated stauract spicules from rocks as old as Early Cambrian have been referred to *Protospongia*. This practice now seems increasingly unwise as our knowledge of Cambrian sponges has improved. We now know that similarly shaped spicules occur in several genera, and that the degree of skeletal union in most of these related sponges was minimal so that individual spicules could have easily become detached, or sponge bodies could have been easily disarticulated upon death.

The Dierespongiidae (Rigby and Gutschick, 1976, p. 79-80) stand as intermediates between the regularly spiculed protosponges and the irregularly spiculed, thick-walled brachiosponges and their relatives (Text-fig. 5). *Hintzespongia* from the Cambrian of Utah (Rigby and Gutschick, 1976, p. 81-83) has a body wall composed of an inner irregularly arranged net and an outer layer of regularly arranged protospongelike spicules (Text-fig. 6). Designation of inner and outer layers is based upon analogy with the younger *Dierespongia* (Rigby and Gutschick, 1976, p. 80-81) in which an irregularly spiculed thick inner part of the sponge is clearly overlain by a more regularly arranged protospongidlike layer. Suppression or loss of the outer, presumably dermal, layer of spicules appears to be the leading trend to the irregularly spiculed, thick-walled sponges that became diverse in Ordovician and younger beds.

The Cambrian-Ordovician Teganiidae (DeLaubenfels, 1955, p. E-70) is a moderately thin-walled group of sponges whose members are characterized



TEXT-FIGURE 6.—Photomicrograph of *Hintzespongia bilamina* Rigby and Gutschick from the Middle Cambrian Marjum Limestone showing the double-layered wall, with the upper layer composed of protospongid-arranged spicules and lower layer composed of irregularly arranged spicules, like in the Teganiidae (X10). *Hintzespongia* is the earliest of the known Dierespongiidae.

by irregular spiculation and numerous small parietal gaps (Finks, 1960, p. 110). They could have been derived from the Dierespongiidae by loss of the outer regularly spiculed part of the sponge wall and by retention of the relatively thin, irregularly arranged skeleton in these conical to sack-shaped sponges. *Ratcliffespongia* (Rigby, 1969), from the Middle Cambrian of western Utah, is strikingly similar to the irregular skeletal layer of *Hintzespongia* (Text-fig. 6) and appears related to *Teganium subsphericum* (Walcott), as illustrated by Hall and Clarke (1899: pl. 1, figs. 19, 21). The Cambrian sponges are coarser textured than the Ordovician, although the proportions of spicule size to parietal gap size are similar. The Malumispongiidae (Rigby, 1967b, p. 769-70) is apparently also a derived family in which irregularly arranged spicules form a thick wall that is unarmored and lacks specialized or enlarged spicules. The Pelikaspongiidae (Rigby, 1970, p. 11-12) are more specialized, though related, thick-walled sponges in which the dermal or gastral surface, or both surfaces, are armored with unspecialized, though often enlarged, hexactines. The Brachiospongiidae (Beecher, 1889) appears to be even more specialized with modified large pentacts forming an armouring layer on the outer surface of the sponges. The Malumispongiidae, Pelikaspongiidae, and Brachiospongiidae all have large parietal gaps.

The Hydnodictyidae (Rigby, 1971, p. 52) and Pyruspongiidae (Rigby, 1971, p. 59) possibly had their origin in Late Cambrian or Early Ordovician time. The two families are represented by sponges which are distinct in having irregular spiculation of the skeletal net and in lacking parietal gaps. Both families appear in the record in the upper part of the Middle Ordovician, but represent a structural grade which might be expected in earlier rocks were the sponge record more complete.

Palmer, in Finks (1970, p. 6) reported that the earliest hexactines in North America occur in the Middle Cambrian *Bolaspidella* zone, although Finks noted that R. E. H. Reid and Douglas Bassett found isolated hexactines in Lower Cambrian rocks in Wales. The oldest known sponge in which hexactines form a regular skeletal net is *Multivasculatus*, described by Howell and Van Houten (1940) from the Upper Cambrian "Gallatin" Formation of the Bighorn Mountains of Wyoming. Finks (1970, Fig. 2) also illustrated *Multivasculatus* from the Upper Cambrian Windfall Formation of central Nevada.

Regularity in skeletal pattern, which is characteristic of the Protospongiidae, is continued in the other great line of hexactinellids, leading to the younger Dictyospongiidae. Finks (1970, p. 9) observed that the Ordovician sponge *Gyathophycus* (Walcott, 1879) is like a thicker walled *Protospongia* and that it is very similar to the primitive dictyosponge, *Dictyospongia* (Hall and Clarke, 1889). Much of the evolutionary history of this major division of the Hexactinellida postdates the Cambrian and took place during the Devonian and Mississippian.

DEMOSPONGEA

In contrast to the Heteractinida and Hexactinellida, which show some rapid evolution within the Cambrian, demosponges have a limited Cambrian record but experienced rapid evolution in the Ordovician. Finks (1970, p. 6) noted that early demosponges have thin walls and are tubular forms, like *Hazelia* (Walcott, 1920, p. 281-88). Poorly known forms like *Wilbernicyathus* (Wil-

son, 1950) from the Upper Cambrian of Texas and *Gallatinospongia* (Okulitch and Bell, 1955) from the Upper Cambrian of Wyoming may well have functioned as the stem from which the Anthaspidellidae developed almost explosively in the Ordovician.

CONCLUSION

Sponges are neither particularly abundant nor diverse in Cambrian rocks of western North America, where only approximately 30 genera of sponges are known. Of these, 18 genera occur in the diverse Burgess Shale fauna and ten of Walcott's Burgess genera (1920) are known only from that locality. Seven of the genera recognized by him, however, are widespread and some, including *Chancelloria*, *Choia*, *Protospongia* and *Diagonella*, are also moderately common.

Sponges occur in a variety of facies in Cambrian rocks, but black shale has produced the most abundant and the most well-preserved forms. Cambrian sponges apparently had skeletal nets which were only weakly united and, as such, required generally quiet water for their preservation. Common spiculitic beds throughout the Cambrian section attest to the abundance of sponges, but also to their fragility.

Sponges first conclusively appear in the Lower Cambrian, but the record there is sufficiently diverse that a Precambrian origin of the phylum is indicated. In Cambrian and younger rocks both calcareous Heteractinida and siliceous Hexactinellida show considerable parallelism in their evolution. From thin-walled, regularly spiculed, early genera at least two lineages diverged in each class to produce, on one hand, thick-walled irregularly spiculed forms and, on the other hand, thin- to thick-walled sponges which preserved much of the ancestral regularity of the skeletal net. Thicker walls must have increased the efficiency of the canal system and, as a consequence, the efficiency of food acquisition. Thicker, more robust walls apparently also allowed the sponges to move into environments of higher energy by Late Cambrian and Early Ordovician time, for sponges of this age occur in deposits of not only the quiet marginal basins but of banks and reefs.

REFERENCES

- Bedford, R., and Bedford, W. R., 1934, New species of Archaeocyathinae and other organisms from the Lower Cambrian of Beltana, South Australia: Kyancutta Mus. Mem. 1, 7 p.
- Beecher, C. E., 1889, Brachiospongiidae: a memoir on a group of Silurian sponges: Mem. Yale Peabody Mus., no. 2, pt. 1, 28 p.
- Dawson, J. W., and Hinde, G. J., 1890, New species of fossil sponges from the Siluro-Cambrian at Little Metis on the Lower St. Lawrence: Royal Soc. Canada, Trans., v. 7, sec. 4, p. 31-55.
- DeLaubenfels, M. W., 1955, Porifera, in Moore, R. C. (ed.), Treatise on Invertebrate Paleontology: Geol. Soc. Amer., and Univ. Kansas Press, Pt. E., p. 21-112.
- Dore, F., and Reid, R. E. H., 1965, *Allonnia tripodophora* nov. gen., nov. sp., nouvelle Eponge du Cambrien inferieur de Carteret (Manche): C. r. Somm. Seanc. Soc. Geol. France, fasc. 1, p. 20.
- Finks, R. M., 1960, Late Paleozoic sponge faunas of the Texas region: the siliceous sponges: Bull. Amer. Mus. Nat. Hist., v. 120, 160 p.
- , 1970, The evolution and ecologic history of sponges during Paleozoic times: in Fry, W. G. (ed.), The Biology of the Porifera: Symposium Zool. Soc. London, no. 25, p. 3-22.

- Hall, James, and Clarke, J. M., 1899, A memoir on the Paleozoic reticulate sponges constituting the family Dictyospongiidae: N. Y. State Mus. Nat. Hist. Mem., no. 2, 350 p.
- Howell, B. F., and Van Houten, F. B., 1940, A new sponge from the Cambrian of Wyoming: Wagner Free Inst. Sci. Bull., v. 15, p. 1-8.
- King, R. H., 1943, New Carboniferous and Permian sponges: Geol. Surv. Kansas Bull. 47, 36 p.
- Miller, S. A., 1889, Class porifera: in North American Geology and Paleontology, Cincinnati, p. 152-67.
- Okulitch, V. J., and Bell, W. G., 1955, *Gallatinospongia*, A new siliceous sponge from the Upper Cambrian of Wyoming: Jour. Paleont., v. 29, p. 460-61.
- Rauff, Hermann, 1893-94, Palaeospongiologie, Erster oder allgemeiner Theil, und Zweiter Theil, erste Hälfte: Palaeontographica, v. 40, 346 p.
- Reid, R. E. H., 1958, A monograph of the Upper Cretaceous Hexactinellida of Great Britain and Northern Ireland, Part 1: Palaeontographical Soc. London, p. i-xlvi.
- Reimann, I. G., 1945, New middle Devonian octactinellids: Buffalo Soc. Nat. Hist. Bull., no. 2, 350 p.
- Rietschel, S., 1968, Die Octactinellida und ihnen verwandte paläozoische Kalkschwämme (Porifera, Calcarea): Paläont. Zeit., v. 42, p. 13-32.
- Rigby, J. K., 1966, *Protospongia hicksi* Hinde from the Middle Cambrian of western Utah: Jour. Paleont., v. 40, p. 549-54.
- , 1967a, A new polyactinal sponge from the Antelope Valley Formation (Ordovician) in the Toiyah Range, Nevada: Jour. Paleont., v. 41, p. 511-15.
- , 1967b, Two new early Paleozoic sponges and the spongelike organism, *Gaspespongia basalis* Parks, from the Gaspé Peninsula, Quebec: Jour. Paleont., v. 41, p. 766-75.
- , 1969, A new Middle Cambrian hexactinellid sponge from western Utah: Jour. Paleont., v. 43, p. 125-28.
- , 1970, Two new Upper Devonian hexactinellid sponges from Alberta: Jour. Paleont., v. 44, p. 7-16.
- , 1971, Sponges of the Ordovician Cat Head Member, Lake Winnipeg, Manitoba, Part III: in Fossils of the Ordovician Red River Formation (Cat Head Member), Manitoba: Contr. to Canadian Paleontology, Geol. Surv. Can. Bull. 202, p. 35-79.
- , and Gutschick, R. C., 1976, Two new Lower Paleozoic hexactinellid sponges from Utah and Oklahoma: Jour. Paleont., v. 50, p. 79-85.
- , and Nitecki, M. H., 1975, An unusually well-preserved heteractinid sponge from the Pennsylvanian of Illinois and a possible classification and evolutionary scheme for the Heteractinida: Jour. Paleont., v. 49, p. 329-39.
- Rushton, A. W. A., and Phillips, W. E. A., 1973, A *Protospongia* from the Dalradian of Clare Island, Co. Mayo, Ireland: Palaeontology, v. 16, p. 231-37.
- Salter, J. W., 1864, On some new fossils from the Lingula Flags of Wales: Quart. Jour. Geol. Soc. London, v. 20, p. 233-441.
- Sdzvy, K., 1969, Unter-und mittelkambrische Porifera (Chancelloriida und Hexactinellida): Paläont. Zeit., v. 43, p. 115-47.
- Sollas, W. J., 1880, On the structure and affinities of the genus *Protospongia* (Salter): Quart. Jour. Geol. Soc. London, v. 36, p. 362-67.
- Walcott, C. D., 1879, Fossils of the Utica Slate: Trans. Albany Inst., for 1883, v. 10, p. 18-19. (This part issued separately in 1879.)
- , 1886, Second contribution to the studies on the Cambrian faunas of North America: U.S. Geol. Surv., Bull. 30, 369 p.
- , 1920, Cambrian Geology and Paleontology IV, No. 6—Middle Cambrian spongiae: Smithsonian Misc. Coll., v. 67, p. 261-364.
- Wetzel, Otto, 1940, Mikropaläontologische Untersuchungen an eozoischen und paläozoischen Kieselgesteinen aus Nord Amerika (U.S.A. und Kanada): Zentralbl. Mineralogie, Abt. B., no. 3, p. 66-86.
- Wilson, J. L., 1950, An Upper Cambrian pleospongid?: Jour. Paleont., v. 24, p. 591-93.

Biostratigraphy and Paleoecology of Cambrian Echinoderms from the Rocky Mountains

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ABSTRACT.—Echinoderms are widespread and fairly common in Cambrian strata from the Rocky Mountains. At least eight echinoderm classes are present, but the total number of genera and species is relatively small, and most echinoderm faunas consist of only one or two species. Cambrian echinoderms are commonly found in beds that were deposited in an offshore subtidal environment, especially in shales of the outer detrital belt. A few echinoderms are also known from the inner detrital belt, and disarticulated plates are locally abundant in the middle carbonate bank.

Echinoderm diversity was fairly low in the Early Cambrian of the Rocky Mountains with restricted occurrences of helicoplacoids, edrioasteroids, and rare eocrinoids. Diversity greatly increased in the Middle Cambrian with many widespread occurrences dominated by eocrinoids (especially *Gogia*), but stylophorans, ctenocystoids, edrioasteroids, possible holothurians, and an apparent crinoid are also present. Echinoderm diversity in this region apparently decreased in the Late Cambrian with only a few occurrences of eocrinoids, stylophorans, and a possible homoiosteleian.

Echinoderms were undergoing their initial major radiation into a poorly-filled marine ecosystem in the Cambrian. This resulted in: 1) a large number of local, short-lived, experimental classes containing few species; 2) a large number of basic body plans, but not utilization of all possible ways of life; 3) primitive morphology in the earliest forms followed by extensive improvements in design, setting the stage for a second major radiation in the Ordovician; and 4) no single echinoderm class dominating the Cambrian record, a pattern much different from that in arthropods. Three main feeding types are known in Cambrian echinoderms: attached (or mobile) high-level suspension feeders, attached or mobile benthic suspension feeders, and mobile benthic or shallow-burrowing detritus feeders. No echinoderm herbivores or carnivores are known from the Cambrian. Morphology was improved by reducing the number of calyx plates and developing better calyx symmetry, elaborating the ambulacra and food-gathering appendages, and developing a columnal-bearing stem. This last adaptation may have triggered the great expansion of high-level suspension feeding, stemmed echinoderms that dominated the rest of the Paleozoic record.

INTRODUCTION

Although echinoderms are widespread in Cambrian rocks from the Rocky Mountains, they usually constitute only a minor part of the total fauna. However, at a few localities, complete echinoderms are the dominant fossil group present, and at many other localities their disarticulated plates and columnals make up a large percentage of the bioclastic particles. Echinoderms are most commonly found in shales of the outer detrital belt, especially in the Middle Cambrian, but they also occur in other rock types and in older and younger strata. Shales (ranging from silty to limy) are the most favorable matrix for preserving complete Cambrian echinoderms, allowing the specimens to be studied by latex casting (see Pl. 1, figs. 1-5). Echinoderms are not common in Cambrian sandstones, and are either difficult to extract or disarticulated in Cambrian carbonates. Most Cambrian echinoderms were gregarious, and the discovery of one complete echinoderm at a locality may mean that hundreds or even thousands of additional specimens are present nearby.

ECHINODERM RANGE AND DIVERSITY

The stratigraphic range and diversity of all known Cambrian echinoderms is shown in Text-figure 1. The number of genera in each class is plotted for specific numbered time intervals (either one, two, or three North American trilobite zones). Eleven echinoderm classes occur in the Cambrian worldwide, and eight of these are present in the Rocky Mountains. Almost half of all Cambrian echinoderm genera are known from the Rocky Mountains (Text-fig. 1) although there are only 16 to 19 genera and 32 to 35 species here. Thus, echinoderms show a pattern much different from that of arthropods in the Cambrian; no class of echinoderms has more than 13 Cambrian genera; whereas trilobites dominate the arthropod record with at least 780 Cambrian genera. Only three echinoderm classes, eocrinoids (Pl. 1, fig. 5), edrioasteroids (Pl. 1, fig. 2), and stylophorans (Pl. 1, fig. 1), were moderately successful and ranged throughout the Cambrian (see Text-fig. 1). All other echinoderm classes were either short-lived, such as helicoplacoids (Pl. 1, fig. 3) and ctenocystoids (Pl. 1, fig. 4), or have an isolated occurrence in the Cambrian before reappearing in the Ordovician, such as crinoids (Pl. 1, fig. 6).

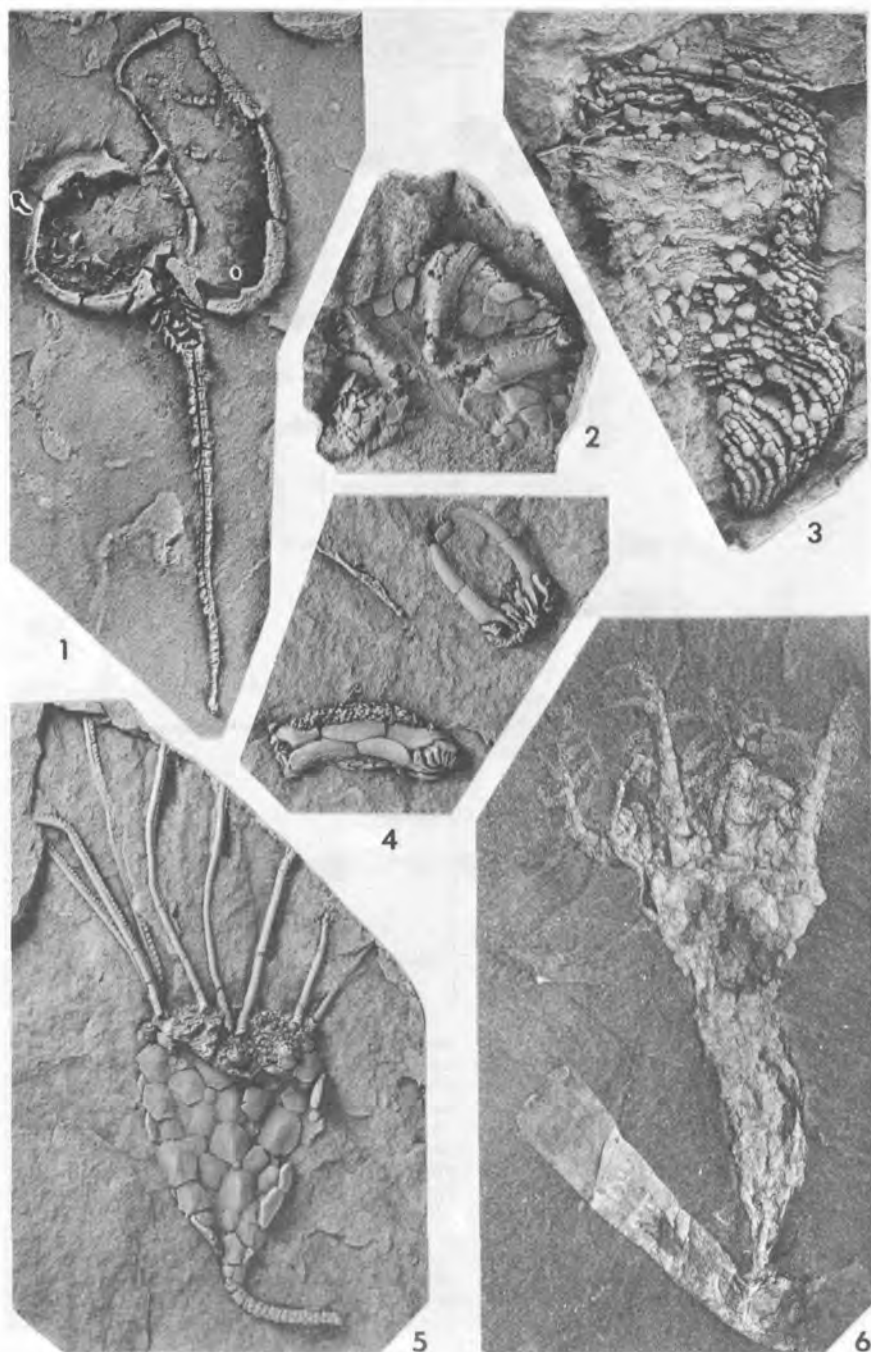
Early Cambrian echinoderms are known from only four localities in the western part of the Rocky Mountains (Text-fig. 2). Diversity is also low, and includes helicoplacoid specimens or plates (Durham and Caster, 1963; Durham, 1967) from all four localities, edrioasteroids (see Durham, 1964, p. 25) from two localities, and an eocrinoid resembling *Gogia* from eastern California (Sprinkle and Durham, in preparation).

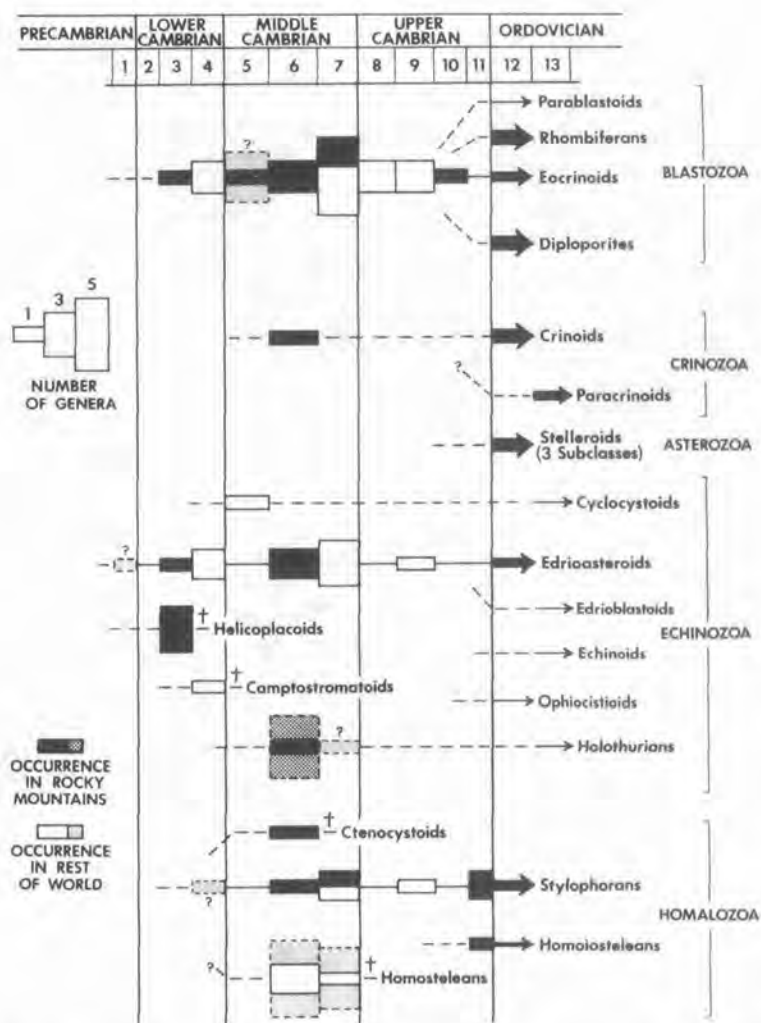
Echinoderms became much more widespread and abundant in the Middle Cambrian (Text-fig. 2); at least 23 localities in the Rocky Mountains have yielded either disarticulated plates or numerous complete specimens. Most of these localities lie farther east than Early Cambrian localities because of the gradually transgressive Cambrian seas. Almost all of these Middle Cambrian occurrences contain eocrinoids (especially the genus *Gogia*; see Sprinkle, 1973, p. 76-105), but other echinoderms have been found including edrioasteroids (Bassler, 1935, p. 5; Bell and Sprinkle, 1977), stylophorans (Sprinkle and Robison, in preparation), ctenocystoids (Robison and Sprinkle, 1969), several possible holothurians (Durham, 1974, p. 752, 755), and an apparent crinoid (Sprinkle, 1973, p. 177-83; Sprinkle and Moore, 1977).

Late Cambrian echinoderms were again reduced in number of occurrences and diversity (Text-fig. 2), perhaps because of morphologic changes, such

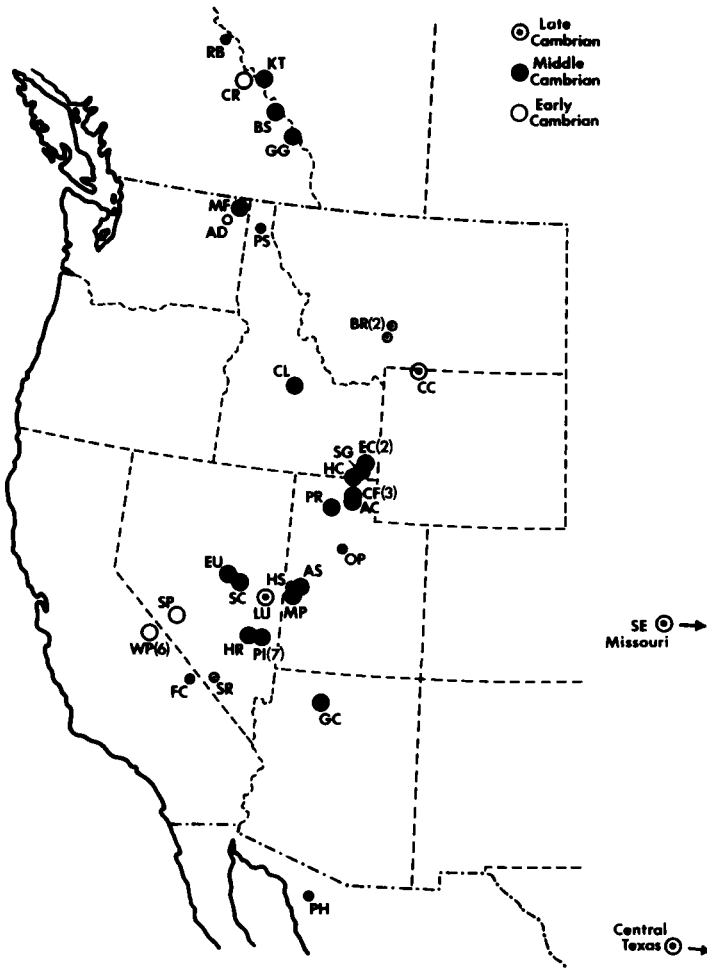
EXPLANATION OF PLATE 1

FIGS. 1-6.—Examples of Cambrian echinoderms from the Rocky Mountains. 1, New stylophoran, Spence Shale (Middle Cambrian), Calls Fort, northern Utah, X3.7. 2, New edrioasteroid, Chisholm Shale (Middle Cambrian), just NW of Pioche, eastern Nevada, X2.5. 3, *Helicoplacus* sp. (helicoplacoid), Poleta Formation (Lower Cambrian), Westgard Pass, eastern California, X2.6. 4, *Ctenocystis utabensis* (ctenocystoid), Spence Shale (Middle Cambrian), Antimony Canyon, northern Utah, X2.8. 5, *Gogia* n. sp. (eocrinoid), Spence Shale (Middle Cambrian), Antimony Canyon, northern Utah, X2.1. 6, *Echmatocrinus brachiatus* (crinoid), holotype GSC 25962B attached to a worm tube, Burgess Shale (Middle Cambrian), north of Field, British Columbia, X1.1.





TEXT-FIGURE 1.—Stratigraphic range and generic diversity of all known Cambrian echinoderms. Black and dark stipple, Cambrian echinoderm occurrences in Rocky Mountains; white and light stipple, Cambrian echinoderm occurrences in rest of world. Size of arrow at right indicates success of class in Early and Middle Ordovician. Stippled genera represent questionable occurrences of three types; questionable identification as echinoderms (such as the Ediacaran genus *Tribrachidium* and the Burgess Shale holothurians), questionable assignment to a class (such as the two Australian genera of haplozoans that I have assigned to the eocrinoids), or classes oversplit at the generic level (in my opinion homostealeans). [Time intervals: 1 = Latest Precambrian (Ediacaran), 2 = *Fallotaspis* Zone, 3 = *Nevadella* Zone, 4 = *Bonnia-Olenellus* Zone, 5 = *Platystrophia-Poliella* plus *Albertella* zones, 6 = *Glossopleura* plus *Bathyriscus-Elrathia* zones, 7 = *Bolaspidea* Zone, 8 = *Cedaria* plus *Crepicephalus* zones, 9 = *Aphelespis* to *Elvinia* zones, 10 = *Taeniecephalus* to *Ellipticocephaloides* zones, 11 = *Saukia* Zone, 12 = Early Ordovician (Canadian), and 13 = Middle Ordovician.] Data from many sources.



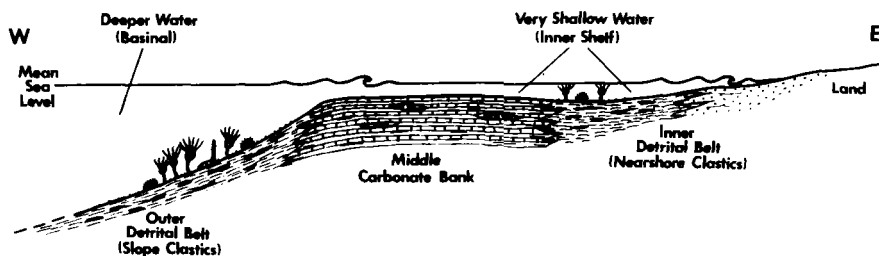
TEXT-FIGURE 2.—Geographic distribution of echinoderm-bearing localities in the Rocky Mountains for the Early Cambrian (open circles), Middle Cambrian (black circles), and Late Cambrian (dotted circles). Large circles indicate localities with numerous complete echinoderms; small circles, localities having only echinoderm plates and/or columnals. [Locality key: AC = Antimony Canyon, N. Utah; AD = Addy, NE Wash.; AS = Antelope Springs, W. Utah; BR = Bridger Range, SW Mont.; BS = Burgess Shale, Brit. Col.; CC = Cooke City, N. Wyo.; CF = Calls Fort, N. Utah; CL = Clayton, Central Idaho; CR = Columbia River Bend, Brit. Col.; EC = Emigration Canyon, SE Idaho; EU = Eureka, Nev.; FC = Furnace Creek, E. Calif.; GC = Grand Canyon, N. Ariz.; GG = Gog Lake, Brit. Col.; HR = Highland Range, SE Nev.; HS = House Range, W. Utah; KT = Mt. Kitchner, Alberta; LU = Lund, E. Nev.; MF = Metaline Falls, NE Wash.; MP = Marjum Pass, W. Utah; OP = Ophir, central Utah; PI = Pioche, SE Nev.; PH = Proveedora Hills, Sonora, Mex.; PR = Promontory Point, N. Utah; PS = Packsaddle Mtn., N. Idaho; RB = Mt. Robson, Brit. Col.; SC = Secret Canyon, central Nev.; SG = Spence Gulch, SE Idaho; SP = Silver Peak, SW Nev.; SR = Spector Range, SW Nev.; and WP = Westgard Pass, E. Calif.] In part from Sprinkle (1973, Text-fig. 25).

as the development of thin-plated calyces, or because of the presence of widespread carbonates which did not favor the preservation of complete specimens. The six occurrences known from the Rocky Mountains contain only eocrinoids (Ulrich, 1929), stylophorans (Ubaghs, 1963), and a single homoioosteleon (Ubaghs, 1963). However, by this time epicontinental seas had covered most of the North American platform, and additional echinoderms are known from the Wilberns Formation of central Texas and from the Davis Formation of southeastern Missouri, where a diverse fauna has now been collected (Sprinkle and Etrimble, 1977; Sprinkle and Stinchcomb, in preparation).

CAMBRIAN DEPOSITIONAL ENVIRONMENTS

Most paleogeographic reconstructions of Cambrian sediments in the Rocky Mountains include three intertonguing belts or zones parallel to shoreline (Palmer, 1960, 1971; Robison, 1960; Oriel and Armstrong, 1971); these have been termed the inner detrital belt, middle carbonate bank, and outer detrital belt (Text-fig. 3). The inner detrital belt consists of sandy and shaly sediment deposited along the western shore of the North American continent. The clastic sediment for these units was derived from the continental landmass to the east and was probably deposited in shoreface and bay environments. Offshore from these areas but still in very shallow water was a carbonate bank made up of limestone or dolomite, often containing horizontal algal laminations, domal or columnar stromatolites, or oncolites. Farther offshore from the bank was the deeper water outer detrital belt, representing outer shelf, basin, or perhaps continental slope deposits. Here siltstone, shale, and dark limestone were deposited by turbidity currents on a slight slope (see Cook and Taylor, 1975). Much of this outer detrital belt sediment was probably derived from material originally in the inner detrital belt which had moved through the bank in chutes or around the bank in areas where it was not developed.

In this model for Cambrian depositional environments in the Rocky Mountains, echinoderms are most common in shallower parts of the outer detrital belt near the edge of the carbonate bank (Text-fig. 3). Most of the Middle Cambrian localities that have yielded multiple-echinoderm faunas (Table 1) appear to represent this region. A few echinoderm occurrences



TEXT-FIGURE 3.—Generalized paleogeographic reconstruction of Cambrian depositional environments along an E-W cross section through the Rocky Mountains showing the inner and outer detrital belts separated by the middle carbonate bank. Complete echinoderms were most common in shallower parts of the outer detrital belt near the edge of the bank; however, some specimens have also been found in the inner detrital belt, and beds or lenses of disarticulated plates and columnals are present in the middle carbonate bank. Section has great vertical exaggeration.

are located in shales of the inner detrital belt, and lenses or beds of disarticulated plates and columnals are locally common in the middle carbonate bank, which was especially widespread during the Late Cambrian. The echinoderms of the bank may have lived locally on the bank surface, or may have been washed in from adjacent detrital areas.

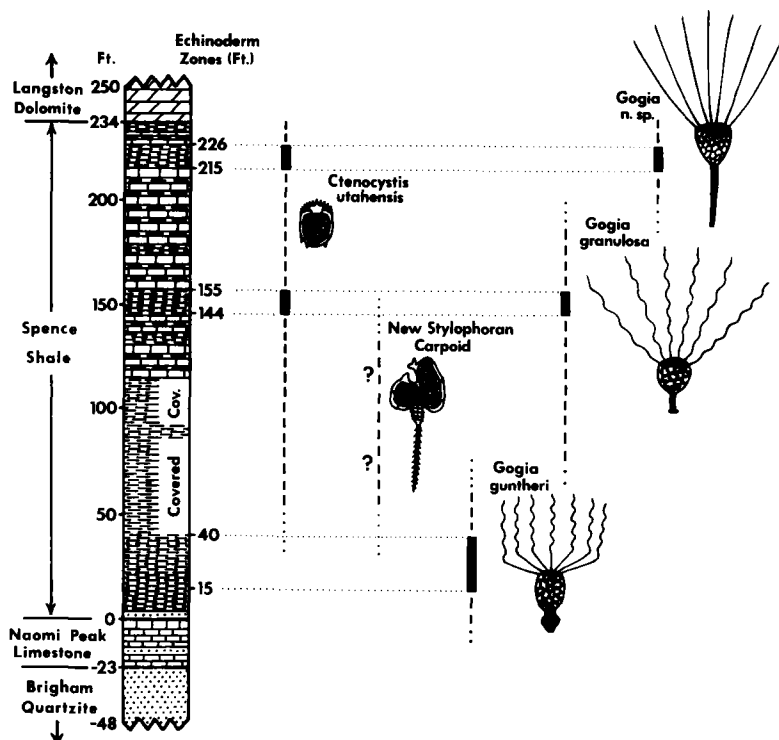
ECHINODERM FAUNAS

Only 13 Cambrian localities (out of 33 total in the Rocky Mountains) have more than one echinoderm genus represented by complete specimens (Table 1). All other localities have produced just one echinoderm species or unidentifiable plates and/or columnals. As many as five echinoderm genera are known from the same locality, but in most cases only two genera and species occur together in the same beds. This is illustrated by the echinoderm fauna from the Spence Shale at Antimony Canyon, northern Utah (Table 1*). Here three distinctive species of the eocrinoid *Gogia* have been found along with ctenocystoids and a rare stylophoran (Text-fig. 4); however, each of the *Gogia* species occurs in a different part of the section. *Gogia guntheri* is a large form with an elongate calyx, an inflated holdfast, and partially spiralled brachioles; it is the only echinoderm found in a 25-foot interval near the base of the Spence Shale. *Gogia granulosa* has an elongate to globular calyx with ornamented plates, a short cylindrical holdfast, and very long spiralled brachioles; it occurs with ctenocystoids in a thin shaly interval

TABLE 1
MULTIPLE ECHINODERM FAUNAS KNOWN FROM CAMBRIAN LOCALITIES
IN THE ROCKY MOUNTAINS

Numbers in () in locality column indicate several closely spaced collecting sites, and * marks locality discussed in text and in Text-figure 4.

Series	Formation	Locality	Echinoderms
Upper Cambrian	Whipple Cave Fm.	1. Lund, Nev.	<i>Nevadacystis</i> <i>Phyllocystis</i> Unident. homoioiostelean
Middle Cambrian	Secret Canyon Fm.	2. Eureka and 3. Secret Canyon, Nev.	<i>Eustypocystis</i> New stylophoran?
	Burgess Shale (Stephen Fm.)	4. Burgess Shale, B.C.	<i>Gogia</i> <i>Echmatocrinus</i> <i>Walcottidiscus</i> "B.S. 'arms'" 1-4? holothurians
	Spence Shale	5. Calls Fort (3), *6. Antimony Canyon 7. High Creek, Utah 8. Spence Gulch, Idaho	<i>Gogia</i> (3 sp.) <i>Ctenocystis</i> New stylophoran
	Lead Bell Shale	9. Emigration Canyon (2), Idaho	<i>Gogia</i> (2 sp.) <i>Ctenocystis</i>
	Chisholm Shale	10. Pioche (7+) and 11. Highland Range, Nev.	<i>Gogia</i> New edrioasteroid
Lower Cambrian	Poleta Fm.	12. Westgard Pass (6), Calif. and 13. Silver Peak, Nev.	<i>Helicoplacus</i> (4+ sp.) <i>Waucobella</i> <i>Polyplacus</i> <i>Stromatocystites</i> <i>Gogia?</i>



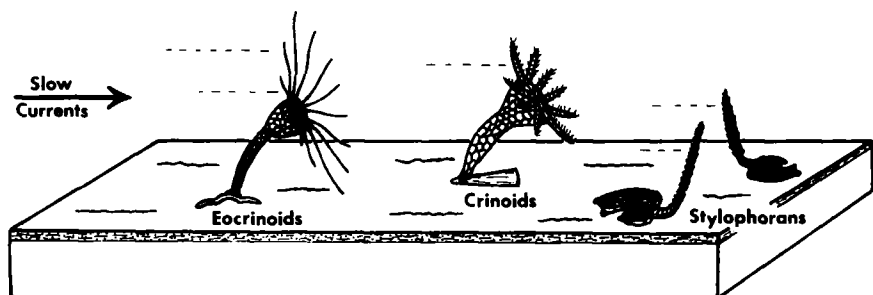
TEXT-FIGURE 4.—Occurrence of echinoderms in the Spence Shale at Antimony Canyon and adjacent sections, northern Utah. Note that three distinct *Gogia* species occur in different parts of the Spence Shale at this section, and that only two echinoderm species are known to occur together at any one level. Measured section from Campbell (1974).

just above the middle of the Spence Shale. A new species of *Gogia* (Pl. 1, fig. 5) having a conical calyx with epispires concentrated near the summit, a long cylindrical holdfast, and fairly long straight brachioles occurs with ctenocystoids in a shaly interval near the top of the Spence Shale (Text-fig. 4). A new stylophoran carpod (Pl. 1, fig. 1) occurs rarely at nearby Spence Shale sections, but has not been found in place or associated with any of these other echinoderms. Thus, only two of these five echinoderm species are known to occur together in the same beds at this section.

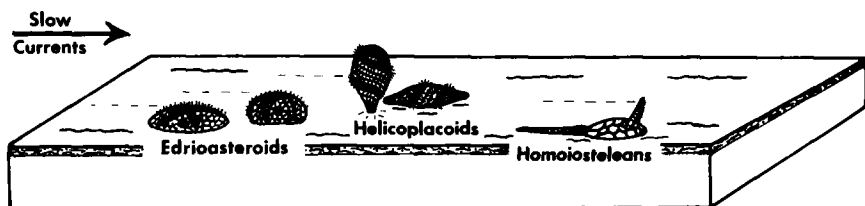
Using the depositional model described earlier (Text-fig. 3) to assign depositional environments to the lithologies present in the Antimony Canyon section (Text-fig. 4), the thick Brigham Quartzite appears to represent the inner detrital belt, the Naomi Peak Limestone and Langston Dolomite, the middle carbonate bank, and the Spence Shale, the outer detrital belt. All of the echinoderm-bearing intervals in the Spence Shale would then represent outer detrital belt shales with bank conditions nearby. The thin-bedded nodular limestone units in the upper part of the Spence (Text-fig. 4) may represent either short intervals of local carbonate bank conditions or repeated down-slope slumps of carbonate debris from the nearby bank.

ECHINODERM PALEOECOLOGY

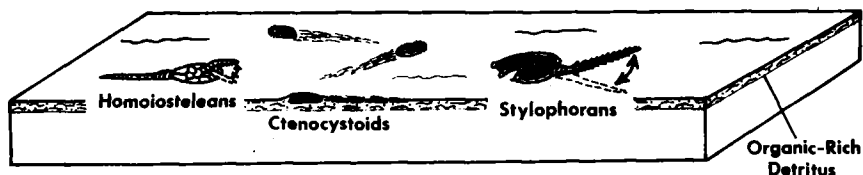
Three general feeding methods appear to have been used by Cambrian echinoderms. Several groups raised their feeding appendages well off the substrate to become attached (or mobile), high-level, suspension feeders (Text-fig. 5A). These include all of the holdfast- or stem-bearing eocrinoids with brachioles, the single known holdfast- and arm-bearing crinoid from the Burgess Shale, and perhaps stylophoran carpooids that could have held their



A



B



C

TEXT-FIGURE 5.—Feeding types in Cambrian echinoderms from the Rocky Mountains. *A*, attached (or mobile) high-level suspension feeders¹ include the holdfast- or stem-bearing eocrinoids and crinoids, and perhaps stylophorans. *B*, attached or mobile low-level suspension feeders include edrioasteroids, helicoplacoids, and perhaps homoiosteleans. *C*, mobile benthic or shallow burrowing detritus feeders include ctenocystoids and perhaps homoiosteleans and stylophorans. Cambrian cyclocystoids probably utilized feeding type *B*; whereas Cambrian homoiosteleans, camptostromatoids, and most holothurians probably utilized feeding type *C*.

long aulacophore up into the current field, facing the food groove either toward or away from the current (see Parsley and Caster, 1975). Other groups lived directly on the sediment surface and were attached or mobile low-level suspension feeders (Text-fig. 5B). These include flat or globular edrioasteroids, helicoplacoids that may either have lived upright or on their sides, and perhaps homoiosteans that could have held their short feeding appendage erect. Several of the carpoid groups were probably mobile benthic or shallow-burrowing detritus feeders (Text-fig. 5C), utilizing a thin surface layer of organic-rich detritus. Ctenocystoids almost certainly belonged in this category, and stylophorans and homoiosteans may also have utilized this thin detritus layer by sweeping their food-gathering appendage back and forth across the bottom. Other Cambrian echinoderm classes not found in the Rocky Mountains (homosteans, cyclocystoids, and camptostromatoids) probably fit into the last two feeding types. Neither true herbivores (such as echinoids that browse on seaweed) nor carnivores (such as starfish that prey on bivalves) are represented by any Cambrian echinoderms. Thus, among echinoderms, the highest levels of the food pyramid were the last to be developed, and did not appear until the Ordovician.

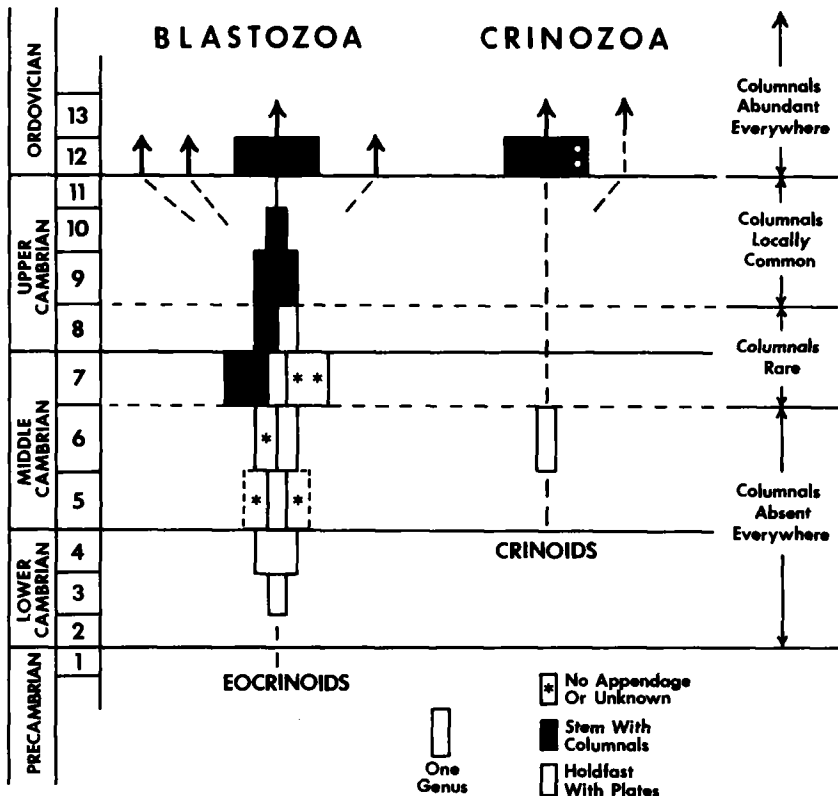
IMPROVEMENTS IN MORPHOLOGY

Cambrian echinoderms had many primitive features in their morphology. Most had numerous irregularly arranged calyx plates with poorly developed pentameral symmetry, rather simple feeding appendages, and, in high-level suspension feeders, a primitive holdfast (Sprinkle, 1973, p. 37)—a multiplated extension of the aboral calyx used to get the echinoderm up off the bottom sediment (see Pl. 1, figs. 5 and 6). Each of these features was gradually improved during the Cambrian, resulting in greater efficiency and the appearance of several new classes in the Ordovician.

The modification of a multiplated holdfast into a longer and more efficient stem composed of columnals was one of the most important improvements. Both eocrinoids and crinoids apparently made this transition independently (Text-fig. 6). The first stemmed eocrinoids have been found in the latest Middle Cambrian (Sprinkle, 1973, p. 38-39), and columnals first appeared in carbonate units at this time. Crinoids apparently did not make this transition until the latest Cambrian or earliest Ordovician, and in some Early Ordovician genera like *Aethocrinus* (Ubaghs, 1969) the transition was still incomplete. Columnals (probably of an eocrinoid origin) gradually became more common during the Late Cambrian (Text-fig. 6), and were abundant in the Ordovician when all crinozoan and blastozoan classes had developed a true stem. This change from a holdfast to a columnal-bearing stem may have been partly responsible for the great success of high-level suspension feeding echinoderms during the remainder of the Paleozoic.

CONCLUSIONS

Cambrian echinoderms show a pattern (see Text-fig. 1) that is characteristic of a phylum just beginning to radiate into a poorly filled marine ecosystem characterized by high productivity (see Tappan, 1971) and little competition. The initial divergence from a common proto-echinoderm ancestor had already taken place in the latest Precambrian (Durham, 1971, p. 1127-28; Ubaghs, 1975, p. 79), and all four Cambrian subphyla probably crossed the Pre-



TEXT-FIGURE 6.—Change from a multiplated holdfast to a stem composed of columnals in eocrinoids (Blastozoa) and crinoids (Crinozoa). The first eocrinoids with a true stem appeared in the latest Middle Cambrian, and by the middle Late Cambrian all known eocrinoids had stems, as did other blastozoan classes appearing in the Ordovician. Crinoids apparently developed a true stem independently from and somewhat later than eocrinoids, probably in the Early Ordovician. Columnals became increasingly common during the Late Cambrian and were abundant everywhere starting in the Early Ordovician. Time intervals (1-13) same as in Text-figure 1. Data from Sprinkle (1973, p. 37-39).

cambrian-Cambrian boundary as separate lineages (Text-fig. 1) and continued to diversify rapidly. The Homalozoa and Echinozoa produced numerous experimental groups in the Cambrian with new designs for suspension and detritus feeding; however, over half of these class-level groups (five out of nine; see Text-fig. 1, bottom) were unsuccessful and soon became extinct. This has resulted in several morphologically distinct classes, each with a short stratigraphic range, limited geographic distribution, and low diversity.

The Crinozoa and Blastozoa, both of which became high-level suspension feeders, produced only one class apiece during the Cambrian (see Text-fig. 1, top). This niche may have been completely open in the Cambrian, but difficult to colonize successfully. Only after several improvements had been made in morphology (reduction, standardization, and imposition of sym-

metry in calyx plating; improvement of ambulacra and food-gathering appendages; and development of a columnal-bearing stem) did these two subphyla produce several new classes (four or five by the Middle Ordovician) and greatly increase their diversity at lower category levels. For the remainder of the Paleozoic, these high-level suspension feeders (especially crinoids) dominated the entire echinoderm record.

Several new echinoderm groups of unknown ancestry, such as stelleroids and echinoids, also appeared in the Ordovician and became fairly important classes during the remainder of the Paleozoic. However, no new classes of echinoderms (except perhaps blastoids) appeared after the Middle Ordovician. Instead, the later Paleozoic record of echinoderms was characterized by standardization of designs to a few successful ones and gradual weeding-out of the less efficient and less diverse classes that had appeared during the Early Paleozoic radiation. All echinoderm classes that survived the extinction at the Permian-Triassic boundary are still living today.

Thus, the initial Cambrian radiation of echinoderms established the basic evolutionary pattern in this phylum for the entire Paleozoic. Echinoderm classes with low diversity and a brief record in the Cambrian and Ordovician should not be considered a problem (see Beerbower, 1968, p. 381; Breimer and Ubaghs, 1974, p. 411); they are a natural consequence of this initial echinoderm radiation into a poorly filled marine ecosystem (Eldredge and Gould, 1972, p. 110-11; Sprinkle, 1976). Other major groups (especially molluscs and nontrilobite arthropods) show a somewhat similar Cambrian record, but this pattern is most strongly displayed by echinoderms because of their distinctive and well-preserved calcite skeletal structures, large number of experimental body plans, and lack of dominance by any one class until later in the fossil record.

ACKNOWLEDGMENTS

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REFERENCES

- Bassler, R. S., 1935, *The classification of the Edrioasteroidea*: *Smithson. Misc. Coll.* 93(8), p. 1-11.
- Beerbower, J. R., 1968, *Search for the past, an introduction to paleontology*: 2nd ed., Prentice-Hall, Inc., Englewood Cliffs, N.J., 512 p.
- Bell, B. M., and Sprinkle, James, 1977, *New edrioasteroid from the Middle Cambrian of Nevada*: *J. Paleont.*, v. 51. (In press.)
- Breimer, Albert, and Ubaghs, Georges, 1974, *A critical comment on the classification of the pelmatozoan echinoderms, I and II*: *Konink. Ned. Akad. van Wet.*, *Proc. Ser. B*, 77(5), p. 398-417.

- Campbell, D. P., 1974, Biostratigraphy of the *Albertella* and *Glossopleura* Zones (lower Middle Cambrian) of northern Utah and southern Idaho: unpub. M.S. thesis, Univ. of Utah, 295 p.
- Cook, H. E., and Taylor, M. E., 1975, Early Paleozoic continental margin sedimentation, trilobite biofacies, and the thermocline, western United States: *Geology*, v. 3(10), p. 559-62.
- Durham, J. W., 1964, The Helicoplacoidea and some possible implications: *Yale Sci. Mag.*, v. 39(2), p. 24-28.
- , 1967, Notes on the Helicoplacoidea and early echinoderms: *J. Paleont.*, v. 41(1), p. 97-102.
- , 1971, The fossil record and the origin of the Deuterostomata: *N. Amer. Paleont. Conv. Proc. Pt. H*, p. 1104-32.
- , 1974, Systematic position of *Eldonia ludwigi* Walcott: *J. Paleont.*, v. 48(4), p. 750-55.
- , and Caster, K. E., 1963, Helicoplacoidea: a new class of echinoderms: *Science*, v. 140(3568), p. 820-22.
- Eldredge, Niles, and Gould, S. J., 1972, Punctuated equilibria: an alternative to phyletic gradualism: in Schopf, T. J. M., ed., *Models in Paleobiology*: Freeman, Cooper and Co., San Francisco, p. 82-115.
- Oriel, S. S., and Armstrong, F. C., 1971, Uppermost Precambrian and lowest Cambrian rocks in southeastern Idaho: *U.S. Geol. Surv. Prof. Paper* 394, 52 p.
- Palmer, A. R., 1960, Some aspects of the early Upper Cambrian stratigraphy of White Pine County, Nevada, and vicinity: in Boettcher, J. W., and Sloan, W. W., Jr. (eds.), *Guidebook to the Geology of East Central Nevada*: Intermountain Assoc. Petrol. Geol., Eleventh Ann. Field Conf., p. 53-58.
- , 1971, The Cambrian of the Great Basin and adjacent areas, western United States: in C. H. Holland (ed.), *Cambrian of the New World*: Wiley-Interscience, New York, p. 1-78.
- Parsley, R. L., and Caster, K. E., 1975, Zoological affinities and functional morphology of the Mitrata (Echinodermata): *Geol. Soc. Amer., Abst. prog.* 7(7), p. 1225-26.
- Robison, R. A., 1960, Lower and Middle Cambrian stratigraphy of the eastern Great Basin: in Boettcher, J. W., and Sloan, W. W., Jr. (eds.), *Guidebook to the Geology of East Central Nevada*: Intermountain Assoc. Petrol. Geol., Eleventh Ann. Field Conf., p. 43-52.
- , and Sprinkle, James, 1969, Ctenocystoidea: new class of primitive echinoderms: *Science*, v. 166(3912), p. 1512-14.
- Sprinkle, James, 1973, Morphology and evolution of blastozoan echinoderms: *Harvard Univ. Mus. Comp. Zoology, Spec. Publ.*, 283 p.
- , 1976, Classification and phylogeny of "pelmatozoan" echinoderms: *Syst. Zool.* v. 25(1), p. 83-91.
- , and Moore, R. C., 1977, Echinodermata: in Moore, R. C., ed., *Treatise on Invertebrate Paleontology, Part T, Echinodermata* 2(1): *Geol. Soc. Amer. and Univ. Kansas Press, Lawrence, Kansas*. (In press.)
- , and Strimple, H. L., 1977, New echinoderms from the Upper Cambrian Davis Formation of Missouri: *J. Paleont.* 51. (In press.)
- Tappan, Helen, 1971, Microplankton, ecological succession, and evolution: *N. Amer. Paleont. Conv., Proc. Pt. H*, p. 1058-1103.
- Ubahgs, Georges, 1963, *Cothurnocystis* Bather, *Phyllocystis* Thoral and an undetermined member of the order Soluta (Echinodermata, Carpoidea) in the uppermost Cambrian of Nevada: *J. Paleont.*, v. 37(6), p. 1133-42.
- , 1969, *Aethocrinus moorei* Ubahgs, n. gen., n. sp., le plus ancien crinoïde dicyclique connu: *Univ. Kansas Paleont. Contr.*, Paper 38, 25 p.
- , 1975, Early Paleozoic echinoderms: *Ann. Rev. Earth Planet. Sci.*, v. 3, p. 79-98.
- Ulrich, E. O., 1929, *Trachelocrinus*, a new genus of Upper Cambrian crinoids. *J. Washington Acad. Sci.*, v. 19(3), p. 63-66.

Stratigraphic Relationships and Depositional Facies in a Portion of the Middle Cambrian of the Basin and Range Province

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ABSTRACT.—Depositional facies in the Middle Cambrian include assemblages of rock assigned to peritidal, shallow-sublittoral, deep-sublittoral, slope, and basin environments. Of these the deep-sublittoral-slope and basin facies are least known and may range from entirely sublittoral to bathyal depths.

Algal-associated rocks are a significant component of the peritidal and shallow-sublittoral environment. Their extension into the sublittoral may be related to the scarcity of grazing or browsing animals over large areas of the shelf. Poor water circulation and elevated salinity may have been a causal factor.

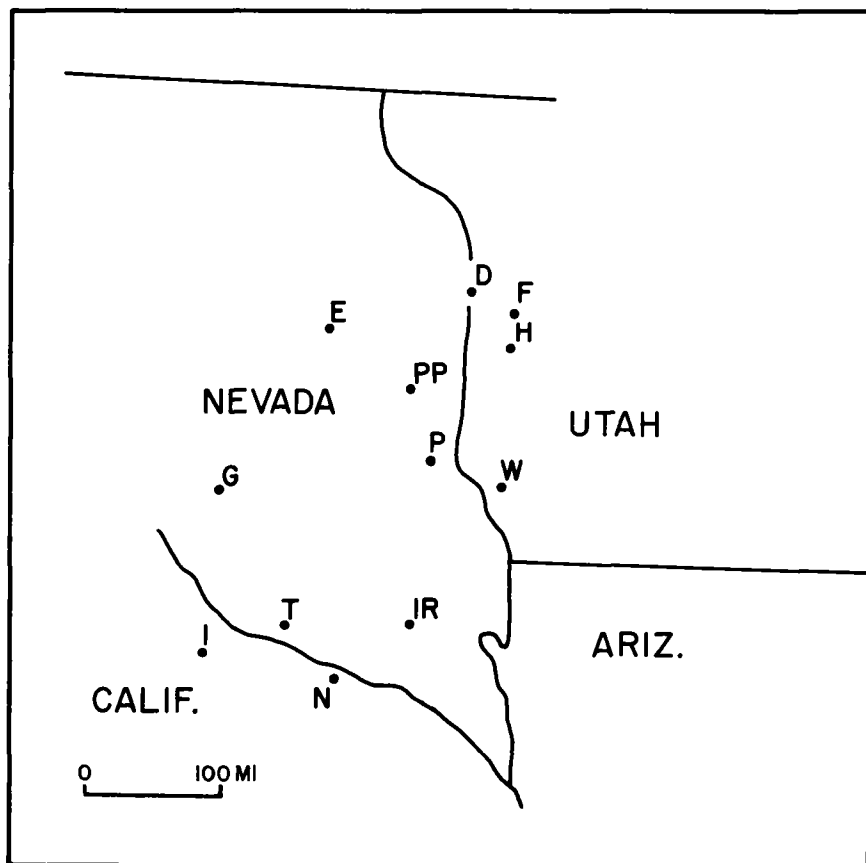
Stratigraphic cycles ("grand cycles") consisting of a lower shale half-cycle and an upper carbonate half-cycle reflect variable subsidence rates and terrigenous input across the shelf. Emergence, reflected in the shoaling upward carbonate half-cycle, culminated with the seaward transport of reworked, nearshore terrigenous sediment. Submergence and the beginning of the next cycle is recorded either within the overlying shale or sandstone unit or at the base of the carbonate half-cycle. Relative sea level shifts may have occurred within the half-cycles rather than at their beginnings.

During the early phase of emergence a depositional topography developed along a slope-break on the shelf with little sediment getting to the basin (starved condition). The upper portion of slopes on the seaward side of this topography may have been a zone of nondeposition and locally of erosion. The basin underwent a filling stage when terrigenous sediment moved across the shelf. During the submergent phase the terrigenous fill was replaced by a seaward progradation of the deep sublittoral and slope carbonates.

INTRODUCTION

In the Basin and Range Province the Middle Cambrian carbonate-dominated shelf owed its existence to a combination of factors. Chief among these was the construction of a broad continental terrace composed largely of terrigenous sediments of Late Precambrian and Early Cambrian age (Stewart, 1972). Much of the material composing the terrace accumulated in shallow sublittoral and peritidal environments (Stewart, 1969; Barnes and Klein, 1975). Carbonate sedimentation of significance developed in the Early Cambrian and has been described by Halley (1974). However, the major expansion of the various carbonate depositional environments occurred after the deposition of the Chisholm Shale and continued for much of the remainder of the Cambrian. The expansion of the carbonate belt was related to the reduction in available terrigenous source area as a consequence of the overall transgressive phase associated with the Sauk Sequence (Wheeler, 1960). Finally, based on meager paleomagnetic data (Irving, 1964), the shelf was located in a low latitude position conducive to carbonate sedimentation.

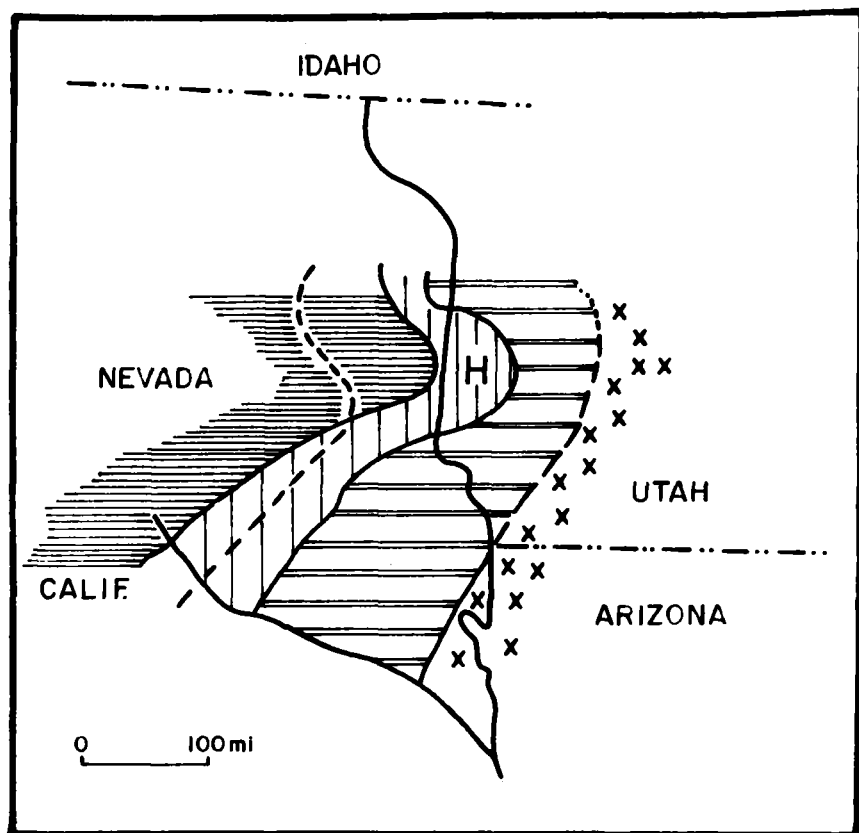
This paper is concerned with a stratigraphic interval encompassing a portion of the *Bathyriscus-Elrathina* and *Bolaspidella* Assemblage Zones of Middle Cambrian age. The lower boundary includes the Whirlwind Formation and its equivalents which contain a distinctive trilobite fauna widely recognized over the eastern Basin and Range (Palmer, 1971, p. 57). The upper boundary is placed at the top of a thin terrigenous unit characterized by

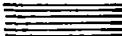

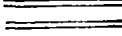





TEXT-FIGURE 1.—Index map of localities referred to in text: D-Deep Creek Range, E-Eureka, F-Fish Springs Range, G-Goldfield, H-House Range, I-Inyo Range, IR-Indian Ridge, N-Nopah, P-Pioche, PP-Patterson Pass, T-Titus Canyon, and W-Wah Range. Palinspastic base after Stewart and Poole (1974).

the trilobite *Eldoradia* (Kepper, 1972, p. 507; Hintze and Robison, 1975, p. 889), which approximates the Middle-Upper Cambrian boundary. Sections within the deep sublittoral facies such as in the House and southern Schell Creek ranges have much better biostratigraphic control with regard to this boundary. In any case, the depositional facies discussed here straddle the boundary.

Maps (Text-figs. 1, 2) used in this paper are plotted on a palinspastic base taken from Stewart and Poole (1974; p. 32), which is corrected for displacements resulting from thrusting, strike slip movements, and oroflexural bending (p. 30-33). Of these displacement factors, thrusting appears not to have significantly altered the position of the major sedimentary belts (Stewart, 1972; p. 1347). In the Basin and Range Province, Cambrian through Lower Devonian stratigraphy shows that the general east to west pattern of



-  BASIN
-  DEEP SUBLITTORAL AND SLOPE
-  PERITIDAL, SHALLOW SUBLITTORAL
-  SHELF - LAGOON
-  MID-BOLASPIDELLA ZONE LITHOFACIES BOUNDARIES
-  APPROX. SEAWARD EDGE, SHALLOW SUBLITTORAL LITHOFACIES, BATHYURISCUS-ELRATHINA ZONE
- H** HOUSE EMBAYMENT

TEXT-FIGURE 2.—Depositional facies map showing approximate seaward edge of shallow-sublittoral zone during *Bathyriscus-Elrathina* Chronozone and subsequent submergence associated with House Embayment. Shelf lagoon probably belongs to shallow-sublittoral facies.

shelf-slope-basin is largely intact. Stewart and Poole's map does not correct for the late Tertiary crustal expansion on the rationale that it may merely balance off against the other displacement factors. However, Hamilton (1975; p. 1098) suggested that the width of the Basin and Range may have been doubled as a consequence of rotational movements on normal faults. This may be a significant factor in evaluating the aerial extent of the depositional environments.

DEPOSITIONAL FACIES

The description and interpretation of Cambrian depositional facies has evolved over the last two decades more or less in pace with growing knowledge of modern depositional environments. Wheeler (1960) discussed a general sedimentologic model for the Cambrian which consisted of a belt of coarse detritus along the margin of the craton followed seaward by carbonates and distally by a belt of detrital fines bypassed across the intermediate zone. That same year, Palmer (1960) coined the terms inner detrital belt, middle carbonate belt, and outer detrital belt to describe this model. These have been, and continue to be, convenient ways to describe the ebb and flow of terrigenous supply and of differential subsidence leading to the development of sandstone, carbonate and shale lithosomes in the Cambrian.

In more recent times Kepper (1972, p. 521) used shelf-lagoon, shoal and outer shelf to describe environmental settings for the middle and outer belt. Further work by Brady and Koepnick (1973, p. 711) and Cook and Taylor (1975, p. 560) has led to the recognition of depositional facies associated with a shelf, slope, and basin configuration.

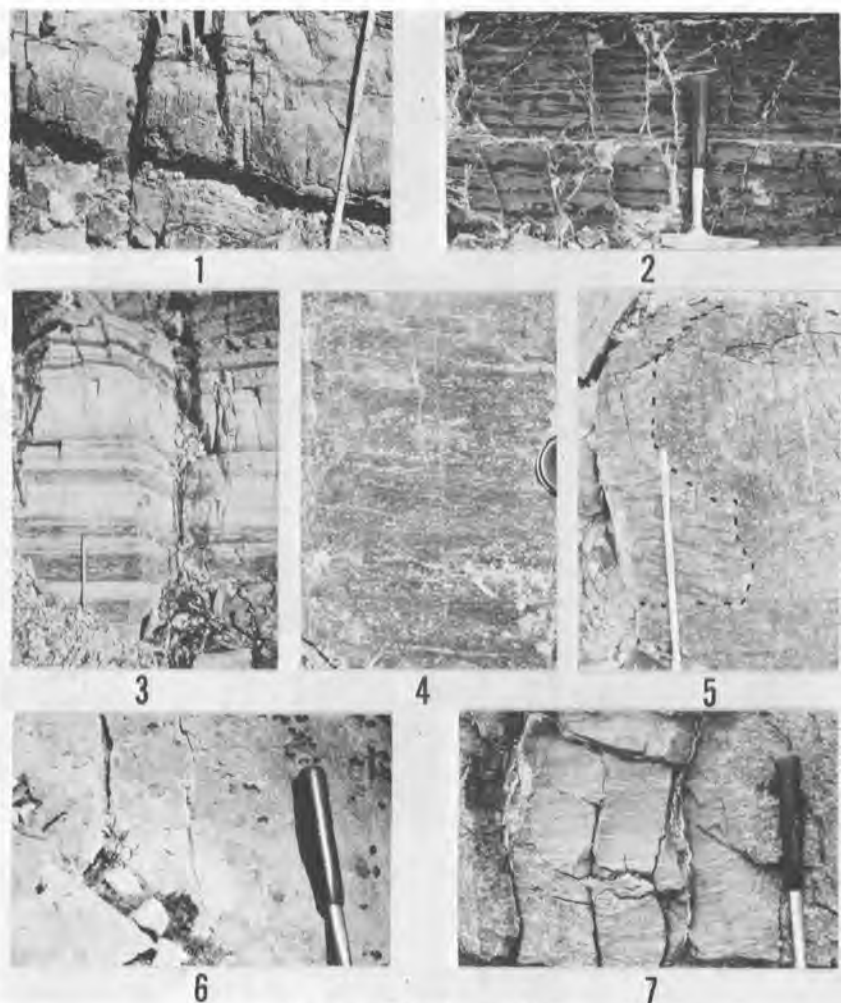
Table 1 shows the depositional facies found in the Middle Cambrian. It is divided into peritidal, shallow-sublittoral, deep-sublittoral and slope, and basin facies. Peritidal facies represent supratidal and intertidal accumulations. Shallow sublittoral designates sediments deposited in zones of active wave and tidal activity as well as those that accumulated in calmer water behind shoals and islands. Based on studies of modern environments, only a few rock types, such as the massive cross-bedded oolitic units, are restricted to this zone. Other rock types are placed here through stratigraphic association. The gradational contacts between lithologies within the shallow sublittoral assemblage as well as with peritidal rocks suggests, from a Waltherian viewpoint, that water depth ranged from one or two meters to a few tens of meters.

Prevailing wind patterns superimposed on a shelf bathymetry may have resulted in calm water conditions over large areas in the shallow sublittoral zone. Sublittoral sedimentation on the shelf south of the House Embayment (Text-fig. 2) is represented by lime mudstones in association with peritidal rocks and suggests quiet water conditions. In contrast to this, much of the shallow sublittoral material north of the embayment consists of allochem bearing wackestones, grainstones and packstones indicating a higher level of water agitation. Such a pattern could be a function of a Cambrian trade wind that blew off the southern shelf and onto the northern one. Lime mudstones characterize the Middle Cambrian carbonate belt and must have been produced by chemical or algal related processes. Stratigraphic and petrographic evidence of a bioclastic or pelagic origin is lacking.

The continental margin model of Stewart (1972, p. 1350) places a continental slope and rise in central to western Nevada during early Cambrian

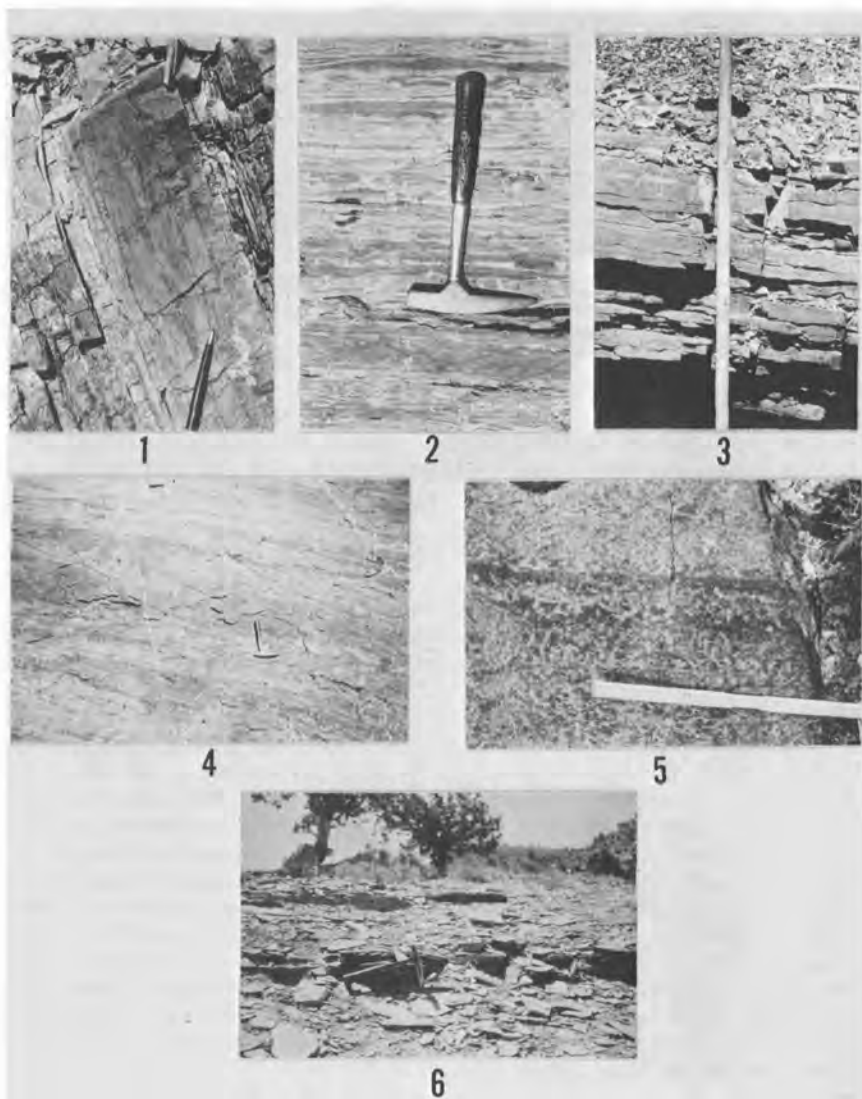
TABLE 1
DEPOSITIONAL FACIES OF THE MIDDLE CAMBRIAN

	PERITIDAL	SHALLOW SUBLITTORAL	DEEP SUBLITTORAL AND SLOPE	BASIN
LITHOLOGY	Stromatolitic boundstones	Oolitic, oncolitic, bioclastic grainstones and packstones	Lime mudstone	
	Thrombolitic boundstones	Silty-sandy bioclastic, pelletal wackestones and lime mudstones	Bioclastic wackestone and packstone	
	Laminoid and irregular fenestral lime mudstone	Dolomitically laminated, thinly bedded and mottled lime mudstone	Pelletal wackestone	Mudstone
	Intraclastic calciruditic and calcarenitic packstones and wackestones	Sandy ferroan dolostone to dolomitic sandstone	Intraclastic calciruditic and calcarenitic packstone	
	Nodular and laminated chert	Intraclastic calcarenite wackestone and packstones	Bedded chert	Claystone
STRUCTURES		Laminoid fenestral lime mudstone	Silt-clay laminations	
	Channels <0.5 m deep	Subhorizontal tubular burrows	Graded beds	
	Sun cracks	Burrow mottling	Slump structures	
	Fenestrae	Small-scale ripple marks	Small-scale scour	Laminated bedding
FOSSILS	Laminated to medium bedding	Small- and medium-scale tabular, tangential crossbeds and trough crossbeds	Burrow mottling	
	Isolated tabular to small mound-shaped algal structures	Laminated to very thick bedding	Laminated to thin bedding	
	Algae	Algae, trilobites, brachiopods	Trilobites (particularly agnostids) brachiopods, sponges	
	Trilobites generally scarce [Where present show low diversity characteristic of adjacent sublittoral]	[Invertebrate material generally uncommon; show low diversity]	[Abundance and diversity higher than shallow sublittoral]	



EXPLANATION OF PLATE 1

- FIG. 1.—Small domal stromatolitic boundstone. Light gray dolostone, dark gray limestone. Highland Peak Limestone, Pioche, Nevada.
- FIG. 2.—Mottled to irregularly bedded dolomitic (light gray) lime mudstone. Laminations present within beds. Probably algal boundstone, Bonanza King Formation, Indian Ridge, Nevada.
- FIG. 3.—Planar stromatolitic boundstone with interbedded intraclastic calciruditic wackestone. Highland Peak Limestone, Pioche, Nevada.
- FIG. 4.—Laminoid fenestral lime mudstone, Step Ridge Member, Highland Peak Limestone, Pioche, Nevada. Camera cover 5 cm.
- FIG. 5.—Isolated algal mass composed of fenestral limestone. Intraclastic calciruditic and calcarenitic wackestone adjacent to mass. Bonanza King Formation, Nopah Range, California. Scale extended 35 cm.
- FIG. 6.—Oncolitic skeletal wackestone, Abercrombie Formation. Deep Creek Range, Utah.
- FIG. 7.—Intraclastic calcarenitic dolostone as channel within thrombolitic boundstone, Bonanza King Formation, Nopah Range, California.



EXPLANATION OF PLATE 2

- FIG. 1.—Sandy ferroan dolostone with ripple marks. Condor Member, Highland Peak Limestone, Pioche, Nevada.
- FIG. 2.—Silty to sandy lime mudstone and skeletal wackestone. Unit K, Highland Peak Limestone, Pioche, Nevada.
- FIG. 3.—Thinly bedded lime mudstone and skeletal wackestone. Marjum Formation, House Range, Utah. Scale in feet.
- FIG. 4.—Cross-bedded oolitic packstone. Swasey Limestone, House Range, Utah.
- FIG. 5.—Burrow structures. Bonanza King Formation, Nopah Range, California. Scale in centimeters.
- FIG. 6.—Papery to shaly calcareous mudstone, Wheeler Shale, House Range, Utah.

time. This model has been incorporated in the upper Cambrian studies in western Nevada by Cook and Taylor (1975, p. 560) and may be represented in the Middle Cambrian of western Nevada by the Emigrant Formation. However, the House Embayment, which extended eastward across a former shallow sublittoral shelf, also shows "slope" and "basin" facies. There is no reason why both of these facies in this case could not have developed within a deep sublittoral zone (above 200 m in depth). It may be significant that the Wheeler Shale of the basin facies in the House Embayment is quite calcareous, whereas the shale in the middle member of the Emigrant seems to contain little calcareous material. If this calcite was originally a fine carbonate sediment rather than a cement, then the absence of calcitic material in the Emigrant shales might be a function of distance from a carbonate source and reflect bathyal conditions below a Cambrian compensation depth.

Descriptions of the physical characteristics of the rocks in each of the facies are available in papers by Kepper (1972, 1974b), Halley (1974, 1975), and Brady and Koepnick (1975). With the exception of the algal boundstones for which further comments drawn from recent work are necessary, the information in Table 1 will suffice for the depositional and stratigraphic model discussed later in this paper. Plates 1 and 2 illustrate some of the lithologies of Table 1.

I have described (Kepper, 1972) planar and low-amplitude linked and nonlinked domal stromatolitic boundstones in association with supratidal and intertidal deposits. In the same paper I suggested that some of the stromatolites may have extended into the subtidal zone. Given calm water conditions and a paucity of grazing and browsing animals, it may be possible for sublittoral algal mats to persist and be preserved as boundstones in the rock record. The prevalence of tidal and wave scour and the presence of browsing animals in modern environments seems to inhibit significant mat growth (Logan et al., 1974a, p. 191). Friedman et al. (1973, p. 554) documented a case where elevated salinities prohibited destructive activities of animals, and mats flourished in a subtidal pool. They noted that high-magnesium calcite formed in these pools. In a short paper (Kepper, 1974, p. 142) I hypothesized that the association of very fine-grained dolomite with the algal deposits might reflect slightly elevated salinities and the precipitation of high magnesian calcite which in turn was the precursor of the dolomite. Skeletal material is rarely present in most of the peritidal rocks, nor is there evidence of burrowing or bioturbation features in them. Dolomitically mottled and bedded lime mudstones intercalated with peritidal material likewise rarely contain skeletal fragments. I had originally interpreted the mottling pattern in these mudstones to be a product of bioturbation (Kepper, 1972, p. 521). However, in a number of cases the dolomitic mottling and bedding contains faint laminations which suggest the possibility that mat-forming algae may be involved. In sum, it appears that bottom working invertebrates, although probably present, were scarce over large portions of the shelf. For much of the time represented by at least the upper half of the Highland Peak and Bonanza King formations, elevated salinity, as a function of poor water circulation, could have been the inhibiting factor.

In contrast to the above, where skeletal material is abundant in peritidal and the associated sublittoral rocks, stromatolites are absent. The Whirlwind Formation in the House and Wah Wah sections is a good illustration of a

nonstromatolitic peritidal deposit. I attribute this to normal salinity conditions on an open shoreline where wave and tidal activity were stronger. It could be argued in both cases that it was the level of current activity alone that was the controlling factor rather than elevated salinity. If current activity was reduced in those areas where stromatolites prevailed, then the salinity argument is at least a possibility. Channel ways between club-shaped stromatolites in the Cambrian of New York contain an abundance of invertebrate material including trilobites. This does not invalidate the possibility of an antipathetic relationship between trilobites or other invertebrates and planar stromatolites because it clearly is a function of mutually exclusive subenvironments.

Thinly laminated dolostone beds or thinly interlaminated limestone and dolostone beds were described as algal boundstones in my measured sections (Kepper, 1972). These contain as much as 50 percent mechanically deposited material that was probably not directly bound by filaments. However, these mechanical deposits are "sandwiched" between algal-bound intervals. Evenly laminated, planar stromatolites apparently are not typical of present-day peritidal surfaces, but as noted in the Persian Gulf by Kendall and Skipwith (1968, p. 1056), the flattening of bedding planes in algal peats is related both to original growth on a flat surface and to the expulsion of moisture from the mat on burial.

Ginsburg et al. (1970, p. 745) suggested criteria for approximating the tidal range in ancient peritidal deposits using an exposure index. Using his method, measuring from the top of the highest bed with horizontal burrow structures to the base of the first fenestral carbonate unit, ranges between one and two meters were obtained from unit K in the Highland Peak at Panaca, Nevada.

Thrombolitic algal boundstones, first described by Aitken (1967, p. 1171), consist of clotted tabular to mound-shaped masses of carbonates a fraction of a meter up to 30 meters thick, separated by channels or broad poorly-defined areas composed of intraclastic calcarenitic or calciruditic material. They occur in association with stromatolitic units in the middle portion of the Bonanza King Formation and have not been recognized farther north. Continuous clotted carbonate beds have been traced laterally for 50 meters before being broken along strike by intraclastic intervals that sometimes show an overhang relationship with the thrombolitic mass. Similar but smaller structures have been noted by Logan et al. (1974a, p. 185) in the intertidal zone at Shark Bay.

Black and light-gray fenestral carbonates containing discontinuous laminoid and irregular fenestrae (Logan et al., 1974b, p. 214) occur in a number of motifs in the Middle Cambrian. They are found as thin beds and as small isolated boundstone masses. The fenestral structures in these settings are commonly partially filled with internal sediments. However, such carbonates also make up significant thicknesses, on the order of 100 meters, of a number of Middle Cambrian units including the Burrows Limestone, Step Ridge Member of the Highland Peak Limestone, Eye of Needle Limestone, Pole Canyon Limestone, and the Eldorado Dolostone. These are normally laminoid structures that contain no internal sediment. Many fenestral structures appear to have passed through a diagenetic history that included dolomitization of the original structure followed by a late stage of calcitization (Kepper, 1974b, p. 1259). These alterations may have destroyed any record of internal sediment. Skeletal material, biogenic structures and filament molds have not been observed in

these rocks. They do contain very small amounts of organic carbon (Kepper, 1974b, p. 1253). Oolitic and oncolitic limestones are gradational with the laminoid units, which suggests a shallow sublittoral environment, perhaps in the lee of shoals. These carbonates were best developed on the more distal portions of the shallow sublittoral zone prior to the submergence event associated with the House Embayment. Aitken (1966, p. 424) found a similar location for his "stromatactoid dolomite," which is equivalent to the fenestral units described here.

Although subaerial shrinkage and gas generation have been given as explanations for such structures, Heckel (1972, p. 14) described a dewatering mechanism within a mud undergoing nonuniform compaction which leads to fenestration. Nonuniform compaction could be the result of localized cementation and/or variations in the binding of the mud by mucilaginous algae or bacteria. The latter might explain the organic carbon in these rocks. Mucilaginous algae (possibly bacteria in some cases) may have played a significant role in binding and locally cementing lime mudstones in the peritidal and sublittoral zones in the Middle Cambrian. I suggested (Kepper, 1975, p. 1145) a portion of the Middle Cambrian carbonate lithosome was an algal biosome.

CYCLIC SEDIMENTATION AND STRATIGRAPHIC RELATIONSHIPS

Aitken (1966) described Middle Cambrian to Middle Ordovician grand cycles consisting of a lower shaly half-cycle gradationally overlain by a carbonate half-cycle. The carbonate half-cycle (Sullivan-type) shows a shoaling upward pattern usually terminating in peritidal deposits (p. 433). Oolitic, oncolitic or intraclastic carbonates occur in the basal portion of the carbonate half-cycle (p. 419). The base of the grand cycle is characterized by a sharp contact between the peritidal carbonates at the top of the lower cycle and the shales in the base of the next cycle.

Aitken (1966, p. 434-435) briefly reviewed a number of causal mechanisms including differential subsidence, differential uplift, climatic and eustatic controls. He required a mechanism to account for regional development of the cycles over a time period in the order of 10 million years, and for a coupling of submergence of the shelf with an increase in the terrigenous input. The shale half-cycle was associated with submergence followed by relatively rapid carbonate sedimentation and the shoaling upward sequence.

The necessity for coupling of submergence with terrigenous influx led Aitken to eliminate most of the mechanisms proposed by earlier workers. Thus an increase in the rate of subsidence or a rapid eustatic rise in sea level (submergence), in his view, would cause a reduction in terrigenous source area and an increase in the distance between source and depositional site. Aitken (1966, p. 437) proposed a tilting craton model which allowed for a coupling of submergence and terrigenous input. Seaward tilting of the craton and terrigenous sedimentation was followed by a carbonate buildup to sea level completing the cycle. However, Kepper (1972, p. 525) observed that terrigenous influx may be associated with a lowering of sea level (emergence) and a reworking of the nearshore detritus rather than submergent conditions. The presence of peritidal rocks within some of the shaly half-cycles demonstrates that terrigenous input was in fact related to emergence.

One of the most useful models relating shelf to slope to basin sedimentation and stratigraphy was developed by Meissner (1967). His model showed the

development of a depositional topography as a consequence of rapid shallow-water carbonate sedimentation involving reef development near the shelf edge. A shoaling upward carbonate half-cycle is coupled with a starved basin to the seaward, which contains little carbonate or terrigenous material. Emergent conditions led to an influx of terrigenous sediments which halted carbonate production and was coupled with a filling of the basin seaward of the reef. The depositional topography led to the existence seaward of the reef of a slope which during the early phase of the emergence was a zone of bypassing and nondeposition. Meissner's reciprocal cyclic sedimentation model (p. 214) is represented by thick carbonate shelf deposits (carbonate half-cycle) equivalent to a thinned basin interval, and a thin terrigenous shelf unit (shale half-cycle) equivalent to a thicker basin interval. His controls for these Permian grand cycles involved glacioeustatic sea level changes on a uniformly subsiding shelf coupled with episodes of rapid carbonate buildup.

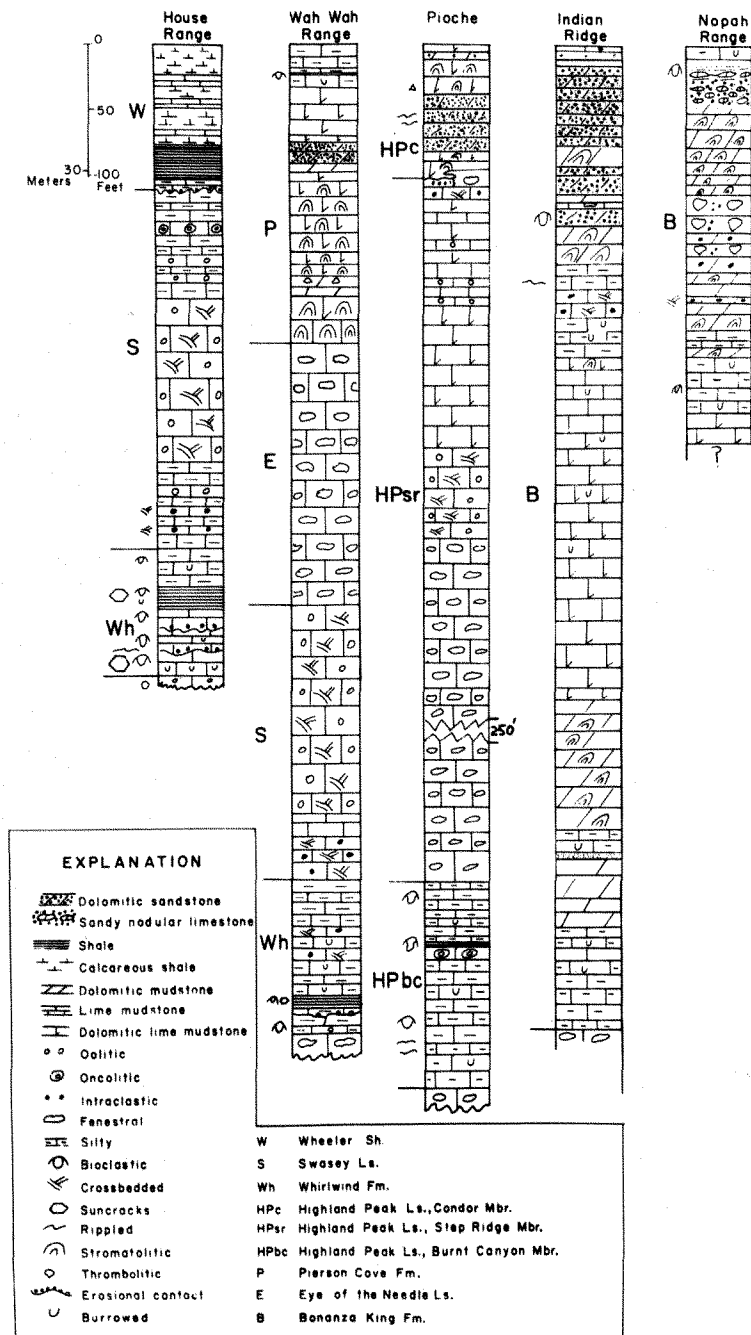
Halley (1974, p. 212) presented a similar reciprocal sedimentation model for the Lower Cambrian. He utilized variable subsidence rather than a glacioeustatic control on the basis of the duration of these cycles as compared to the known periodicity of Pleistocene eustasy. Briefly, his model consists of the following events:

1. An increase in the rate of subsidence is associated with development of a carbonate bank and restriction of terrigenous sedimentation to the eastern, inner edge of the shelf.
2. A decrease in the rate of subsidence leads to emergence, widespread peritidal conditions and the westward migration of terrigenous sediment. The basin, seaward of the shelf, is "starved" for the terrigenous component.
3. A thin terrigenous blanket covers the shelf and ends carbonate sedimentation there. The basin is subject to fill by terrigenous material.
4. An increase in the rate of subsidence leads to the initiation of the next cycle.

The early events (1 and 2) of the model lead to a thick carbonate shelf unit and a thin basin unit, whereas the later one (3) results in a thickened basin interval and an equivalent thin terrigenous-dominated unit in the shelf sections. A model combining the idea of a depositional topography with variable rates of subsidence seems to apply to cyclic patterns in the *Bathyriscus-Elrathina* and *Bolaspidella* Assemblage zones.

Text-figure 3 shows a series of five measured sections covering a portion of the *Bathyriscus-Elyathina* Assemblage Zone in the eastern Basin and Range area. A shaly half-cycle represented by the *Ehmaniella*-bearing Whirlwind Formation is easily seen in the three northern sections. However, in the two sections to the south, this interval is recognized by the appearance of sandy carbonate above a thick interval of relatively "clean" limestone or dolostone. The latter, in turn, overlies *Glossopleura*-bearing shales of the upper Carrara Formation. The shaly half-cycle shows peritidal features in the House and Wah Wah sections but generally shallow sublittoral conditions are suggested for most of this interval.

The overlying carbonate half-cycle shows a distinctive lateral variability which may bear on the question of how these carbonate platforms are constructed after the initial terrigenous half-cycle. Sections toward the break in



TEXT-FIGURE 3.—Measured sections illustrating stratigraphic relationships for a portion of the *Bathyriscus-Elrathina* Assemblage Zone.

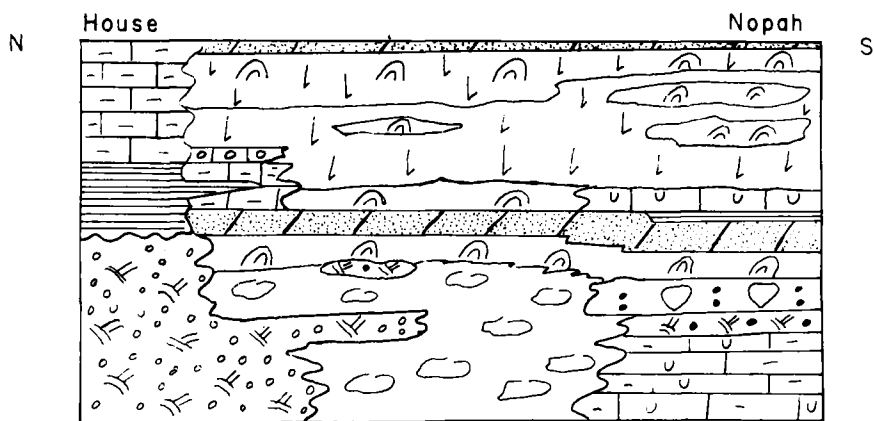
slope between the shallow and deep sublittoral show cross-bedded oolitic grainstones and packstones. Those toward the interior start with laminoid fenestral limestone. Farther south burrowed, sandy lime mudstones and skeletal wackestones replace the fenestral units. The slope-break location for the oolitic belt and the existence of a lime mud blanket to its leeward is similar to the modern Bahama Platform. The carbonate half-cycle shows a shoaling upward stratigraphy culminating in a series of peritidal boundstones. In the House Range Section this emergence may be represented by a diastem between the Wheeler Shale and the underlying Swasey (White, 1973, in Hintze and Robison, 1975, p. 886). The next cycle begins in the House Range with thinly bedded silty limestones and laminated calcareous shales of the Wheeler Shale. According to Hintze and Robison (1975, p. 886), at least the lower fifth of the Wheeler belongs in the *Bathyriscus-Elrathina* Assemblage Zone. The remainder of the Wheeler and the overlying Marjum Formation contain a *Bolaspidella* fauna.

Sections to the south show a distinctive rust-colored ferroan dolomitic sandstone overlying the peritidal deposits. These sandstones show small-scale cross-bedding, ripple marks, and burrow structures indicating shallow sublittoral deposition. Most significantly, the underlying stromatolitic boundstones are not sandy, and a sharp boundary, probably a diastem, exists between the two. Very thin beds of this sandstone are interbedded with the overlying carbonates. This thin terrigenous interval represents the beginning of the next cycle. In the Indian Springs and Nopah section "*Ehmania*" is an index fossil for the interval (basal Banded Mountain Member of the Bonanza King Formation). No fossils have been found in the equivalent unit in the Highland Peak Limestone (Condor Member), but a small collection of trilobites from the lower Pierson Cove Formation in the Wah Wah Section was examined by A. R. Palmer and "*Ehmania*" was identified. Thus the interval under discussion lies within the *Bathyriscus-Elrathina* Assemblage Zone.

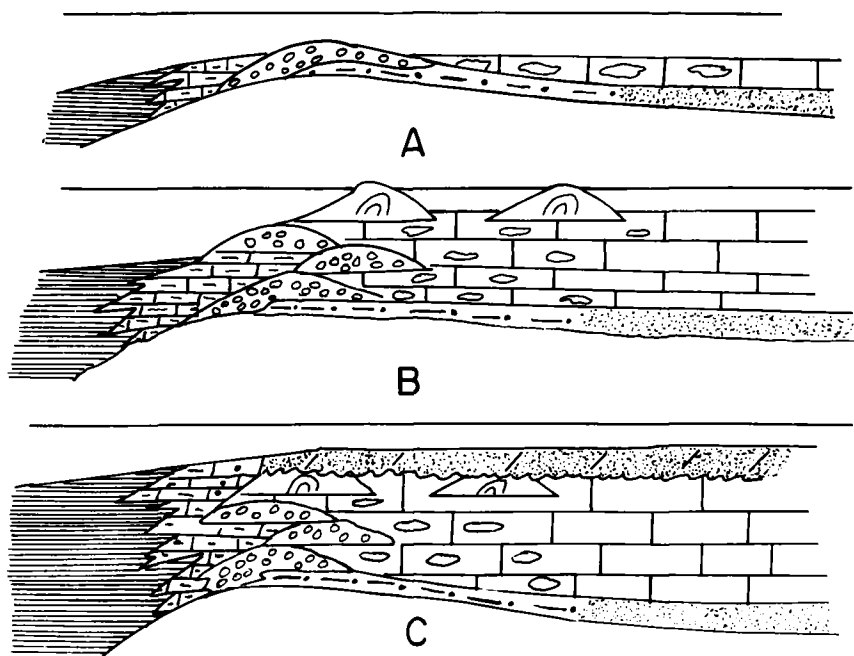
Text-figure 4 is a schematic cross section showing an interpretation of these stratigraphic relationships beginning with the post-Whirlwind carbonate half-cycle and ranging to the top of the Middle Cambrian. A second schematic, Text-figure 5, is a sedimentologic model which attempts to explain the stratigraphy associated with these cyclic patterns.

The cross-bedded oolitic limestones formed a shoaling sand belt seaward of the lime muds and appear to have created a shallow sublittoral shelf-lagoon in which the laminoid fenestral carbonates could accumulate. Lack of skeletal material or bioturbation features in these muds suggests that poor water circulation and possibly increased salinity may have inhibited most bottom-dwelling organisms. Mucilagenous algae and/or bacteria were the prime organisms present in these muds. Shoreward, to the south and east, the muds are sandy and contain burrow structures and fragments of trilobites, indicating that bottom conditions were more conducive to vagrant benthic life.

Because the optimum conditions for carbonate sedimentation are associated with warm shallow waters and because this sedimentation can keep pace with subsidence, a depositional topography may develop (Meissner, 1967, p. 210). This is reflected in the shoaling upward succession of the carbonate half-cycle. The unconformity beneath the Wheeler Shale and beneath the dolomitic sandstones may record the same episode of emergence although it is not clear



TEXT-FIGURE 4.—Schematic stratigraphic cross section shows inferred vertical-lateral relationships in an interval including the *Bathyriscus-Elrathina* Assemblage Zone (post-Whirlwind portion) and the *Bolaspidella* Assemblage Zone. Symbols same as on Text-figure 2.



TEXT-FIGURE 5.—Schematic sedimentologic model for the lower half of Text-figure 4:

- A. Submergence, beginning of carbonate half-cycle, oolite belt with leeward shelf-lagoon.
- B. Emergence, shoaling upward sequence, development of starved basin and depositional topography with zone of nondeposition on upper slope.
- C. "Shale" half-cycle with terrigenous sediment transported across shoal, basin deposition.

how close this surface approaches isochroneity. It is possible that emergence and erosion happened over the oolite shoal first while shoaling was occurring in the area immediately south of the slope-break. When emergence finally affected the area to the south, continued subsidence, perhaps at a more rapid rate along the slope-break, led to an area starved for sediment. This subsidence along the slope-break, while peritidal conditions existed just to its leeward, could have led to a depositional topography with sufficient slope to allow sediment to bypass and currents to scour the bottom locally. Submergence of the peritidal zone led to the movement of terrigenous material across it and into the deepening basin of the House Embayment. Because much of the terrigenous material was by-passing across the shallow sublittoral zone, the sand and shale units overlying the algal boundstones are quite thin. The basin shale, however, is considerably thicker. Locally, as illustrated by the Condor Member at Pioche and the Whirlwind Formation in Utah, peritidal conditions persisted during the emergence which allowed nearshore terrigenous material to sweep westward across the shelf. This same pattern shows up in Aitken's shale half-cycle. Submergence in some cases may not be recorded until the carbonate half-cycle begins. The uppermost portion of the shale half-cycle and lower portion of the carbonate cycle represent submergence. Thus, the relative sea level shifts occur within half-cycles and not just at their bases.

On the shallow sublittoral shelf the carbonate half-cycle is represented by lime mudstones and peritidal units recording numerous subcycles. The cycle extends to near the top of the Middle Cambrian where a thin terrigenous unit associated with peritidal rocks (unit K of Kepper, 1972, p. 522) makes a sharp contact with the underlying peritidal carbonates. Unit K is the beginning of the next cycle which continues into the Upper Cambrian.

In the House Embayment to the north, laminated calcareous shales of the lower half-cycle represent basin center deposits and reflect a significant shift of depositional environments as illustrated in Text-figure 2. Thin-bedded silty limestone in the lower Pierson Cove in the Wah Wah section and in this same stratigraphic position in the ranges east of the House Range probably are slope deposits that formed a broad apron between the shallow sublittoral shelf and the basin. The laminated shales of the Wheeler are replaced by the thin-bedded lime mudstones of the Marjum Formation, which has been described as a slope deposit (Brady and Koepnick, 1973, p. 711). These slope limestones prograde westward across the embayment because the basal limestones rise from the lower *Bolaspidea* Zone in the House Range to near the top of the Middle Cambrian in the Schell Creek and Eureka areas.

BONANZA KING AND EMIGRANT FORMATIONS

Stratigraphic relationships and depositional facies between the Bonanza King and Emigrant formations in western Nevada and eastern California are not as well known as those just described. The distribution of the depositional facies is shown in Text-figure 2. The dolomitic siltstones and sandstones in association with peritidal rocks that divide the Bonanza King into the lower Papoose Lake and upper Banded Mountain members can be traced westward through Titus Canyon in the Grapevine Mountains to the Last Chance Range. Massive, thin-bedded to laminated intraclastic limestones and dolostones are common both below and above the sandstone unit. The cross-bedded

oolitic limestones characteristic of the outer shallow sublittoral zone to the north are missing. The peritidal interval that characterizes the upper Middle Cambrian in the Highland Peak, Pierson Cove, and Trippe (Deep Creek and Fish Springs ranges) formations is also present in the Bonanza King of California and Nevada.

In western Nevada the Emigrant Formation is divided into three members (Albers and Stewart, 1972, p. 20): a lower silty limestone, a middle shale, and an upper, cherty, thin-bedded limestone member. The Middle-Upper Cambrian boundary lies in the lower part of the upper member (p. 21). Slump structures and intraclastic calcarenitic packstones occur in the upper member and probably represent a slope facies. The underlying shale unit is considered a basin deposit.

In the Inyo Range a thin, dolomitized section called Bonanza King (Ross, 1965, p. 17) appears to represent a transition between the Bonanza King farther east associated with sublittoral and peritidal conditions and the slope and basin facies of the Emigrant. This section contains much platy to shaly, thin-bedded to laminated, cherty dolostone. Although slump structures and conglomerates are missing, it has characteristics in common with the two limestone members of the Emigrant. It may be significant that slump structures in the upper Middle Cambrian seem to occur only in the thin-bedded limestones that overlie shales, suggesting that post-depositional compaction of the underlying shales may have triggered the slumping. The overall picture in the southwestern Basin and Range Province is of a more gradual change from a shallow sublittoral shelf to the deeper water basin than appears to the northeast.

CONCLUSIONS

Depositional facies representing peritidal, shallow-sublittoral, deep-sublittoral, slope, and basin environments are recognized in the Middle Cambrian of the Basin and Range Province. Major cycles ("grand cycles") consisting of intercalations of these facies, which were controlled by variable subsidence, serve to establish sedimentologic models and ultimately time-stratigraphic relationships across a shelf-slope-basin bathymetry.

ACKNOWLEDGMENTS

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REFERENCES

- Aitken, J. D., 1966, Middle Cambrian to Middle Ordovician cyclic sedimentation, southern Rocky Mountains of Alberta: *Bull. Canad. Petrol. Geol.*, v. 14, p. 405-41.
 ———, 1967, Classification and environmental significance of cryptalgal limestones and dolomites, with illustrations from the Cambrian and Ordovician of southwestern Alberta: *J. Sediment. Petrol.*, v. 37, p. 1163-78.
 Albers, J. P., and Stewart, J. H., 1972, Geology and mineral deposits of Esmeralda County, Nevada: *Nev. Bur. Mines and Geol. Bull.*, v. 78, 80 p.
 Barnes, J. J., and Klein, G., 1975, Tidal deposition in the Zabriskie Quartzite (Cambrian), eastern California and Western Nevada: in Ginsburg, R. N. (ed.), *Tidal deposits*: Springer-Verlag, New York, p. 163-69.
 Brady, M. J., and Koepnick, R. B., 1973, Transition from shelf to basinal carbonates in Middle Cambrian Marjum Formation of House Range, western Utah—paleo-environmental analysis: *Amer. Assoc. Petrol. Geol. Bull.*, v. 57, p. 771 (Abstr.).
 Cook, H. E., and Taylor, M. E., 1975, Early Paleozoic continental margin sedimentation,

- trilobite biofacies, and the thermocline, western United States: *Geology*, v. 3, p. 559-62.
- Friedman, G. M., Abraham, A. J., Braun, M., and Miller, D. S., 1973, Generation of carbonate particles and laminites in algal mats—example from sea-marginal hypersaline pool, Gulf of Aqaba, Red Sea: *Amer. Assoc. Petrol. Geol. Bull.*, v. 57, p. 541-57.
- Ginsburg, R. N., Bricker, O. P., Wanless, H. R., and Garret, Peter, 1970, Exposure index and sedimentary structures of a Bahama tidal flat: *Geol. Soc. Amer., Abst. Prog.*, v. 2(7), p. 744.
- Halley, R. B., 1974, Repetitive carbonate bank development and subsequent terrigenous inundation, Cambrian Carrara Formation, southern Great Basin: unpub. Ph.D. thesis, State Univ. New York, Stony Brook, 377 p.
- , 1975, Peritidal lithologies of Cambrian carbonate islands, Carrara Formation, southern Great Basin: *in* Ginsburg, R. N. (ed.), *Tidal deposits*: Springer-Verlag, New York, p. 279-88.
- Hamilton, Warren, 1975, Neogene extension of the western United States. *Geol. Soc. Amer., Abst. Prog.*, v. 7(7), p. 1098.
- Heckel, P. H., 1972, Possible inorganic origin for stromatolites in calcilitite mounds in the Tully limestone, Devonian of New York: *J. Sediment. Petrol.*, v. 42, p. 7-18.
- Hintze, L. F., and Robison, R. A., 1975, Middle Cambrian stratigraphy of the House, Wah Wah and adjacent ranges in western Utah: *Geol. Soc. Amer. Bull.*, v. 86, p. 881-91.
- Irving, E., 1964, *Paleomagnetism and its application to geological and geophysical problems*: Wiley, New York, 359 p.
- Kendall, C. G. St. C., and Skipwith, P. A. d'E., 1968, Recent algal mats of a Persian Gulf lagoon: *J. Sediment. Petrol.*, v. 38, p. 1040-58.
- Kepper, J. C., 1972, Paleoenvironmental patterns in Middle to Lower Upper Cambrian interval in eastern Great Basin: *Amer. Assoc. Petrol. Geol. Bull.*, v. 56, p. 503-27.
- , 1974a, Antipathetic relation between Cambrian trilobites and stromatolites: *Amer. Assoc. Petrol. Geol. Bull.*, v. 58, p. 141-43.
- , 1974b, Origin of massive banded carbonates with "bluebird structures" in the Cambrian of the eastern Great Basin: *J. Sediment. Petrol.*, v. 44, p. 1251-61.
- , 1975, Is the Middle Cambrian carbonate belt in the Basin and Range region an algal biosome?: *Geol. Soc. Amer., Abst. Prog.*, v. 7(7), p. 1144.
- Logan, B. W., Hoffman, P., and Gebelein, C. D., 1974a, Algal mats, cryptalgal fabrics, and structures, Hamelin Pool, western Australia: *in* *Evolution and diagenesis of Quaternary carbonate sequences, Shark Bay, Western Australia*: *Amer. Assoc. Petrol. Geol., Mem.* 22, p. 140-94.
- , 1974b, Inventory of diagenesis in Holocene-recent carbonate sediments, Shark Bay, western Australia: *in* *Evolution and diagenesis of Quaternary carbonate sequences, Shark Bay, western Australia*: *Amer. Assoc. Petrol. Geol., Mem.* 22, p. 195-247.
- Meissner, F. F., 1967, Cyclic sedimentation in Middle Permian strata of the Permian basin, west Texas and New Mexico: *in* Elam, J. G., and Chuber, S. (eds.), *Cyclic sedimentation in the Permian Basin*: 2nd ed., *W. Texas Geol. Soc. Symp.*, p. 203-32.
- Palmer, A. R., 1960, Some aspects of the early Upper Cambrian stratigraphy of White Pine County, Nevada, and vicinity: *in* Boettcher, J. W., and Sloan, W. W., Jr. (eds.), *Guidebook to the Geology of East Central Nevada*: Intermountain Assoc. Petrol. Geol., 11th Ann. Field Conf., p. 53-58.
- , 1971, The Cambrian of the Great Basin and adjacent areas, western United States: *in* Holland, C. H. (ed.), *Lower Paleozoic rocks of the world: Cambrian of the New World*, Vol. 1: Wiley-Interscience, New York, p. 1-78.
- Ross, D. C., 1965, *Geology of the Independence Quadrangle, Inyo County, California*: U.S. Geol. Surv. Bull., v. 1181-O, 64 p.
- Stewart, J. H., 1969, Upper Precambrian and Lower Cambrian strata in the southern Great Basin, California and Nevada: U.S. Geol. Surv. Prof. Paper, 620, 206 p.
- , 1972, Initial deposits in the Cordilleran Geosyncline: evidence of a Late Precambrian (<850 m. y.) continental separation: *Geol. Soc. Amer. Bull.*, v. 83, p. 1345-60.
- , and Poole, F. G., 1974, Lower Paleozoic and uppermost Precambrian Cordilleran miogeosyncline, Great Basin, western United States: *in* Dickinson, W. R. (ed.), *Tectonics and sedimentation*: Soc. Econ. Paleont. Miner. Spec. Pub. 22, p. 28-57.
- Wheeler, H. E., 1960, Early Paleozoic tectono-stratigraphic patterns in the United States: *Int. Geol. Congr. XXI*, pt. 8, p. 47-56.

Middle Cambrian Trilobite Biostratigraphy of the Great Basin

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ABSTRACT.—Trilobites are virtually the only fossils that have been used for zonation of the Middle Cambrian. A single zonal scheme has been gradually developed for most of North America, but that scheme disregards the existence of major biofacies. In the Great Basin two almost mutually exclusive marine biofacies are commonly encountered, and evidently faunal exchange was limited by shoal-water carbonate barriers. A restricted-shelf biofacies is characterized by sparse, low-diversity, endemic, polymeroid faunules, whereas an open-shelf biofacies has common to abundant, high-diversity, mixed endemic and cosmopolitan, polymeroid and agnostoid faunas. Sporadic and in places extensive displacement of Middle Cambrian environments caused intertonguing of lithofacies and associated biofacies, and therefore phylogenetically unrelated faunas succeed one another in vertical sections. Recent studies have shown that some index taxa have significantly longer stratigraphic ranges than formerly recorded, and agnostoids, which probably were pelagic, have distribution patterns different from those of most polymeroids, which probably were mostly benthic. To more realistically reflect the major faunal patterns and their relationships, three sets of coeval trilobite assemblage zones are proposed to accommodate most of the known Middle Cambrian trilobites of the Great Basin. The zonal sets are based on 1) restricted-shelf polymeroid genera, 2) open-shelf polymeroid genera, and 3) open-shelf agnostoid species. A total of 13 assemblage-zones, one unnamed zone, and three barren interzones are considered. Correlation of restricted- and open-shelf faunas may be difficult even within the same mountain range in the Great Basin, but agnostoid assemblages of the open-shelf biofacies correlate well with faunas on other continents. Typical polymeroid biomere patterns are not evident in the Middle Cambrian of the Great Basin.

INTRODUCTION

Trilobites are virtually the only fossils that have been used for zonation of the Middle Cambrian. In North America a succession of zonal concepts has been proposed (*e.g.*, Howell and others, 1944; Rasetti, 1951), and they reflect development of knowledge concerning Cambrian trilobites. However, in the establishment of zonal schemes, biostratigraphers have generally disregarded the existence of major intracontinental biofacies. A notable exception is the dual zonation by Lochman-Balk and Wilson (1958). Nevertheless, their set of "extracratonic" zones applies only to Acadian faunas that now, on the basis of plate-tectonic theory, may have been secondarily derived from a European source, and they included all other North American faunas within a single set of zones.

It is my ultimate purpose to define an alternative Middle Cambrian biostratigraphic scheme for the Great Basin that will contain a separate set of zones for each major trilobite biofacies. At this time, space limitations allow only a preliminary outline of three such zonal sets. Faunas are better known for some facies than others. Therefore, as new information becomes available, some of the less-studied units mentioned below may require modification or refinement.

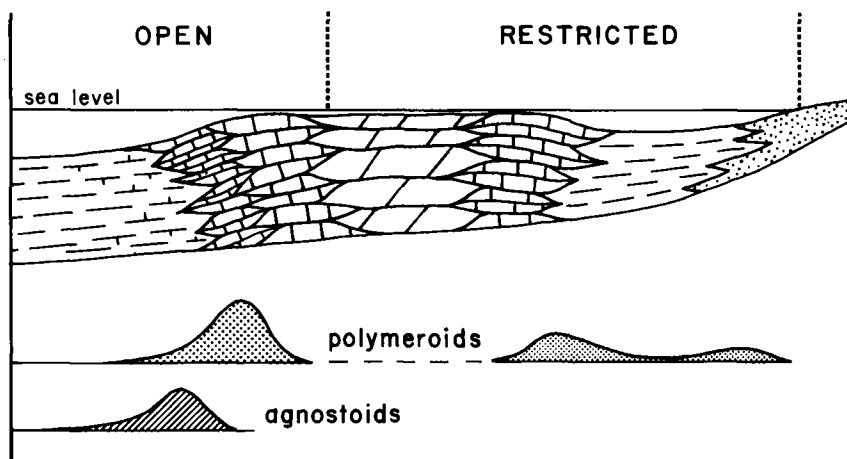
Traditionally the lower and upper boundaries of the Middle Cambrian in North America have been negatively defined by the highest occurrence of olenellid trilobites and by the lowest occurrence of representatives of the

Cedaria Zone. Intercontinental correlation of these boundaries is difficult, and working groups of the Cambrian Subcommittee of the International Stratigraphic Commission are currently evaluating possible boundary-stratotypes and correlation. Recently Daily and Jago (1975) presented evidence for correlating the top of the type Middle Cambrian of Europe (top of *Lejopyge laevigata* Zone) with a horizon well up in the *Cedaria* Zone in North America, and I have collected undescribed fossils from Nevada that tend to support their correlation. However, until a decision is reached by the Cambrian Subcommittee, for purposes of this paper, I continue to recognize the traditional lower and upper boundaries of the Middle Cambrian in North America.

LITHOFACIES AND BIOFACIES

Palmer (1973) has explained the global distribution of major Cambrian trilobite faunas in terms of restricted and unrestricted access to open oceans. The distribution of Middle Cambrian trilobites in the Great Basin is in accord with Palmer's interpretation.

Two almost mutually exclusive marine biofacies are commonly encountered in the Great Basin. Evidently faunal exchange between biotopes was limited by shoal-water carbonate barriers (Text-fig. 1) and changes in environmental parameters such as salinity and temperature. Lithofacies patterns usually show that a carbonate platform of variable extent was flanked by lagoonal muds and near-shore sands on one side, and by outer-shelf muds on the other side. An inner restricted-shelf biofacies is found in limestone and shale, and sometimes sand. Generally it is characterized by sparse, low-diversity, endemic, polymeroid faunules. An outer open-shelf biofacies also is found in limestone and shale, but is characterized by common to abundant, high-diversity, mixed endemic and cosmopolitan, polymeroid and agnostoid faunas. Trilobites tend to be most abundant near the seaward margin of the carbonate lithofacies (Text-fig. 1).



TEXT-FIGURE 1.—Generalized model for lithofacies of the Middle Cambrian shallow shelf, and relative abundance of polymeroid and agnostoid trilobites. Not drawn to scale.

Unnamed *Centropleura*-bearing strata in the Toiyabe Range of central Nevada (Stewart and Palmer, 1967) may contain a third and more seaward biofacies, which possibly represents the deeper shelf or a basinal environment. However, that biofacies is so poorly known in the Middle Cambrian of the Great Basin that it is not considered further at this time.

Sporadic and sometimes extensive displacement of Middle Cambrian environments caused intertonguing of lithofacies and associated biofacies. A cross sectional diagram (Text-fig. 2) from eastern Nevada to central Utah illustrates the intertonguing of lithofacies in western Utah, particularly in the House Range, which was often a boundary area and consequently has an excellent succession of Middle Cambrian faunas. Also, because of the intertonguing of biofacies, phylogenetically unrelated faunas commonly succeed one another in vertical sections.

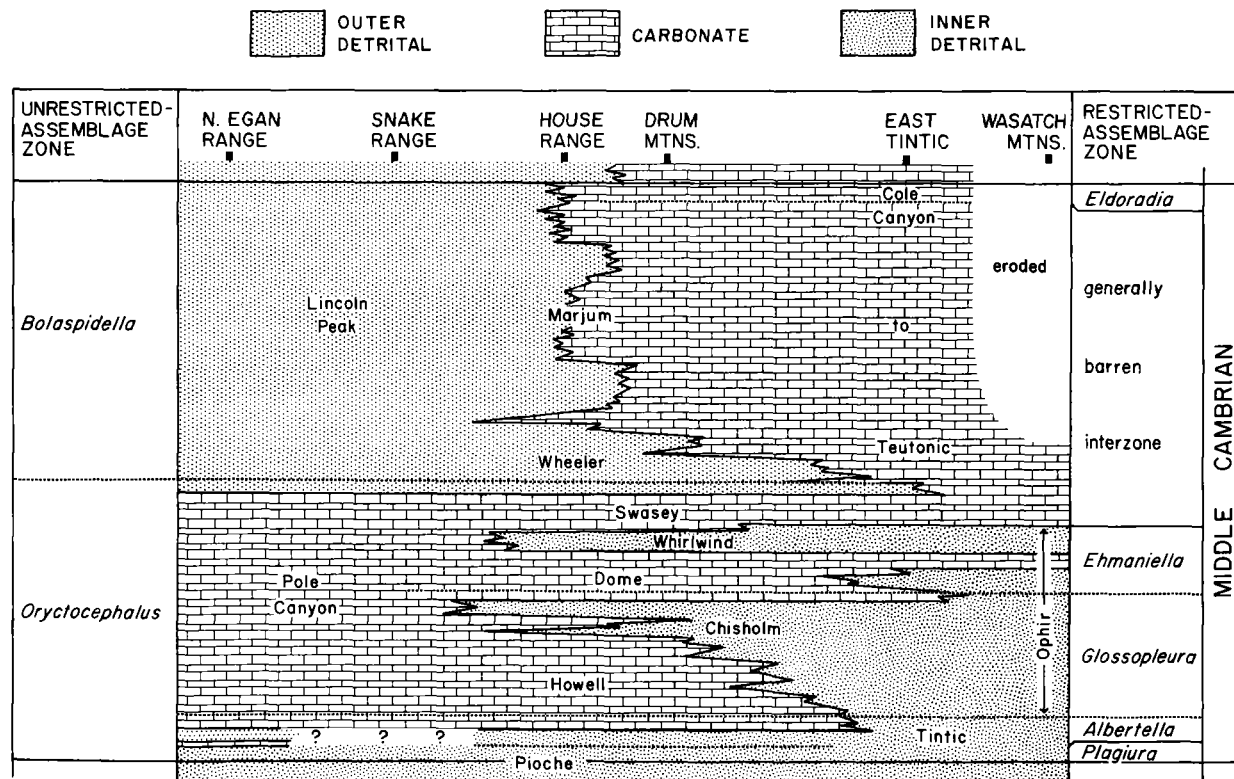
BIOSTRATIGRAPHY

The observed ranges of selected genera that are commonly encountered in the shallow restricted- and open-shelf biofacies of the Great Basin are illustrated in Text-figures 3 and 4. These figures also include supplementary information on reported generic ranges of trilobites from the Canadian Rocky Mountains. The selection of genera is subjective, but an effort has been made to include those forms most likely to be encountered by field geologists. As they become better documented, other genera may need to be added to the charts.

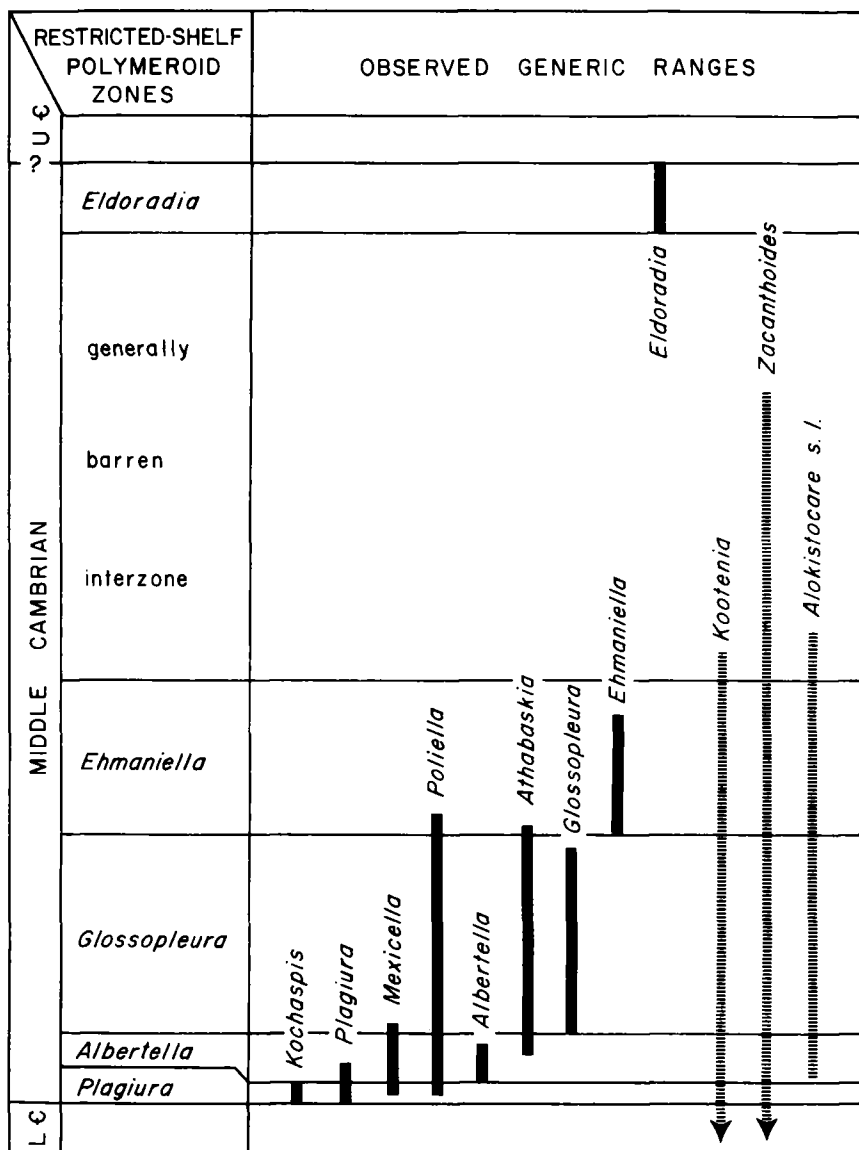
Alokistocare s.l., *Kootenia* and *Zacanthoides* are long ranging and evidently eurytopic. They tend to be most common in the restricted-shelf biofacies, but certain species may be locally abundant in the open-shelf biofacies. For economy of space, the stratigraphic ranges of these three genera are plotted only on Text-figure 3.

On the basis of available biostratigraphic data, both published and unpublished, I propose three coeval sets of zones to accommodate most of the known Middle Cambrian trilobite faunas of the Great Basin. One set of zones is applied to the shallow restricted-shelf biofacies and includes only polymeroid assemblages, which are usually separated in space from other trilobite assemblages. The other two sets of zones are applied to the shallow open-shelf biofacies and are based on polymeroid and agnostoid trilobites. Most polymeroids were probably benthic or nektobenthic whereas the agnostoids were probably pelagic (Robison, 1972b). Major differences in structure of the hypostoma suggest strong divergence in the food and feeding habits of polymeroids and members of the *Agnostina* (Robison, 1972a). The two groups also differ markedly in distribution patterns. Geographically, polymeroid genera tend to be provincial whereas many agnostoid genera and species have global distribution within oceanic and open-shelf biofacies. Stratigraphically, except for one eodiscid (*Pagetia*), agnostoid genera were unaffected by factors that caused major replacement in open-shelf polymeroid genera during the middle Middle Cambrian in western North America (Text-fig. 4). For these reasons, the polymeroids and agnostoids are treated with separate zonal nomenclature even though they are commonly associated in the same rocks.

Each zone is characterized by an assemblage of trilobite taxa that has been repeatedly encountered in the same homotaxial position during regional study. The base of each zone is defined by the first appearance of either the taxon for which the zone is named or by an assemblage of fossils characteristic of the zone. Usually the top of each zone is defined by the first appearance of fossils char-



TEXT-FIGURE 2.—Cross-sectional diagram from eastern Nevada (left) to central Utah (right) illustrating the distribution of major Middle Cambrian lithofacies and polymeroid trilobite zones. Inferred time planes are horizontal. Actual Middle Cambrian rock thickness ranges from about 650 m in the east to over 1200 m in the west.



TEXT-FIGURE 3.—Zonation and observed stratigraphic ranges of common polymeroid genera. Solid lines indicate restricted-shelf genera. Broken lines indicate eurytopic genera with composite ranges from restricted- and open-shelf biofacies; known occurrences between *Ehmaniella* and *Eldoradia* zones are mostly from the open-shelf biofacies.

Brief summaries of the restricted-shelf assemblage-zones follow. The relationship of polymeroid zones and major lithofacies is illustrated by Text-figure 2, and observed generic ranges are plotted on Text-figure 3.

Plagiura Assemblage Zone.—Deiss (1939, p. 1000) apparently was the first to designate a *Plagiura* Zone, and although olenellid trilobites were absent, he considered the unit to be the highest zone of the Lower Cambrian. Following the conclusions by Rasetti (1951, p. 86), and in accord with subsequent usage, I provisionally include the *Plagiura* Assemblage-Zone in the Middle Cambrian. The unit is a synonym of the *Plagiura-Kochaspis* Zone of Rasetti (1951, p. 90-93) and the *Plagiura-Poliella* Faunizone of Lochman-Balk and Wilson (1958, p. 320).

The *Plagiura* Assemblage-Zone is characterized by *Plagiura* and *Kochaspis*. Additional common to rare genera in the Great Basin are *Feldaspis*, *Mexicella*, *Onchocephalus*, *Poliella*, and *Schistometopus*. Except for *Mexicella*, the same genera have been reported from this interval in the Canadian Rockies (Rasetti, 1951, p. 90-93; 1957). Although *Kootenia* and *Zacanthoides* range from the upper Lower Cambrian to at least the middle Middle Cambrian, they are unknown from this zone. *Alokistocare* s. l. (= *Amecephalus* is part of the *Plagiura* assemblage in Canada.

Faunas of the *Plagiura* Zone are poorly documented in the Great Basin. I have collected undescribed fossils from an interval 15 to 25 m below the top of the "Brigham Quartzite" in Two Mile Canyon near Malad, Idaho, and D. P. Campbell has collected undescribed fossils from the basal two metres of the Tatow Member of the Pioche Formation in the House Range of western Utah. Elements of the assemblage also are known from the Susan Duster Member of the Pioche Shale in the Pioche district, Nevada (Palmer, 1964, p. 26-27), and in the Carrara Formation in southern Nevada and adjacent California (Palmer, 1971, p. 13; Palmer and Halley, in press).

Albertella Assemblage-Zone.—As a name, first for a distinctive fauna (Burling, 1914) and later for a zone (e.g., Deiss, 1939; Howell and others, 1944), *Albertella* has been in common use for over 60 years. In the Great Basin the zone is characterized by *Albertella* and *Mexicella*, as well as new genera being described by Palmer (Palmer and Halley, in press). During the mid-*Albertella* Chronozone, carbonate deposition was greatly reduced, and was even absent from parts of the Great Basin region. Autochthonous associations within single beds indicate that the elimination of carbonate barriers allowed restricted- and open-ocean faunas to intermingle, and may partly account for the unusually high taxonomic diversity that is encountered at some localities (cf., Resser, 1939b; Fritz, 1968; Campbell, 1974).

Albertella faunas are known from the Twin Knobs Formation of southern Idaho and the uppermost Brigham Quartzite and lower to middle Naomi Peak Member of the Twin Knobs Formation in northern Utah (Campbell, 1974). Undescribed representatives are present in the upper half of the Tatow Member of the Pioche Formation at several localities in western Utah (Hintze and Robison, 1975, p. 882-84). Fritz (1968) has described an *Albertella* fauna from the Pioche Shale of eastern Nevada, and Palmer (1971; Palmer and Halley, in press) has documented other occurrences in the Pioche and Carrara formations of southern Nevada and adjacent California.

Glossopleura Assemblage-Zone.—This is one of the most widely distributed zones in the Middle Cambrian of North America, and at many localities in the

eastern Great Basin the fauna consists predominantly or entirely of *Glossopleura*. Where other trilobite genera are associated, the most common of these are *Alokistocare*, *Athabaskia*, *Kootenia*, and *Zacanthoides*. A detailed biostratigraphic analysis of the *Glossopleura* Zone has not been published for any section in the Great Basin; however, unpublished investigations have been made by Oldroyd (1973) and Campbell (1974).

Ehmaniella Assemblage-Zone.—This unit is represented throughout most of the eastern Great Basin and is usually characterized by low species diversity, commonly one species per bed, but great abundance of disarticulated individuals. Fossiliferous beds are usually sparse and irregularly distributed. The total fauna is largely undescribed, but appears to be dominated by species of *Ehmaniella*. A few collections contain *Kootenia*, undetermined simple ptychoparioids, and lingulide brachiopods. One of the most diverse faunas, which has been collected from oolitic beds in the lower Dome Limestone of the House Range, contains *Ehmaniella*, *Kootenia*, *Poliella*, *Spencella*?, two undetermined ptychoparioid genera, the molluscs *Helcionella* and *Scenella*, and rare articulate and inarticulate brachiopods.

In 1939, Deiss (p. 1005) tentatively designated an *Ehmaniella* Zone in the upper Stephen Formation of the Canadian Rockies, and based on numerical analysis Schwimmer (1975) named an *Ehmaniella* Zone in Montana and Wyoming. Neither author discussed boundaries or characters of their zones, and therefore the zonal concept presented here is essentially new. The lowest observed occurrences of *Ehmaniella*, which define the base of the *Ehmaniella* Assemblage-Zone in the Great Basin, are in the basal beds of the Ute Formation of northern Utah (Campbell, 1974) and about 25 m above the base of the Dome Limestone of the House Range in western Utah (Oldroyd, 1973). *Ehmaniella* faunules tend to be most prevalent in the following formations in the eastern Great Basin: Ute, upper shale member of the Ophir, Whirlwind, and Burnt Canyon Member of the Highland Peak. Previous reports of *Ehmaniella* in the Spence Shale. (Resser, 1939a) and "*Ptarmigania strata*" (Resser, 1939b) appear to be in error.

Although *Ehmaniella* is known only from restricted-shelf facies in the Great Basin, two species have been reported from what are here interpreted to be open-shelf facies in the Canadian Rockies. Rasetti (1951, p. 103-5) indicated that *E. burgessensis* and *E. waптаensis* are rare elements in his *Pagetia bootes* faunule in the lower Stephen Formation (=Burgess Shale), and the former species provides the name for his *E. burgessensis* fauna from high in the Stephen. Additional stratigraphic data on these species has been provided by Fritz (1971).

Ehmaniella to Eldoradia barren interzone.—This interval includes most of the upper half of the Middle Cambrian in the eastern Great Basin (cf. Text-figs. 2 and 3). It consists of 600 to 700 m of predominantly limestone and dolomite, and generally lacks metazoan body fossils. Kepper (1975) concluded that many of these carbonate rocks are of algal origin and were formed in a broad region of peritidal to subtidal environments. Unstable or unfavorable levels of salinity and temperature may account for the general lack of trilobites and other metazoa.

Eldoradia Assemblage-Zone.—This is a new zone that is mainly represented in the eastern Great Basin, particularly in the Fish Springs Member of the Trippe Limestone, but it also is present in the Eureka district of central Nevada (Hintze and Robison, 1975, p. 889). The fauna is usually found in shaly

limestone interbedded with algal boundstone and flat-pebble limestone conglomerate. These rock types, in combination with desiccation cracks, small channel-fill deposits and other features, suggest broad tidal-flat environments. Generally only a single species, *Eldoradia prospectensis*, is encountered. It occurs sporadically, but disarticulated sclerites may be concentrated in small lenses and channel-fill deposits.

The fauna of the *Eldoradia* Zone is mostly undescribed, and in addition to *Eldoradia prospectensis* it rarely includes species of *Asaphiscus*, *Blainia*, *Bolaspidella*, and *Modocia*. These additional genera are more typical of the open-shelf biofacies in the Great Basin and are generally associated with *Eldoradia* only in the more seaward or transitional parts of the restricted biofacies. However, in other areas such as Montana, Arizona, and Texas, *Bolaspidella* and *Modocia* are found in rocks that may prove to represent restricted-shelf environments.

Regional facies relations, trace fossils, and sedimentary criteria together indicate that the habitat of *Eldoradia* in the Clarks Spring Member of the Secret Canyon Shale near Eureka, Nevada, may have been in an unusual area of local shoaling on the outer part of the Cambrian shelf.

In much of central and western Utah the *Eldoradia* Zone is succeeded by a thick barren interzone below a fairly widespread *Crepicephalus* fauna in the Upper Cambrian. Therefore, as noted by Hintze (1974), the shaly *Eldoradia*-bearing Fish Springs Member, which has an average thickness of about 30 m, is an important marker unit near the middle of an approximately 1000-metre interval of mostly barren carbonates.

Open-Shelf Polymeroid Assemblage-Zones

The open-shelf biofacies is generally characterized by a succession of more continuously fossiliferous strata than is the restricted-shelf biofacies. A shallower, higher energy subfacies, near the seaward margin of the carbonate platform, tends to have high taxonomic diversity, and the trilobites are usually disarticulated and are commonly preserved in biosparites. A deeper, lower energy, more seaward subfacies tends to have lower taxonomic diversity, and the trilobites may be articulated and are commonly preserved in laminated fine-grained rocks. Palmer and Campbell (1975, also see paper in this volume) have described the relations of trilobite faunas in these two subfacies, which they refer to as the "zacanthoidid and *Ogygopsis* biofacies," in an interval that temporally correlates with the *Albertella* Assemblage-Zone of the restricted-shelf facies.

On the average, trilobite genera that are common in the open-shelf biofacies have longer temporal ranges than genera that are common in the restricted-shelf biofacies (cf. Text-figs. 3 and 4), and this may reflect the influence of more stable environments and trophic resources on the open shelf. The polymeroids fall naturally into two generic assemblages. For the oldest group I propose the new name *Oryctocephalus* Assemblage-Zone, and the youngest group fits a modified concept of the previously defined *Bolaspidella* Assemblage-Zone (Robison, 1964a, c).

Oryctocephalus Assemblage-Zone.—Many genera previously assigned to the *Bathyriscus-Elrathina* Assemblage-Zone are included in this new zone, which is erected because of taxonomic problems with both *Bathyriscus* and *Elrathina*, and because of significant modification of concept from that previously applied

to the *Bathyriscus-Elrathina* Zone. *Wenckchemnia* and *Bathyriscus* appear to represent opposite ends of an evolutionary continuum and *Bathyriscus* probably should be regarded as a senior synonym of *Wenckchemnia*. If that synonymy is accepted, *Bathyriscus* has an observed range through most of the Middle Cambrian. Furthermore, because it is at least as common, if not more common, in the overlying *Bolaspidella* Zone, it is not appropriate to continue to use the name *Bathyriscus* in zonal nomenclature. *Elrathina* probably should be regarded as a junior synonym of *Syspacephalus*, which has been previously used to designate an upper Lower Cambrian zone (Howell and others, 1944). In view of these problems, which I intend to discuss in more detail in a separate paper, *Bathyriscus-Elrathina* is abandoned as a zone name and *Oryctocephalus* is proposed as a partial substitute that includes a greater geologic interval but is restricted to shallow outer-shelf biofacies.

Among polymeroids commonly encountered in the *Oryctocephalus* Zone are *Alokistocare*, *Bathyriscus* (= *Wenckchemnia*), *Kootenia*, *Ogygopsis*, *Olenoides*, *Oryctocephalus*, *Syspacephalus* (= *Elrathina*), and *Zacanthoides*. Although *Kootenia*, *Ogygopsis*, *Olenoides*, *Syspacephalus*, and *Zacanthoides* all range from the Lower Cambrian into the *Oryctocephalus* Zone, the assemblage of lower Middle Cambrian genera differs markedly from older faunas by the absence of *Bonnia* and olenellids and by the appearance of *Alokistocare*, *Bathyriscus*, and *Oryctocephalus*. A large number of additional genera are found in the *Oryctocephalus* Zone, but available data is inadequate for meaningful analysis of ranges at this time. However, with more information, I expect that many of these genera and their species will prove to be useful biostratigraphic indices and a much more refined zonation will be possible.

A single section with a continuous succession of *Oryctocephalus* faunas is not known. Nevertheless, a fairly complete sequence can be pieced together from the Great Basin and the Canadian Rockies. The oldest representatives are in the middle Carrara Formation of southern Nevada (Palmer and Halley, in press) and in the lower and middle Mount Whyte Formation in Canada (Rasetti, 1951, p. 87-90). A slightly younger fauna is rather widespread in southern Idaho and northern Utah (uppermost Twin Knobs Formation and Spence Tongue of Lead Bell Shale; Campbell, 1974), western Utah (undifferentiated unit in the lower Abercrombie Formation in Deep Creek Range), eastern Nevada (undifferentiated unit in Pioche Shale of Fritz, 1968), and in southern Nevada and adjacent California (parts of Carrara Formation of Palmer and Halley, in press). An intermediate fauna (*Ogygopsis klotzi* and *Pagetia bootes* faunules of Rasetti, 1951, p. 101-104) is found in the Stephen Formation in Canada, and the uppermost faunas, known from many undescribed collections, are rather widely distributed in central and eastern Nevada (upper 1-2 m of Pole Canyon Limestone and basal Geddes Formation) and western Utah (upper 1-2 m of Swasey Limestone and basal one-fifth of Wheeler Formation). These uppermost faunas in the Drum Mountains of western Utah have been described in unpublished studies by Randolph (1973) and White (1973).

The agnostoids *Pagetia* and *Peronopsis* are commonly associated with all but about the lowermost one-fifth of the *Oryctocephalus* fauna.

Bolaspidella Assemblage-Zone.—The concept of this zone, which has been previously discussed (Robison, 1964a, b), is here modified to exclude agnostoid trilobites. The zone is well developed in the central part of the Great

Basin and extends through approximately the upper half of the Middle Cambrian. Representative faunas commence about 27 m above the base of the Wheeler Shale and range into the basal Weeks Formation in the House Range of western Utah (Robison, 1964a, 1971). Characteristic genera are *Bathyriscus*, *Bolaspidella*, *Elrathia*, *Modocia*, and *Olenoides*. Less common polymeroids are *Asaphiscus*, *Brachyaspidion*, *Semisphaerocephalus*, and *Spencella*. Several other genera are more rarely encountered, and associated agnostoids tend to be common to abundant.

Three subzones were defined in the House Range (Robison, 1964a), but subsequent study has shown that only the *Lejopyge calva* Subzone can be recognized on a regional scale, and the characteristic taxa of that unit here are transferred to the agnostoid zonation.

Open-Shelf Agnostoid Assemblage-Zones

Many agnostoid species have distinctive morphology, cosmopolitan distribution, and relatively short stratigraphic ranges. Therefore, the zones of this set are based on assemblages of species rather than assemblages of genera as in the zonal sets for polymeroids.

The eodiscids currently are classified with the Agnostida (e.g., Harrington and others, 1959), but may deserve recognition as a separate order. In features such as hypostomal structure, lack of basal lobes, and retention of an articulating half ring on the anterior thoracic segment, the Eodiscina show greater similarity to polymeroids than to members of the Agnostina. It is perhaps significant that *Pagetia*, which is the only eodiscid known from the Middle Cambrian of western North America, disappeared near the *Oryctocephalus-Bolaspidella* boundary along with several polymeroid genera (Text-fig. 4). Because of insufficient study and probable differences in mode of life, species of *Pagetia* are not used as guide fossils in this zonal scheme. However, further investigation may well demonstrate a significant biostratigraphic value for these species in the lower half of the Middle Cambrian in the Great Basin.

Since Westergård's (1946) monographic study, the Middle Cambrian of Scandinavia has been mostly zoned with agnostoid species, and has come to be recognized as a standard for world reference. Some of the same agnostoid zones can be recognized in the Great Basin. A few species have longer relative stratigraphic ranges in the Great Basin than in Scandinavia, but thus far no evidence has been found that indicates a lack of homotaxial succession for those species common to both provinces. The few polymeroids previously used for zonation in Scandinavia are unknown in North America, and the zonal scheme used in this section differs from Westergård's because it is based entirely on assemblages of agnostoid species. Furthermore, Westergård's concept of zones is not explicitly described and the boundaries of his zones are not necessarily based on first appearances of species. The sequence of agnostoid zones for the Great Basin is given in Text-figure 5 and descriptions follow below. Where appropriate, previously defined or revised zonal names are used, and two new zonal names, *Peronopsis bonnerensis* and *Ptychagnostus praecurrens*, are proposed.

Peronopsis bonnerensis Assemblage-Zone.—In this new zone *P. bonnerensis* (= *P. lautus*) is commonly associated with *Peronopsis brighamensis* and various species of *Pagetia*. The zone is present in northern Idaho (Lakeview Limestone), southern Idaho and northern Utah (uppermost Twin Knobs Formation and

	Lochman-Balk & Wilson 1958	PROPOSED ZONES - GREAT BASIN		
		Restricted-shelf polymeroids	Open-shelf	
			polymeroids	agnostoids
MIDDLE CAMBRIAN	<i>Bolaspidella</i>	<i>Eldoradia</i> -----	<i>Bolaspidella</i>	<i>Lejopyge calva</i>
		barren interzone		unnamed
				<i>Ptychagnostus punctuosus</i>
	<i>Bathyriscus- Elrathina</i>	-----	<i>Oryctocephalus</i>	<i>Ptychagnostus atavus</i>
		<i>Ehmaniella</i>		<i>Ptych. gibbus</i>
	<i>Glossopleura</i>	<i>Glossopleura</i>		barren interzone
<i>Albertella</i>	<i>Albertella</i> ↔	<i>Ptych. praecur.</i>		
<i>Plagiura- Poliella</i>	<i>Plagiura</i>	barren interzone ----- <i>Peronopsis bonnerensis</i>		

TEXT-FIGURE 5.—Inferred chronocorrelation of zones from Lochman-Balk and Wilson (1958) and this paper. *Ptychagnostus praecurrens* Zone is presently known only from the Canadian Rocky Mountains.

Spence Tongue of Lead Bell Shale), western Utah (lower Abercrombie Formation), and southern Nevada (Carrara Formation; Palmer and Halley, in press).

P. bonnerensis is the oldest known representative of the Agnostina in western North America. However, older species of *Peronopsis* have been described from the upper Lower Cambrian in the eastern United States (Rasetti and Theokritoff, 1967).

Peronopsis bonnerensis to *Ptychagnostus praecurrens barren interzone*.—The open-shelf agnostoid biofacies is unknown in the Great Basin in an interval that corresponds to the middle and upper *Glossopleura* Zone of the restricted-shelf facies. This is apparently the result of regional expansion of restricted-shelf environments at the expense of open-shelf environments.

Ptychagnostus praecurrens Assemblage-Zone.—The species for which this new zone is named has been reported from Sweden, Siberia, British Columbia, and may be present in Norway and England. The open-shelf facies is unknown from this interval in the Great Basin. However, *P. praecurrens* (= *Triplagnostus burgessensis*), which is the ancestral species of *Ptychagnostus*, is present in the Burgess Shale Member of the Stephen Formation in British Columbia (Rasetti, 1951, p. 136-37), and is the basis for recognition of this zone in western North America. It is associated with *Peronopsis montis* and *Peronopsis columbiensis* (Fritz, 1971, fig. 5).

The *P. praecurrens* Zone in Canada correlates with the *Paradoxides pinus* Zone of Westergård (1946) in Sweden. *P. praecurrens* first appears and is most common in the *P. pinus* Zone and ranges upward into the *Ptychagnostus gibbus* Zone in Sweden, but it is not known to occur in the *P. gibbus* Zone of North America.

Ptychagnostus praecurrens to *Ptychagnostus gibbus barren interzone*.—Regional expansion of carbonate lithofacies is indicated in an interval that includes the Dome through Swasey Formations and some equivalent units in the Great Basin (see Text-fig. 2). A few, either biostratigraphically nondiagnostic or new agnostoids, have been collected from the uppermost metre of the Swasey Limestone at a few localities in western Utah, but otherwise the interval appears to be barren of agnostoids.

Ptychagnostus gibbus Assemblage-Zone.—Westergård (1946) developed the concept of this zone in Sweden, and its nominate species is cosmopolitan. In addition to Scandinavia, *P. gibbus* has been reported from Australia, England, Poland, Siberia, and North America (New York, Nevada, Utah). In the open-shelf facies of the Great Basin, *P. gibbus* may be common to abundant in the basal beds of the Geddes, Lincoln Peak, Wheeler, and some correlative units. Other agnostoids commonly associated with *P. gibbus* in the Great Basin are *Ptychagnostus intermedius*, *Ptychagnostus seminula*, *Peronopsis fallax*, and *Peronopsis* cf. *P. matthewi*. Less common associates are *Euagnostus opimus*, *Peronopsis gaspensis*, *Peronopsis montis*, and a new species of *Peronopsis* similar to *P. depressa*.

Faunas with *Ptychagnostus intermedius* and *Peronopsis montis* occur in the "black band" of the Eldon Formation in British Columbia (Aitken and others, 1972, p. 14) and the lower Meagher Formation in Montana, and represent the *Ptychagnostus gibbus* Zone in those regions.

Ptychagnostus atavus Assemblage-Zone.—Westergård (1946) designated a "zone of *Tomagnostus fissus* and *Ptychagnostus atavus*" in Sweden. *P. atavus* is cosmopolitan (Scandinavia, England, Newfoundland, western U. S., Australia, China, U. S. S. R.), but except for eastern Newfoundland, *Tomagnostus* is unknown from North America. Therefore, the revised name, *Ptychagnostus atavus* Assemblage-Zone, is proposed for the Great Basin.

In Nevada and Utah *P. atavus* may be common to abundant in the upper four-fifths of the Wheeler, basal Marjum, and correlative units of the open-shelf facies. It is commonly associated with *Peronopsis interstricta* and *Peronopsis fallax* and less commonly with *Peronopsis ferox*, *Peronopsis segmenta*, *Baltagnostus euryptyx*, and *Hypagnostus parvifrons*.

Ptychagnostus punctuosus Assemblage-Zone.—As used here, the base of the *P. punctuosus* Zone is defined on the first appearance of *P. punctuosus affinis*, which in the House Range is about 15 m above the base of the Marjum Formation. This revised zone is probably equivalent to Westergård's (1946) zones of *Hypagnostus parvifrons* and *Ptychagnostus punctuosus*. The former name is abandoned because *H. parvifrons* first appears well down in the *P. atavus* Zone as used in both Scandinavia and the Great Basin. Furthermore, in Utah *H. parvifrons* is known to range through most of the upper half of the Middle Cambrian, and in Scandinavia the zone apparently does not include a distinctive biostratigraphic assemblage.

Both subspecies of *P. punctuosus*, *P. p. affinis* and *P. p. punctuosus* are present in the Great Basin, but are relatively rare. Only a few specimens have been collected in the House Range, Utah, and the northern Egan Range and Eureka district in Nevada. Several other agnostoid species are present in this zone in the Great Basin, but occurrences tend to be sporadic and relative stratigraphic ranges are inadequately known. Some of the more significant species are *Ptychagnostus richmondensis*, *Ptychagnostus hybridus* and *Ptychagnostus nanus*, *Ptychagnostus atavus* ranges 115 m into the base of the *P. punctuosus* Zone in the House Range.

Unnamed zone.—An interval in the upper Marjum Formation and some equivalent units of the Great Basin has a relatively rare agnostoid fauna with mostly long-ranging species such as *Hypagnostus parvifrons* and *Baltagnostus eurypyx*. The interval probably correlates closely with the "Zone of *Ptychagnostus lundgreni* and *Goniagnostus nathorsti*" of Westergård (1946) in Sweden. However, with the exception of *Ptychagnostus nanus* (= *P. lundgreni nanus* of Westergård), none of the species reported from the *P. lundgreni*-*G. nathorsti* Zone of Sweden have been discovered in the Great Basin. I have collected *P. nanus* from isolated outcrops in the House Range, Utah, and in the Eureka district, Nevada, but unfortunately in both instances the stratigraphic position is uncertain. Nevertheless, in the Eureka district *P. nanus* is associated with *P. punctuosus punctuosus*, whereas in Sweden the ranges of those two species are not known to overlap (Westergård, 1946, p. 100). Until more information is available on the faunas of this interval, I prefer to leave the zone unnamed.

Lejopyge calva Assemblage-Zone.—This unit was originally defined as a subzone of the *Bolaspidella* Assemblage-Zone (Robison, 1964a), but is here elevated to zonal rank. *L. calva* has been found in considerable abundance at many localities in the central Great Basin, and Palmer (1968) has recorded its presence in Alaska. In the House Range it has an observed range through the upper 16 m of the Marjum Formation and the lower 28 m of the Weeks Formation. Rarely *L. calva* has been found in association with *Ptychagnostus aculeatus*, *Utagnostus trispinulus* and new species of *Lejopyge*, *Ptychagnostus* and *Hypagnostus*.

Because *P. aculeatus* is cosmopolitan whereas *L. calva* is only known from western North America, *P. aculeatus* might be a preferable name for this zone. However, reports indicate that *P. aculeatus*, although it is a distinctive cosmopolitan species, is a relatively rare faunal element at practically all localities. In the Great Basin only a few specimens have been found in two collections from 1.5 and 3.0 m above the base of member B of the Emigrant Springs Limestone at Patterson Pass, Nevada. Therefore, because of its regional abundance, and also because of its restricted stratigraphic range, *L. calva* is retained as the nominate species for this zone.

CORRELATION

Chronocorrelation of Great Basin trilobite faunas is somewhat of a paradox. On one hand, the cosmopolitan distribution and rapid evolution of many Middle Cambrian agnostoid species allows reasonably confident correlation of faunas from the open-shelf facies of the Great Basin with certain faunas in Australia, Asia and Europe. On the other hand, it may be difficult to correlate faunas of the restricted- and open-shelf facies even within the same mountain range in the Great Basin. For example, *Lejopyge* and *Eldoradia* faunas are

separated in the central and northern House Range by less than 30 km, but their temporal relations have only been approximately determined because of facies changes and the lack of adequate physical and biological bases for precise correlation.

Inferred chronocorrelation of the three proposed zonal sets is illustrated in Text-figure 5. Faunas from some intervals are not well documented and further refinement probably will be possible. Dashed lines indicate an uncertain position for some boundaries, and the arrows indicate some mixing of restricted- and open-shelf faunas during the *Albertella* Chronozone.

The extensive eastward shift of lithofacies in the middle Middle Cambrian (base of *Ptychagnostus gibbus* Zone) coincides with a major change in biofacies patterns in much of the Great Basin (Text-fig. 2). Rather abrupt lithofacies changes can be recognized in other parts of the world at the base of the *P. gibbus* Zone (for example, base of Exsulans Limestone or *Acrothele* Conglomerate in Sweden, base of "black band" of the Eldon Formation in the Canadian Rocky Mountains), and may have resulted from a eustatic rise in sea level. Whatever the cause, pervasive effects of a physical event coupled with the appearance of *P. gibbus* provide an exceptional datum horizon for intercontinental correlation of Cambrian rocks and fossils, and I anticipate that it will prove to be one of the best chronohorizons in the Cambrian System.

BIOMERES

The extensive middle Middle Cambrian shift of lithotopes in the Great Basin was accompanied by immigration of facies faunas of the upper *Oryctocephalus* Zone and was followed by major extinction and replacement of polymeroid genera near the base of the *Bolaspidella* Zone. This faunal change is somewhat similar to that on which biomere boundaries are defined in the Upper Cambrian, and perhaps the factors that caused abrupt and near total discontinuity of polymeroid genera and families in shelf areas during the Late Cambrian were beginning to have effect as early as the middle Middle Cambrian. Nevertheless, several polymeroid genera range into younger rocks, and although only common genera are included in the range charts of Text-figures 3 and 4, they are adequate to demonstrate the absence of typical biomere patterns in the Middle Cambrian of the Great Basin.

ACKNOWLEDGMENTS

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REFERENCES

- Aitken, J. D., Fritz, W. H., and Norford, B. S., 1972, Cambrian and Ordovician biostratigraphy of the southern Canadian Rocky Mountains: 24th Int. Geol. Congr., Field Excursion A19 Guidebook, 57 p.
- Burling, L. D., 1914, Early Cambrian stratigraphy of the North American Cordillera, with discussion of *Albertella* and related faunas: Geol. Surv. Can., Mus. Bull., v. 2(17), p. 93-129.
- Campbell, D. P., 1974, Biostratigraphy of the *Albertella* and *Glossopleura* Zones (lower Middle Cambrian) of northern Utah and southern Idaho: unpub. M.S. thesis, Univ. Utah, 295 p.

- Clark, D. L., and Robison, R. A., 1969, Oldest conodonts in North America: *J. Paleont.*, v. 43, p. 1044-46.
- Daily, Brian, and Jago, J. B., 1975, The trilobite *Lejopyge* Hawle and Corda and the Middle-Upper Cambrian boundary: *Palaeont.*, v. 18, p. 527-50.
- Deiss, Charles, 1939, Cambrian formations of southwestern Alberta and southeastern British Columbia: *Geol. Soc. Amer. Bull.*, v. 50, p. 951-1026.
- Fritz, W. H., 1968, Lower and early Middle Cambrian trilobites from the Pioche Shale, east-central Nevada, USA: *Palaeont.*, v. 11, p. 183-235.
- , 1971, Geologic setting of the Burgess Shale: *N. Amer. Paleont. Conv., Proc.* (1969), pt. 1, p. 1155-70.
- Harrington, H. J., and others, 1959, Arthropoda 1, in Moore, R. C. (ed.), *Treatise on invertebrate paleontology*, Part O: *Geol. Soc. Amer. and Univ. Kansas Press*, Lawrence, Kansas, 560 p.
- Hintze, L. F., 1974, *Eldoradia*, a helpful arthropod amongst barren boundstones in western Utah: *Geol. Soc. Amer. Abst. Prog.*, v. 6(3), p. 192-93.
- , and Robison, R. A., 1975, Middle Cambrian stratigraphy of the House, Wah Wah, and adjacent ranges in western Utah: *Geol. Soc. Amer. Bull.*, v. 86, p. 881-91.
- Howell, B. F., and others, 1944, Correlation of the Cambrian formations of North America: *Geol. Soc. Amer. Bull.*, v. 55, p. 993-1003.
- International Subcommittee on Stratigraphic Classification, 1976, *International stratigraphic guide*: Hedberg, H. D. (ed.), *Wiley-Interscience*, New York, 200 p.
- Kepper, J. C., 1975, Is the Middle Cambrian carbonate belt in the Basin and Range region an algal biosome?: *Geol. Soc. Amer. Abst. Prog.*, v. 7(7), p. 1144-45.
- Lochman-Balk, Christina, and Wilson, J. L., 1958, Cambrian biostratigraphy in North America: *J. Paleont.*, v. 32, p. 312-50.
- Oldroyd, J. D., 1973, Biostratigraphy of the Cambrian *Glossopleura* Zone, west central Utah: unpub. M.S. thesis, Univ. Utah, 140 p.
- Palmer, A. R., 1964, *Pioche Shale faunules*: in Merriam, C. W., *Cambrian rocks of the Pioche mining district, Nevada*: U.S. Geol. Surv. Prof. Paper 469, p. 25-27.
- , 1968, Cambrian trilobites of east-central Alaska: U.S. Geol. Surv. Prof. Paper 559-B, 115 p.
- , 1971, The Cambrian of the Great Basin and adjacent areas, western United States: in Holland, C. H. (ed.), *Lower Paleozoic rocks of the world*, Vol. 1: *Cambrian of the New World*, Wiley-Interscience, New York, p. 1-78.
- , 1973, Cambrian trilobites: in Hallam, A. (ed.), *Atlas of palaeobiogeography*: Elsevier, New York, p. 3-11.
- , and Campbell, D. P., 1975, Biostratigraphic implications of trilobite biofacies: *Albertella* Zone, Middle Cambrian, western United States: *Geol. Soc. Amer. Abst. Prog.*, v. 7(7), p. 1222-23.
- , and Halley, R. B., in press, Physical stratigraphy and trilobite biostratigraphy of Lower and Middle Cambrian Carrara Formation in the southern Great Basin: U.S. Geol. Surv. Prof. Paper.
- Randolph, R. L., 1973, Paleontology of the Swasey Limestone, Drum Mountains, west central Utah: unpub. M.S. thesis, Univ. Utah, 73 p.
- Rasetti, Franco, 1951, Middle Cambrian stratigraphy and faunas of the Canadian Rocky Mountains: *Smithson. Misc. Coll.*, v. 116(5), p. 1-277.
- , 1957, Additional fossils from the Middle Cambrian Mt. Whyte Formation of the Canadian Rocky Mountains: *J. Paleont.*, v. 31, p. 955-72.
- , and Theokritoff, George, 1967, Lower Cambrian agnostid trilobites of North America: *J. Paleont.*, v. 41, p. 189-96.
- Resser, C. E., 1939a, The Spence Shale and its fauna: *Smithson. Misc. Coll.* v. 97(12), p. 1-29.
- , 1939b, The *Ptarmigania* strata of the northern Wasatch Mountains: *Smithson. Misc. Coll.* v. 98(24), p. 1-72.
- Robison, R. A., 1964a, Late Middle Cambrian faunas from western Utah: *J. Paleont.*, v. 38, p. 510-66.
- , 1964b, Middle-Upper Cambrian boundary in North America: *Geol. Soc. Amer. Bull.*, v. 75, p. 987-94.
- , 1964c, Upper Middle Cambrian stratigraphy of western Utah: *Geol. Soc. Amer. Bull.*, v. 75, p. 995-1010.
- , 1971, Additional Middle Cambrian trilobites from the Wheeler Shale of Utah: *J. Paleont.*, v. 45, p. 796-804.

- , 1972a, Hypostoma of agnostid trilobites: *Lethaia*, v. 5, p. 239-48.
- , 1972b, Mode of life of agnostid trilobites: 24th Int. Geol. Congr., Proc., Sect. 7, p. 33-40.
- Schwimmer, D. R., 1975, Quantitative taxonomy and biostratigraphy of Middle Cambrian trilobites from Montana and Wyoming: *Math. Geol.*, v. 7, p. 149-66.
- Stewart, J. H., and Palmer, A. R., 1967, Callaghan window—a newly discovered part of the Roberts thrust, Toiyabe Range, Lander County, Nevada: U.S. Geol. Surv. Prof. Paper 575-D, p. 56-63.
- Westergård, A. H., 1946, Agnostidea of the Middle Cambrian of Sweden: *Sveriges Geol. Unders. Arsbok* 40(1), 140 p.
- White, W. W., 1973, Paleontology and depositional environments of the Cambrian Wheeler Formation, Drum Mountains, west-central Utah: unpub. M.S. thesis, Univ. Utah, 134 p.

Lower Dresbachian (Upper Cambrian) Platform to Deep-Shelf Transition in Eastern Nevada and Western Utah: An Evaluation through Lithologic Cycle Correlation

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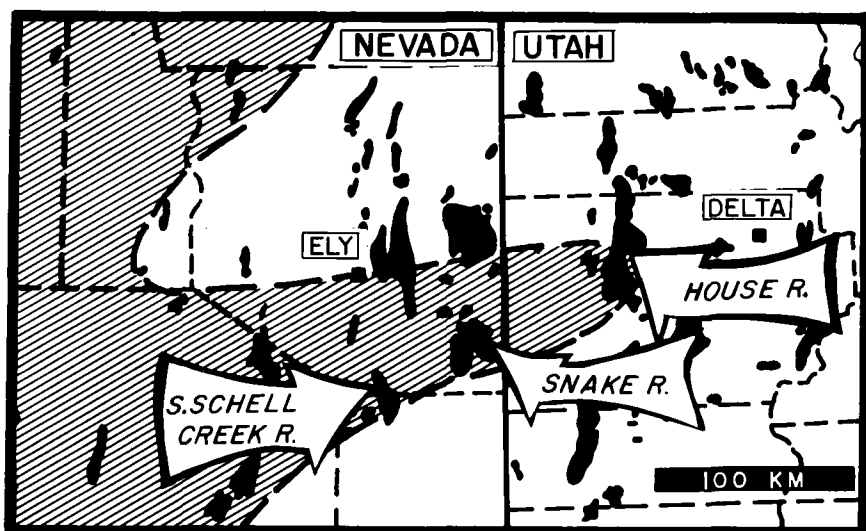
ABSTRACT.—Strongly asymmetric lithologic cycles are present in strata of *Crepicephalus* Zone age in the House Range, Utah, and the southern Schell Creek and Snake ranges of Nevada. These cycles include elements of two distinct lithofacies complexes: 1) a platform-margin high-energy complex, composed of oolitic grainstone, algal boundstone, and skeletal and oncolitic packstone and grainstone; and 2) a deep-shelf low-energy complex, composed of burrowed wackestone, nodular mudstone, and laminated mudstone. A model is synthesized to describe the dynamics of the depositional system. Cycle tops represent the inflection points from gradual shallowing to rapid deepening. These are correlated among and within mountain ranges to develop an empirical time scale with higher resolution than that provided by current biostratigraphy, and to yield a basis for estimating local paleoslope and depth ranges for each lithofacies.

INTRODUCTION

The Cambrian lithologic succession of the east-central Great Basin results from an interplay between the sediments generated in a shallow water, easterly "carbonate belt" of relatively clean carbonate grainstone and algal boundstone, and a deeper water, westerly "outer detrital belt" of argillaceous shale and silty limestone (Palmer, 1960). The boundary between these belts is frequently irregular, due to the development of embayments of the outer detrital belt into the carbonate belt. This study is an investigation of the nature of the complex represented by transition from the carbonate belt platform to the outer detrital belt deep shelf in and adjacent to an embayment that opened westward and oceanward from the House Range, Utah, into eastern Nevada during the time represented by the *Crepicephalus* Zone of early Dresbachian age (Text-fig. 1).

The platform to deep-shelf transition was studied in three mountain ranges. Carbonate platform lithologies are well developed in member B of the Emigrant Springs Formation in the southern Schell Creek Range, Nevada, and in the Big Horse Member of the Orr Formation, House Range, Utah. Deeper water lithologies are best developed in the Lincoln Peak Formation, Snake Range, Nevada. In the House Range, transition from shallow-water platform carbonates to deeper water, clastic-rich basinal lithologies takes place within a northeast to southwest exposure belt 14 km long.

A detailed examination of the successions of lithologies in all three ranges revealed the presence of strongly asymmetric upward-shallowing cycles. Correlation of the tops of these cycles within and among mountain ranges provides an empirical time scale with finer resolution than is possible through current biostratigraphic techniques. This increased resolution permits estimation of paleoslope and depth ranges for each lithofacies across the platform to deep-shelf transition. Evidence for these conclusions is presented below.

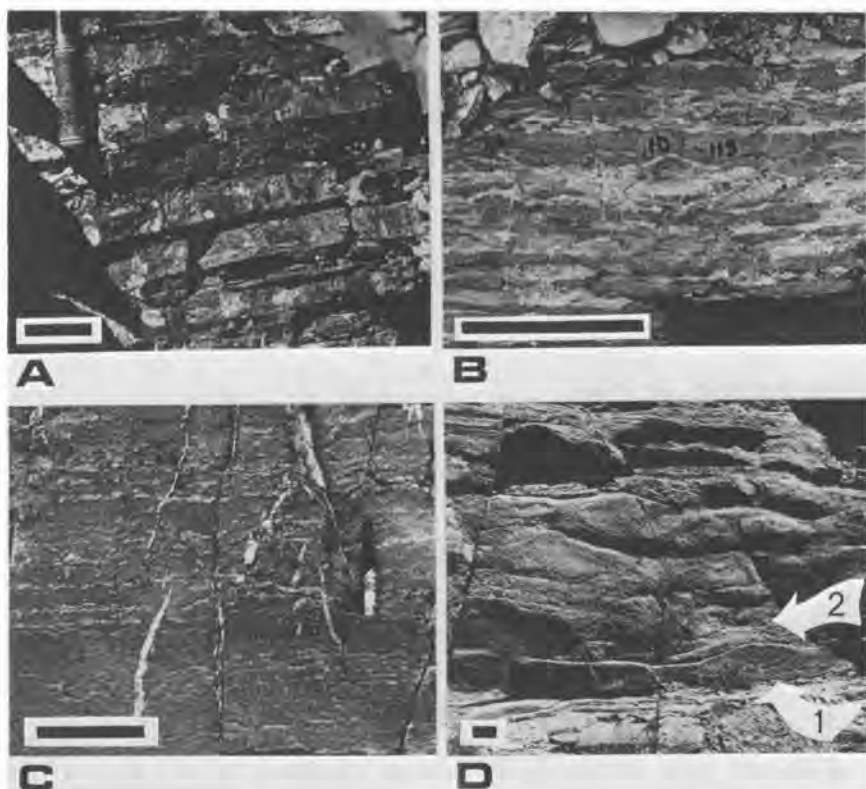


TEXT-FIGURE 1.—Locality map of the Dresbachian sections examined in this paper. The cross-hatched pattern illustrates the approximate configuration of the "outer detrital belt" embayment into the "carbonate belt" during early *Crepicephalus* Zone time (after Palmer, 1971).

DEPOSITIONAL SYSTEM

Six lithofacies characterize the platform to deep-shelf transition. The lithofacies can be separated into two depositional groups: a deep-shelf low-energy complex, reflecting conditions below wave base; and a platform-margin high-energy complex, reflecting conditions above wave base.

The lithofacies of the deep-shelf low-energy complex are: 1) laminated-mudstone lithofacies, which is represented by dark-gray to black, pyritic arenaceous lime mudstone interbedded with quartz-rich siltstone and shale. The lime mudstone occurs in laterally continuous beds 1 to 6 cm thick (Text-fig. 2A), composed of quartz silt, carbonate micropeloids, micrite, and finely fragmented skeletal debris. Internally the beds have millimeter laminations often displaying micro-Bouma sequences. Burrows are rare. All of the characteristics indicate that this facies developed under low-energy conditions in poorly oxygenated water; 2) nodular-mudstone lithofacies, which consists of dark-gray lime mudstone occurring as nodular discontinuous or wavy continuous beds 2 to 4 cm thick (Text-fig. 2B), interbedded with siltstones and shales. The limestones are composed of peloids, medium to coarse skeletal debris, and minor quartz silt. The nodules are internally cross-bedded, with alternating laminations of terrigenous silt and carbonate peloids. The presence of coarser constituents and the development of cross-bedding indicate a shallower depositional environment than that of the laminated mudstone lithofacies; and 3) burrowed-wackestone lithofacies, which consists of a light- to medium-gray wackestone, characteristically forming massive ledges (Text-fig. 2C). Constituent grains are predominately carbonate peloids with associated complete to fragmented hyolithid, trilobite, and inarticulate brachio-



TEXT-FIGURE 2.—Scale bar is 10 cm.

- A. Laminated-mudstone lithofacies; interbedded lime mudstone and quartz-rich silt and shale.
- B. Nodular-mudstone lithofacies; note the development of the wavy-continuous and nodular-discontinuous bedding.
- C. Burrowed-wackestone lithofacies; massive weathering ledge with thin dolomitic partings.
- D. Skeletal and oncolitic packstone and grainstone; note the development of (1) grainstone megariipples with (2) thin-packstone interbeds.

pod debris. Thin orange dolomitic laminations are concentrated along stylolitic seams. Mud- and spar-filled burrows, 1 to 2 mm in diameter, are abundant. An environment of low current and wave energy is suggested by the abundance of micrite. Low organic content and dense bioturbation suggest deposition in well-oxygenated water.

The lithofacies of the platform-margin high-energy complex are: 4) skeletal- and oncolitic-packstone and grainstone lithofacies, which consist of two vertically successive subfacies. A lower, medium-gray, evenly bedded skeletal packstone is in beds 2 to 4 cm thick interbedded with thin wackestone; and an upper, medium-gray oncolitic grainstone is in beds 5 to 20 cm thick, interbedded with skeletal packstone. The upward trend is toward in-

creased grain coarseness and oncolite abundance and decreased micrite matrix. Within both subfacies a coarser rippled skeletal or oncolitic grainstone is interbedded with thin packstone or wackestone. In the upper subfacies oncolitic grainstone megariipples 0.02 to 0.2 m high and 0.5 to 1.5 m long are present (Text-fig. 2D). The interbedding of wackestone with coarse megaripped grainstone suggests an environment located below normal wave base, but affected periodically by storm waves; 5) oolitic-grainstone lithofacies, which consist of medium to light gray-weathering grainstone occurring in massive beds 1 to 3 m thick. It is composed of well-sorted ooids developed on nuclei of skeletal fragments, intraclasts, and grains of quartz. Medium- to high-angle cross-bedding occurs in sets 0.2 to 0.7 m thick. Contact with the invariably underlying oncolitic grainstone is gradational and characterized by low-angle crossbeds with alternating ooid-rich and oncolite-rich laminations. The depositional environment was shallow, normal marine with high grain mobility maintained by normal wave turbulence and tidal currents; and 6) algal-boundstone lithofacies, which are composed of two distinct morphologies of algal boundstone. One is a medium-gray, nonlaminated, clotted, globose thrombolite (Aitken, 1967), and the other is a light-gray, laminated, stacked-hemispheroid stromatolite (Logan, et al., 1964). Thrombolite bioherms, composed of the algae *Epiphyton* and *Girvanella*, developed on a substrate of either megaripped oncolitic grainstone or burrowed wackestone. Height of the bioherms ranges from 1.5 to 10.0 m, but actual relief above the bottom was generally less than one meter. Coarse skeletal and intraclastic grainstone and packstone fill the interthrombolite channels. In the intertidal environment a zonation of algal morphotypes developed, and *Epiphyton-Girvanella* thrombolites formed a peripheral subtidal barrier around an intertidal core of stromatolites (Lohmann, 1975). The association of the algal boundstone, with coarse grainstone channels and normal marine faunas (Eby, 1975) indicates a shallow subtidal to intertidal depositional environment with moderate wave energies for this lithofacies.

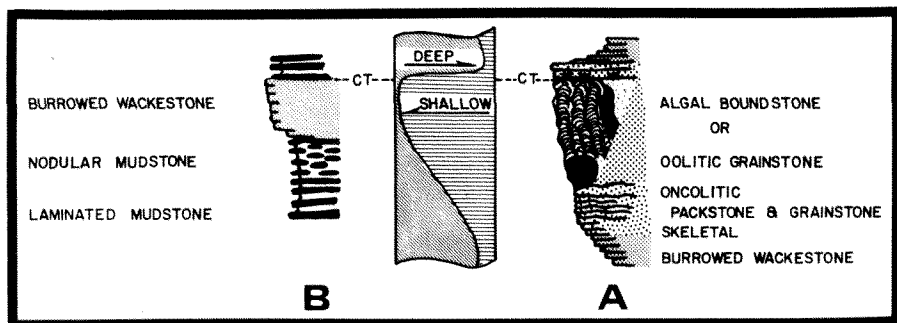
The bioherms are capped by a transition zone 0.3 to 0.5 m thick, reflecting the return to a deeper, subtidal environment. In association with this change, the intertidal stromatolitic core developed into a globose to vertically digitate subtidal *Epiphyton-Renalcis* thrombolite (Lohmann, 1975). This is directly overlain by a thin grainstone of superficially coated ooids and then by a thin skeletal packstone. Deeper water mudstones occur directly above this transition.

An additional lithofacies, the quartz-silt lithofacies, is not a predictable component of the upward-shallowing carbonate cycle. It consists of a dark brown-weathering terrigenous silt developed as either quartz-cemented (1 to 2 cm thick) interbeds or as ledges 0.1 to 1.0 m thick. This lithofacies may reflect the periodic westward flood of inner shelf clastics across the carbonate platform.

A model for depositional environments of the platform- to deep-shelf complexes described above is illustrated in Text-figure 4.

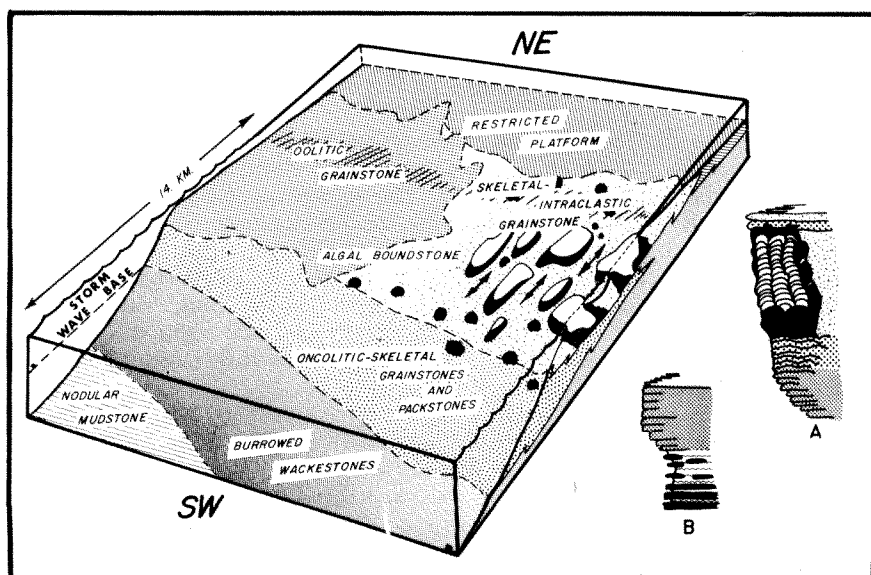
NATURE AND CORRELATION OF CYCLES

The successions of lithofacies shown in Text-figures 3 and 4 form repeating asymmetrical cycles that reflect a gradual upward shallowing of the depositional environments, followed by a rapid deepening. The upward shallowing is evidenced by: 1) upward coarsening of skeletal and allo-



TEXT-FIGURE 3.—Typical cycles of (A) the platform-margin high-energy complex and (B) the deep-shelf low-energy complex are illustrated with an interpretive depth curve. The abrupt termination of each cycle coincides with a rapid deepening event. Cycle top (CT) is placed at the inflection from shallowing to deepening.

chemical grains, with a concomitant decrease in micrite; 2) upward increase in abundance of shallow subtidal and intertidal algal boundstone, oncolites, and ooids; and 3) upward increase in high-energy bedforms such as large-scale cross-bedding and megarippled grainstones. The elements of these gradually upward-shallowing cycles can be combined to form an ideal cycle (from deepest to shallowest) of laminated mudstone, nodular mudstone, burrowed wackestone, skeletal and oncolitic packstone and grainstone, and algal



TEXT-FIGURE 4.—Schematic illustration of the spatial and environmental relationships of lithofacies and of typical cycles characteristic of (A) the platform-margin high-energy complex (B) and the deep-shelf low-energy complex.

boundstone or oolitic grainstone. The quartz-silt lithofacies generally occurs in the lower part of the carbonate cycle, but its exact position is not predictable, suggesting an alternative genesis from that of the carbonate lithofacies.

The algal-boundstone and oolitic-grainstone lithofacies occupy equivalent positions within cycles. Both form above megarippled oncologic grainstone, but do not co-occur (Text-fig. 4). The separation probably results from local environmental differences at the platform margin, related perhaps to the slope of the margin. If the slope is gradual the zone of wave impingement will be broad, and wave energy, distributed over a wide area, will be low. As a result, algae may colonize the relatively stable substrate and develop an effective wave baffle, which destroys the hydrographic conditions necessary for ooid formation. Conversely, if the slope is steeper, the zone of wave turbulence will be narrower, thus maintaining the movement of substratal grains and preventing the development of algal boundstones. Consequently, ooid formation may predominate.

Actual cycles observed in the field correlate well with parts of the ideal cycle. Individual components may be poorly represented, but they are always present. Moreover, lithofacies never occur out of sequence. The fidelity of the observed cycles compared to the ideal cycle requires a nonrandom, predictable succession of events to produce the cyclicity (Coogan, 1972).

Cycles developed from the alternation of progradation and subsidence of the platform margin. Apparent subsidence of the platform margin could result from a eustatic change in water depth or tectonic subsidence of the margin. The thick accumulation of miogeoclinal sediments in this area during the Cambrian requires a continued tectonic subsidence of the shelf, but does not eliminate the possible contribution of eustatic shifts to the genesis of cyclicity. The asymmetry of the cycles requires only a marked increase in the rate of apparent subsidence. The abruptness of the shift from gradual shallowing to rapid deepening, illustrated by the sharp terminations in the typical cycles (Text-fig. 3), is supported by changes observed in the algal bioherms through this transition.

As water depth increased, the formerly intertidal biohermal complex was rapidly transgressed. Stromatolites are capped by black, subtidal *Epiphyton-Renalcis* thrombolites (Lohmann, 1975). The occurrence of high wave energies and high deposition rates is indicated by the development of grainstones of superficially coated ooids. These grade into a thin skeletal packstone that is directly overlain by deeper water, burrowed wackestone (Text-fig. 5A). This transition occurs within 0.2 to 0.4 m. If gradual deepening had occurred, the algal boundstones could have maintained their intertidal position, or greater cycle symmetry would have developed. The sharpness of this transition indicates that deepening must have been rapid.

Cycles of the deep-shelf complex, exemplified by lithologies of the Snake Range, terminate with equal sharpness. The relatively shallow burrowed-wackestone lithofacies is overlain by the deepest lithofacies, the laminated-mudstone lithofacies, within a 0.5 to 1.0 m transition (Text-fig. 5B).

Because of the rapidity of events that terminated the cycles and their representation in all sections, regardless of lithofacies, cycle tops may be correlated and interpreted as effectively synchronous among sections. Evidence for this is provided by comparison of sections in the House Range, Utah, and the Snake and southern Schell Creek ranges of Nevada, using as a datum the base



TEXT-FIGURE 5.—Illustrations of the abrupt termination of the shallowing upward cycles. Scale bar is 20 cm.

- A. The platform-margin high-energy complex: algal-boundstone lithofacies (A.B.) is overlain by a thin grainstone transition bed (T).
- B. The deep-shelf low-energy complex: burrowed-wackestone lithofacies (B.W.) is overlain by a thin silt-rich transition zone (T).

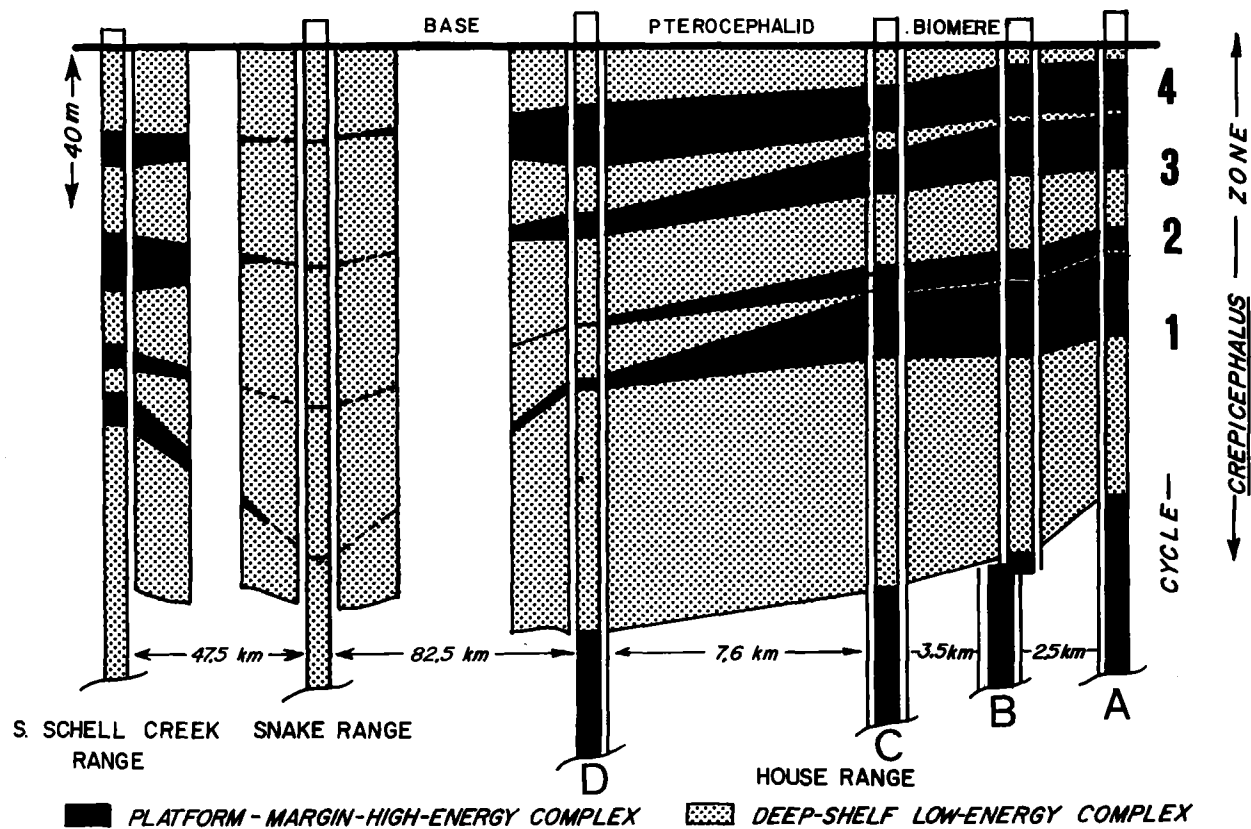
of the Pterocephaliid Biome, a distinct faunal change that is independent of the depositional dynamics of the sections (Palmer, 1972). Text-figure 6 demonstrates the obvious reliability of the cycle-top correlations. These correlations permit division of the poorly subdivided *Crepicephalus* Zone into four regionally recognizable time units—a more than two-fold increase in time-stratigraphic resolution!

IMPLICATIONS OF CORRELATION USING CYCLE TOPS

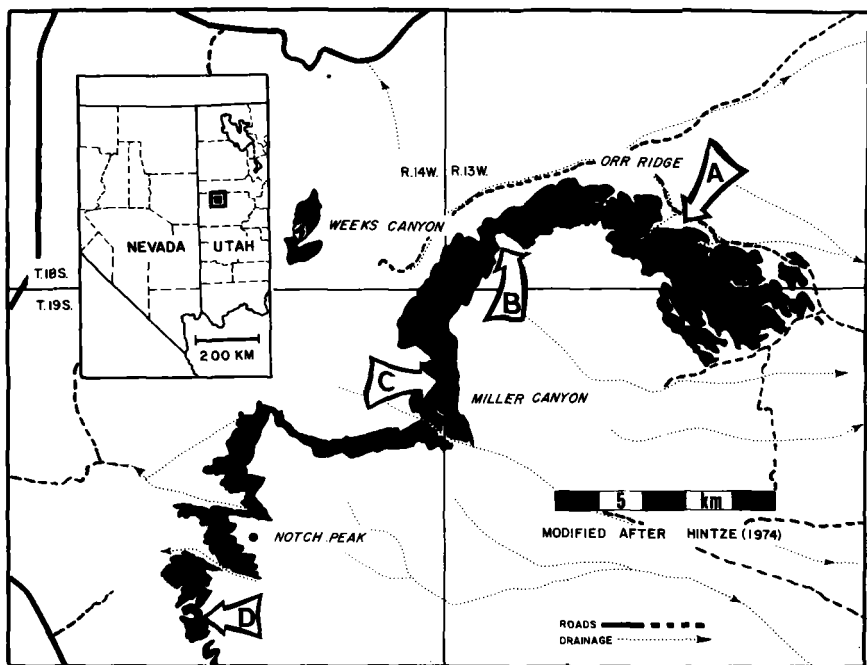
Four sections measured in the House Range of western Utah (Text-fig. 7), lie roughly perpendicular to depositional strike, as indicated by the measurement of primary depositional features including stromatolite elongation and directions of cross-bedding, slumping, and progradation. The correlation of cycle tops in these sections and the distribution of lithofacies within each cycle, illustrated in Text-figure 8, demonstrate a gradual off-platform thickening of the *Crepicephalus* Zone sedimentary interval and permit estimation of the depth ranges of each lithofacies and of the paleoslope across the platform to deep-shelf transition.

DEPTH RANGES FOR THE LITHOFACIES

Each lithofacies is formed by a unique combination of environmental factors, which are highly correlated to depth including light penetration (which



TEXT-FIGURE 6.—Regional correlation of cycles. Location of sections is illustrated in Text-figures 1 and 7.

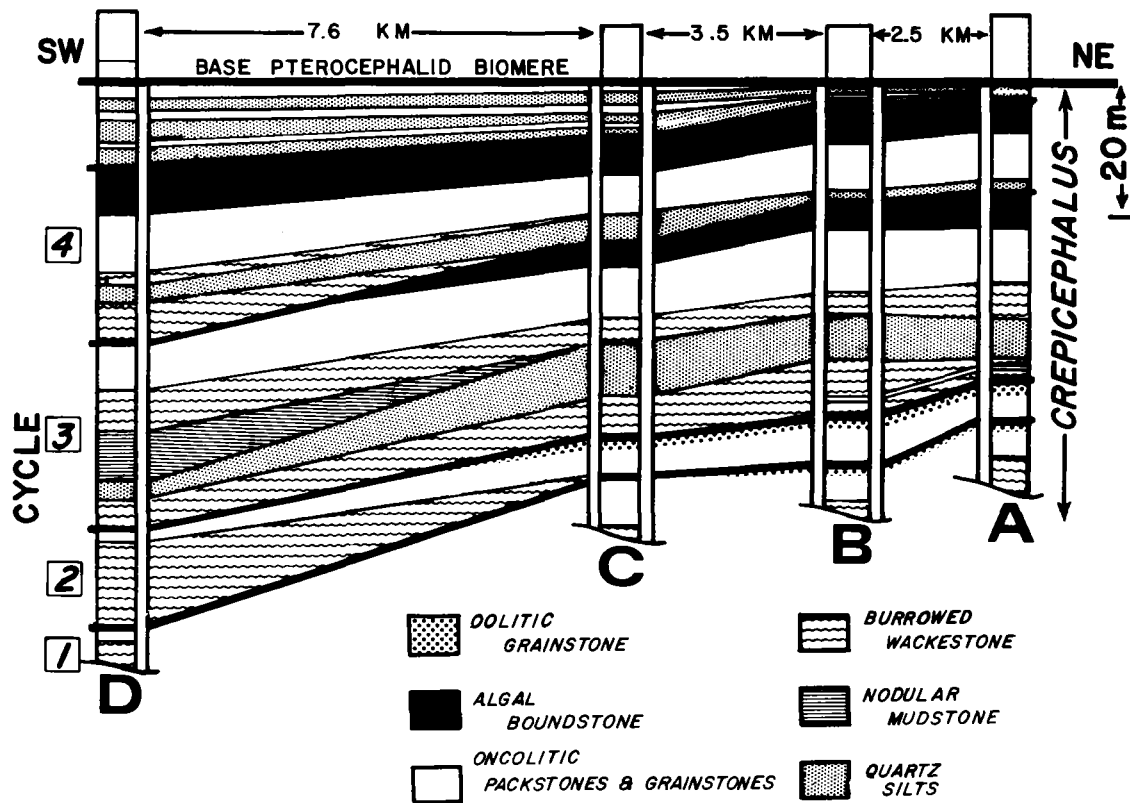


TEXT-FIGURE 7.—Outcrop map of the Big Horse Member of the Orr Formation in the House Range, Utah, with section locations used for cycle correlation (Text-figs. 6 and 8) indicated by arrows.

affects algal development), and wave energy. These factors define limits of depth zones within which a lithofacies may form. The typical cycle, described earlier, reflects an upward-shallowing succession of depositional environments, the relative depth ranges of which can be represented by distances between the boundaries of lithofacies. By examining the lithofacies progressively downward from an intertidal, zero depth datum, absolute depth ranges for each lithofacies can be determined, subject to the restriction that upward shallowing of a cycle must be produced by gradual sediment accumulation in a basin. Emergence of the basin through eustatic or tectonic shifts must not occur. Because subsidence of the basin may have continued during the shallowing, depth estimates for each lithofacies are maximum figures.

Depth estimates obtained from evaluation of detailed lithofacies distributions in the House Range as illustrated in Text-figure 8, are:

- 1) platform-margin high-energy complex (0-15 m);
 - a) algal-boundstone lithofacies (0-6 m),
 - b) skeletal- and oncolitic-packstone and grainstone lithofacies (6-15 m),
 - c) effective wave base is approximately 15 m in depth; and
- 2) deep-shelf low-energy complex (15 to greater than 30 m);



TEXT-FIGURE 8.—Correlation of cycles within the House Range, Utah, illustrating the distribution of lithofacies.

- a) burrowed-wackestone lithofacies (15-25 m),
- b) nodular-mudstone lithofacies (greater than 20 m),
- c) extension of depth estimates to the cycles of the Snake Range provides an estimate for the lower boundary of the nodular-mudstone and the upper boundary for the laminated-mudstone lithofacies (30 m). Absence of a deeper recognizable lithofacies prevents the determination of a lower boundary for the laminated-mudstone lithofacies.

Estimates of depth ranges for each lithofacies suggest the accumulation of all lithofacies at shallow to intermediate depth, typical of the depositional realm of the continental shelf.

ESTIMATES OF LOCAL PALEOSLOPE

Estimation of the paleoslope across the platform-to-basin transition requires the recognition of an upper plane reflecting original horizontality and a lower surface reflecting original topography, and knowledge of original spatial distribution of at least two sections. The westward increase in sediment thickness between sections in the House Range within a single structural block (Text-fig. 7) provides the means for a simple estimate of the local westward paleoslope. Because cycle tops, although synchronous, terminate in different lithofacies, their correlation provides the lower topographic plane. If complete infilling of the basin has occurred (as evidenced by the development of intertidal algal boundstone such as in cycle 3 of Text-figure 8), the upper horizontal plane is also provided. When the basin has not completely filled, the horizontal reference plane may be identified by determining points of equal depth in each section. As discussed above, the boundaries between lithofacies are indicative of depth; thus, correlation of a lithofacies boundary among sections constructs the needed horizontal plane. For example, consider the boundary between the burrowed-wackestone and oncolitic-skeletal-packstone and the grainstone lithofacies of cycle 3 in Text-figure 8.

For estimates of paleoslope to have some reliability, sediment compaction must be comparable in both shallow- and deeper-water lithologies. Thinning of shallow-water lithologies has occurred through stylolitization and compaction, and as much as 50 percent compaction has occurred in oolitic grainstones that occur higher in the Pterocephaliid Biome (Brady, 1975, personal communication). The shale-rich deeper-water lithofacies have undergone similar compactional shortening, as evidenced by the compactional draping of shale interbeds over lime mudstone nodules. Thus a paleoslope estimate can be realistic. Future determination of accurate compactional ratios for the lithofacies will increase precision in the paleoslope estimates given below.

Using the detailed correlation developed for the House Range, two estimates of paleoslope can be made. The first, an average slope determined by comparing the deepest section D to the shallowest section A, ranges from 0.3 to 1.5 m/km. The second estimate, a determination of slope between adjacent sections, is more sensitive to variation due to local topography, compactional differences, and measurement errors. It ranges from 0.3 to 2.4 m/km. Both estimates lie within the range of slope determined for modern continental

shelves. For example, shelf slope in the Gulf of Mexico, off the coast of Texas, ranges from 0.25 to 2.5 m/km (Irwin, 1965).

CONCLUSION

Environmental analysis of lithofacies and recognition of asymmetrical cycles of deposition can be used to improve precision of time-stratigraphic correlation and to indirectly estimate such additional environmental factors as depositional depth and paleoslopes on ancient continental shelves.

ACKNOWLEDGMENTS

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REFERENCES

- Aitken, J. D., 1967, Classification and environmental significance of crypt-algal limestones and dolomites with illustrations from the Cambrian and Ordovician of south-western Alberta: *J. Sediment. Petrol.*, v. 37, p. 1163-78.
- Coogan, A. H., 1972, Recent and ancient carbonate cyclic sequences: *in* Elam, J. G., and Chuber, S. (eds.), *Cyclic Sedimentation in the Permian Basin*: W. Texas Geol. Soc., Midland, Texas, p. 5-16.
- Eby, R. G., 1975, Early Upper Cambrian biofacies of the central Great Basin: *Geol. Soc. Amer., Abst. Prog.*, v. 7(7), p. 1063-64.
- Hintze, L. F., 1974, Preliminary geologic map of the Notch Peak Quadrangle, Millard County, Utah: U.S. Geol. Sur., Misc. Field Stud. Map MF-636.
- Irwin, M. L., 1965, General theory of epeiric clear-water sedimentation: *Amer. Assoc. Petrol. Geol. Bull.*, v. 49, p. 445-59.
- Logan, B. W., Rezak, Richard, and Ginsburg, R. N., 1964, Classification and environmental significance of algal stromatolites: *J. Geol.*, v. 72, p. 68-83.
- Lohmann, K. C., 1975, Stromatolite-thrombolite associations in shallow-water carbonates of western Utah: *Amer. Assoc. Petrol. Geol., Ann. Mtg. Abst.*, v. 2, p. 44-45.
- Palmer, A. R., 1960, Some aspects of the early Upper Cambrian stratigraphy of White Pine County, Nevada, and vicinity: *in* Boettcher, J. W., and Sloan, W. W., Jr. (eds.), *Guidebook to the Geology of East Central Nevada*: Intermountain Assoc. Petrol. Geol., 11th Ann. Field Conf., p. 53-58.
- , 1971, The Cambrian of the Great Basin and adjacent areas, western United States: *in* Holland, C. H. (ed.), *Cambrian of the New World*, Wiley-Interscience, New York, p. 1-77.
- , 1972, Discussion, Upper Cambrian faunal patterns on the craton: *Geol. Soc. Amer. Bull.*, v. 83, p. 927-30.

Depositional History of the Upper Dresbachian-Lower Franconian (Upper Cambrian) Pterocephaliid Biomere from West Central Utah

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ABSTRACT.—The study includes exposures of the Upper Dresbachian–Lower Franconian interval in the Deep Creek, Fish Springs, Dugway, and East Tintic mountains. Five environments of deposition are recognized within the study area and are designated: (1) peritidal, (2) lagoonal, (3) shoal, (4) terrigenous-platform, and (5) open shelf.

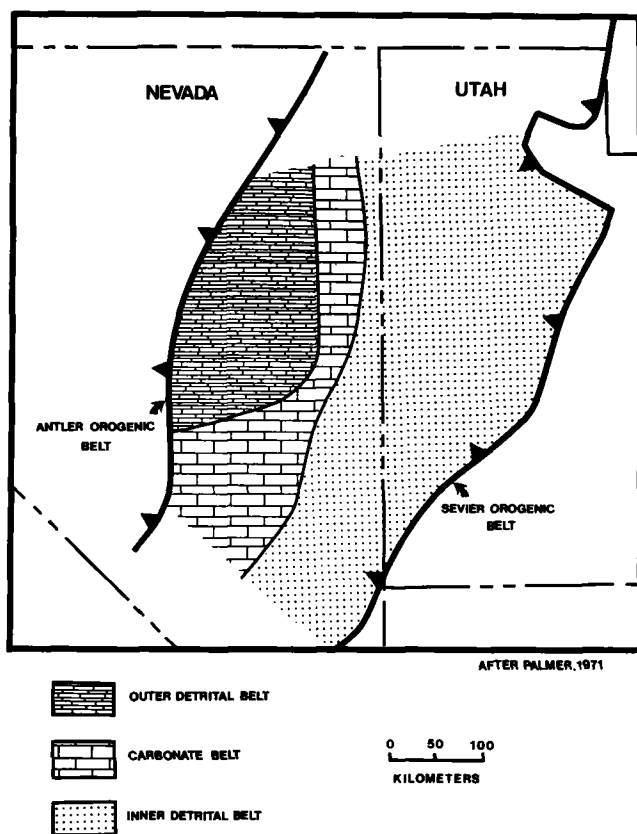
At the beginning of biomere time, lagoonal carbonates were deposited across the study area. Marine transgression, occurring in late *Aphelaspis* Zone time, spread open-shelf sediments eastward across the western half of the area. To the east, shoal, lagoonal, and peritidal carbonates accumulated, producing a shallow-marine carbonate bank. This depositional configuration persisted into early *Dunderbergia* Zone time. Subsequent westward progradation of the carbonate bank displaced open-shelf deposits beyond the western limit of the study area. This produced a broad, shallow water, carbonate platform composed of restricted-marine, lagoonal basins and areas of peritidal sedimentation. Near the end of carbonate deposition on the platform, gradual submergence reduced areas of peritidal sedimentation. By middle *Elvinia* Zone time, restricted-marine carbonate sedimentation was replaced by regional deposition of normal-marine shales of the terrigenous-platform environment. Termination of clastic deposition in late *Elvinia* Zone time permitted regional accumulation of open-shelf carbonates through the end of biomere time.

INTRODUCTION

In the past decade, biostratigraphic research has greatly increased information on Cambrian faunas and on temporal relations among Cambrian exposures in the Great Basin. Perhaps the most important work in this area is Palmer's (1971) synthesis of Cambrian physical and biostratigraphic data for the Great Basin region. Of particular interest is his discussion of lithofacies distributions and depositional environments for Middle and Upper Cambrian strata. Palmer divided these rocks into three interfingering lithofacies belts, paralleling the north-trending Cambrian shoreline. The pattern (Text-fig. 1) consists of a middle belt of shoal-water carbonates that grades into more argillaceous rocks to the east and west. The eastern or inner detrital belt is composed of shales and a few thin, arenaceous carbonates, interpreted as shallow, near-shore deposits associated with the craton margin. The western or outer detrital belt is composed of shales with numerous interbeds of thin limestones, interpreted as somewhat deeper, open-marine deposits.

Although Palmer's (1971) regional depositional model is widely accepted, there is a surprising dearth of modern sedimentological information for the Cambrian of the Great Basin. In the past four years, however, sedimentological research in this area has increased dramatically (Kepper, 1972, 1974, 1975; Koepnick and Brady, 1973, 1974; Halley, 1973; Lilley and others, 1974; Rees and others, 1974, 1976; Lohmann, 1975; Cook and Taylor, 1975; Moore, 1975), yet much remains to be learned about Cambrian depositional environments in the Great Basin region.

The objective of this report is to present a depositional model for the late Dresbachian–early Franconian interval in west-central Utah. The basic

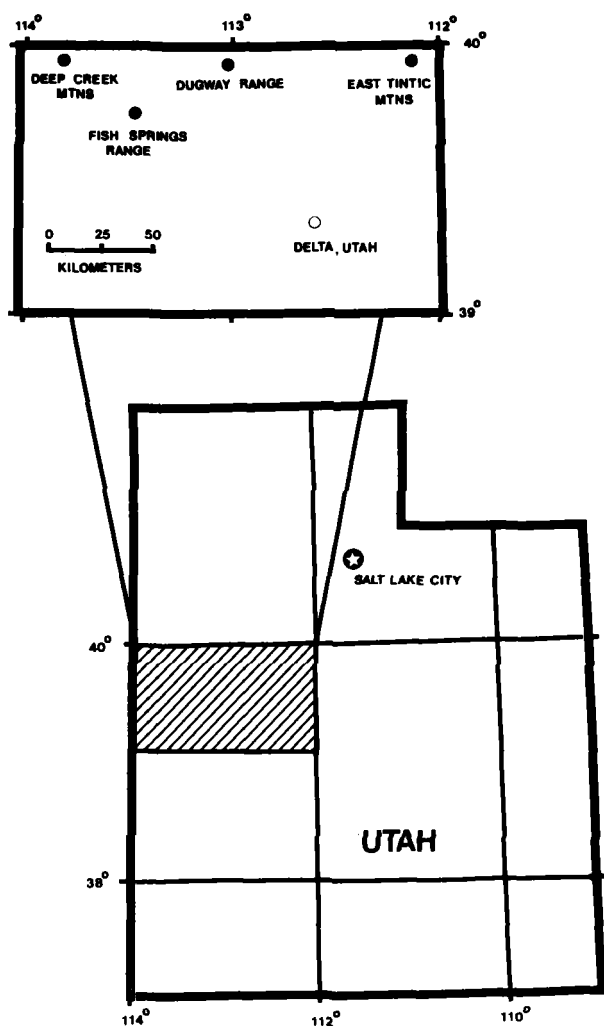


TEXT-FIGURE 1.—Lithofacies belt patterns for the Middle *Elvinia* Zone. Text-figure shows the northward regional depositional trends inferred for the Upper Cambrian of the Great Basin.

data on which the following interpretations are based are presented in Koepnick (1976). The area of investigation includes exposures in the Deep Creek, Fish Springs, Dugway, and East Tintic mountains (Text-fig. 2). The study area forms a 144 km transect across west-central Utah at high angle to the north-trending Cambrian depositional strike. The study interval is encompassed by the Ptercephaliid Biomere (Palmer, 1965) representing one of the best-documented Cambrian biostratigraphic units in the Great Basin. The biomere contains a related sequence of nonagnostid trilobite faunas which provide the temporal framework for the study (Text-fig. 3). Diverse stratigraphic nomenclature has been applied to the rocks within the study area. The nomenclature and the biostratigraphy are summarized in Text-figure 4.

ENVIRONMENTS OF DEPOSITION

Five environments of deposition are recognized within the study area and are designated: 1) peritidal, 2) lagoonal, 3) shoal, 4) terrigenous-plat-



TEXT-FIGURE 2.—Index map for the study area.

form, and 5) open shelf. Rocks of the peritidal, lagoonal, and shoal environments constitute a shallow-marine carbonate bank complex represented by the Johns Wash Limestone of the Deep Creek and Fish Springs ranges, and by the Upper Straight Canyon and Lower Fera formations in the Dugway Range. Shales and thin limestones of the terrigenous-platform environment overlie the carbonate bank complex and are represented by the Corset Springs Shale of the Deep Creek and Fish Springs ranges, by the major shale in the Fera Formation of the Dugway Range, and by the shaly interval in the Opex Formation of the East Tintic Mountains. The open-shelf environment is represented by the Dunderberg and Candland shales of the Deep Creek and Fish

	TAENICEPHALUS ZONE
PTEROCEPHALIID BIOMERE	ELVINIA ZONE
	DUNDERBERGIA ZONE
	PREHOUSIA ZONE
	DICANTHOPYGE ZONE
	APHELASPIS ZONE
	CREPICEPHALUS ZONE

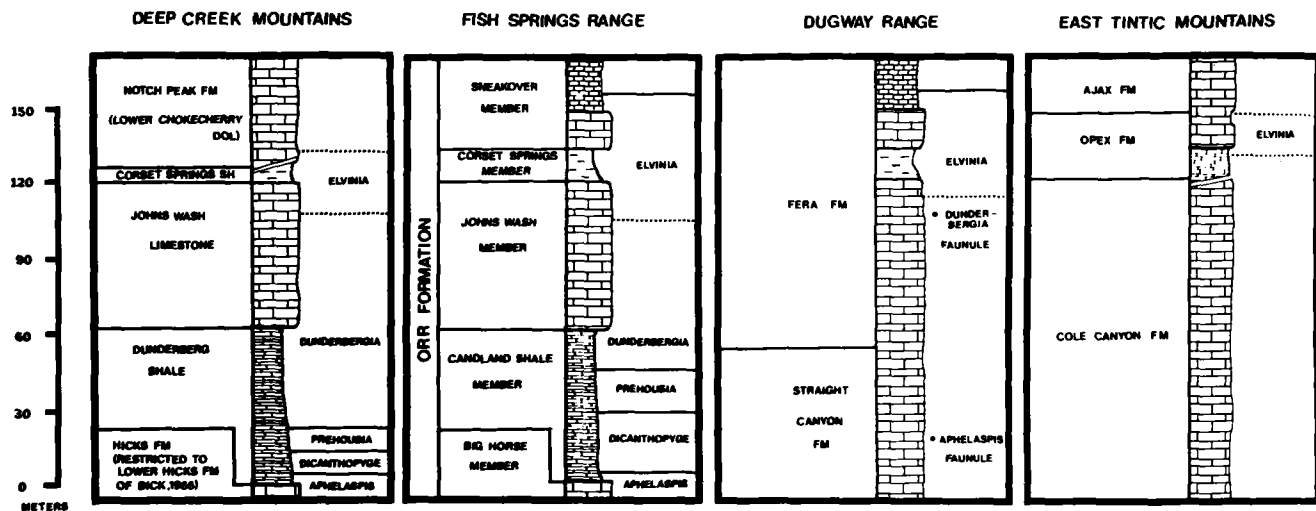
TEXT-FIGURE 3.—Trilobite faunal zonation within the Pterocephaliid Biomere.

Springs ranges, the Lower Sneakover Limestone in the Fish Springs Range, the Upper Fera Formation in the Dugway Range, and the Upper Opex Formation in the East Tintic Mountains.

Peritidal environment.—Carbonates within the peritidal environment are commonly recognized in modern and ancient intertidal and supratidal deposits (Matter, 1967; Roehl, 1967; Laporte, 1971; Kendall and Skipwith, 1969; Shinn and others, 1969; Heckel, 1972). Within the study area, tidal-flat carbonates are often intimately interbedded with very shallow subtidal deposits. Thus, the term "peritidal" is used to acknowledge this association while describing the dominant characteristics of this environment.

Fine-grained, laminated dolomite, pellet grainstone with fenestral fabric (Tebbutt and others, 1965), and intraclast lime grainstone with rip-up clasts of laminated dolomite comprise the principal rock types in this environment. Dolomites commonly exhibit shrinkage cracks and millimeter-scale lamination reminiscent of planar stromatolites (Davies, 1970). The presence of shrinkage cracks and fenestral fabrics in these carbonates indicates periodic exposure and drying of sediments, as would be expected on intertidal and supratidal flats (Shinn, 1968; Laporte, 1971; Heckel, 1972).

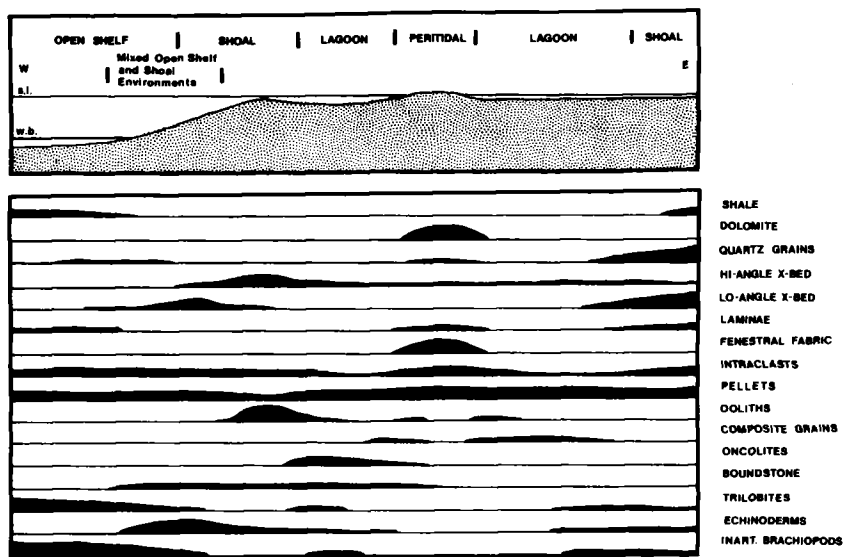
Dolomitization is interpreted as a penecontemporary process affecting carbonate sediments deposited on supratidal flats. Undolomitized carbonates exhibiting desiccation features and fenestral fabrics are interpreted as intertidal deposits. Intertidal carbonates are commonly interbedded with limestones lacking desiccation features and containing ooliths, oncolites, and skeletal debris



TEXT-FIGURE 4.—Regional summary of stratigraphic nomenclature and biostratigraphy for the Pterocephaliid Biome. Dashed lines to the right of the stratigraphic columns represent inferred trilobite faunal boundaries.

typical of subtidal deposits. Intraclast lime grainstones also contain abundant constituents characteristic of subtidal carbonates and are interpreted to represent sedimentation in tidal channels.

Lagoonal environment.—The lagoonal environment is represented by shallow-subtidal, sparsely fossiliferous marine carbonates deposited landward of shoal and open-shelf environments (Text-fig. 5). Peritidal, lagoonal and shoal environments comprise a shallow-marine bank (Text-fig. 5) that was extant from *Dicathopyge* Zone time to early *Elvinia* Zone time in the central and western part of the study area. Oolitic and bioclastic grainstones of the shoal environment accumulated along the seaward margin of the bank, producing topographic relief locally. The interior of the bank was composed of a series of subtidal basins interspersed with areas of peritidal sedimentation. The shallow-carbonate platform attained a maximum east-west dimension of 80 kilometers during late *Dunderbergia*-early *Elvinia* Zone time. Bank marginal relief and the physical extent of the shallow platform damped out ocean waves moving onto the bank. Consequently, exchange of normal-marine water with water of the interior lagoon was inhibited, resulting in the accumulation of unfossiliferous, pellet, composite-grain lime packstone and grainstone. The composite grains in these carbonates closely resemble modern grapestone (Purdy, 1963; Taylor and Illing, 1969; Windland and Matthews, 1974). Sparsely fossiliferous lime packstone and grainstone were deposited over less-restricted parts of the lagoon.



TEXT-FIGURE 5.—Distribution of biotic and inorganic constituents and primary depositional structures across the carbonate bank. The text-figure illustrates the position of depositional environments with respect to idealized bank topography and indicates the inferred relation of topography to mean sea level (s.l.) and normal wave base (w.b.). Width of dark areas proportional to the relative abundance of the constituents.

Shoal environment.—The shoal environment is interpreted as a shallow-subtidal, high-energy environment containing oolitic, bioclastic, and pelletoidal grainstones. This environment is principally developed along the seaward margin of the carbonate bank, but also occurs along the eastern edge of the study area, where it is associated with the craton margin (Text-fig. 5).

Oolitic grainstone typically represents the crest of high-energy shoals along the seaward margin of the carbonate bank complex. Storms moving across the bank margin occasionally piled oolitic sediment above normal high-tide level. This process is suggested by the presence of large, low-angle cross-bed sets and horizontally stratified units interpreted as foreshore and backshore beach deposits (Harms and others, 1975). Furthermore, layers of carbonate mudstone exhibiting desiccation features are interbedded with the oolitic grainstones and may represent peritidal deposits associated with the crest of the bank margin.

High angle, tabular, and festoon crossbeds are typical depositional structures in bioclastic grainstones deposited on the proximal part of the seaward flank of the bank margin (Text-fig. 5). These carbonates are interpreted as middle to upper shoreface deposits. Pelletoidal grainstones, exhibiting low-angle, hummocky cross stratification (Harms and others, 1975: p. 87), characterize the more seaward, lower shoreface, and offshore deposits.

The distribution of rock types and general environmental interpretation is similar to that developed for Mississippian carbonates of southwestern Illinois by Carozzi and Roache (1967), and is consistent with the findings of Ball (1967) for shelf marginal sand bodies on the Bahama platform.

Terrigenous-platform environment.—The terrigenous-platform environment is composed of fossiliferous, glauconitic shales with occasional interbeds of bioclastic lime packstone, graded pelletoidal grainstone, and rounded-pebble conglomerate. These units were deposited in a shallow, low-energy marine environment overlying the carbonate bank complex.

The greatly increased faunal content of the terrigenous-platform sediments, as compared with underlying lagoonal carbonates, indicates improved marine circulation developed with initiation of clastic deposition. Although clastic sedimentation precluded carbonate deposition over most of the region, *in situ* accumulation of bioclastic lime packstone occurred where clastic sedimentation rates were low. Periods of traction transport and erosion are indicated for some carbonate units by the presence of internal erosion surfaces, graded bedding, angular intraclasts, and cross-bedding. These sedimentary features are interpreted as evidence for storm transport and deposition on the shallow-marine platform. However, storm transport cannot account for the high degree of clast rounding in conglomeratic units. Rounding appears to be the product of wave abrasion in an intertidal environment. Similarly rounded clasts and conglomeratic sediments are known from modern terrigenous-tidal flats (Van Straaten, 1954; Evans, 1958; Reineck, 1967). However, the presence of glauconite and abundant skeletal debris in terrigenous-platform sediments indicates that marine conditions were widespread. The occurrence of rounded pebbles in conglomerates probably indicates the existence of local shoals.

Water depths are thought to have remained shallow throughout the deposition of terrigenous-clastic sediments. This is suggested by evidence indicating intertidal shoals, numerous units with evidence of traction transport,

and cross-bedded grainstones and domal stromatolites in units immediately overlying terrigenous-platform deposits.

Open-shelf environment.—This environment is composed of limestones and shales deposited under low-energy, normal-marine conditions. Rocks in this environment are divided into autochthonous and allochthonous groups (Cook and others, 1972). Autochthonous deposits accumulated largely *in situ*, whereas allochthonous units are composed of resedimented material transported from adjacent depositional environments.

Autochthonous rock types include trilobite packstone; echinoderm, trilobite packstone, and wackestone; renaloid boundstone; and fissle shale. The presence of abundant and unabraded skeletal debris, shale, and fine-grained carbonate sediment suggests a normal-marine environment with low-energy bottom conditions. Also, interbedded units of elongate, nonlaminated boundstone display a morphology commonly developed under low-energy subtidal conditions (Aitken, 1967; Ahr, 1972; Riding and Toomey, 1972).

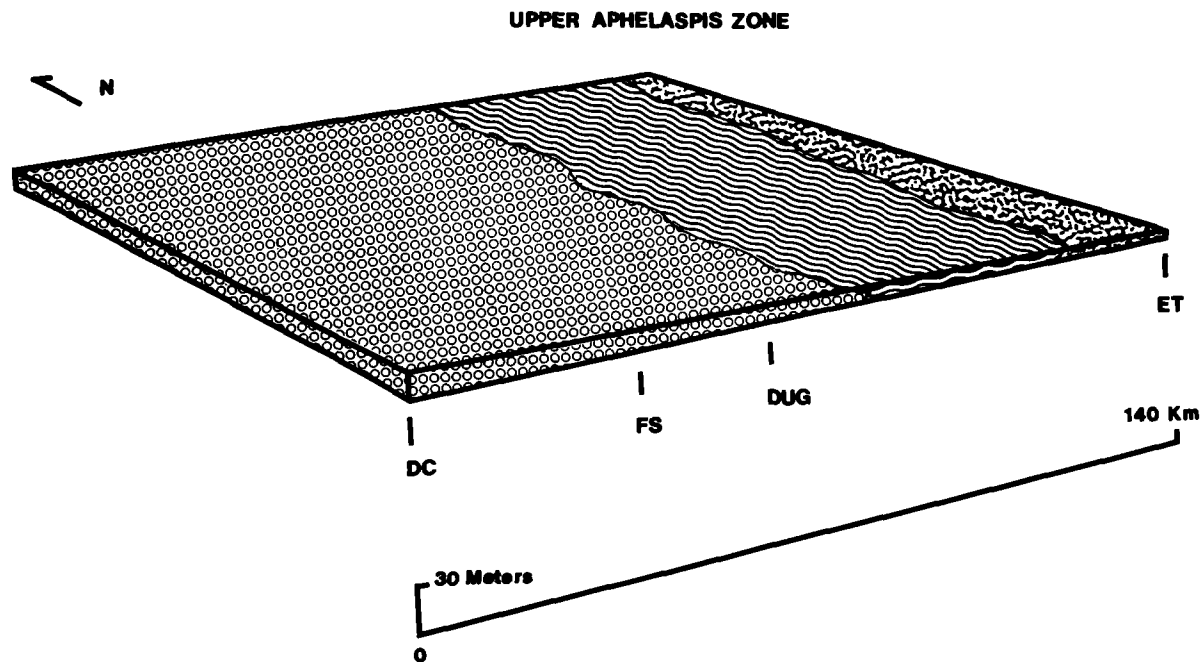
In the Dunderberg and Candland shales of the Deep Creek and Fish Springs ranges, open-shelf deposits are mainly composed of shale with thin interbeds of trilobite packstone. These sediments accumulated seaward of the carbonate bank and were thus unprotected from open-ocean wave action. In order to accumulate shales and fine-grained carbonate sediment under these conditions, deposition must occur below normal wave base (Irwin, 1965; Heckel, 1972; Wilson, 1974).

Allochthonous carbonates are restricted to the Dunderberg and Candland shales of the Deep Creek and Fish Springs ranges. These deposits include echinoderm grainstone and flat-pebble conglomerate. Allochthonous carbonates fit Meichner's (1964, p. 174) definition of allodapic limestones in that the deposits are composed of shallow water, carbonate constituents transported into a contemporaneous, deeper-water depositional environment. For example, echinoderm grains are absent from the limestones and shales interbedded with allochthonous carbonates. Thus, echinoderm grains in allochthonous units are exotic constituents, probably derived from the adjacent, echinoderm-rich shoal environment. Flat-pebble conglomerates also contain abundant echinoderm grains, and exhibit intraclasts of carbonate mudstone unlike any lithology in the open-shelf environment. The only similar carbonates are interbedded with oolitic grainstones of the shoal environment.

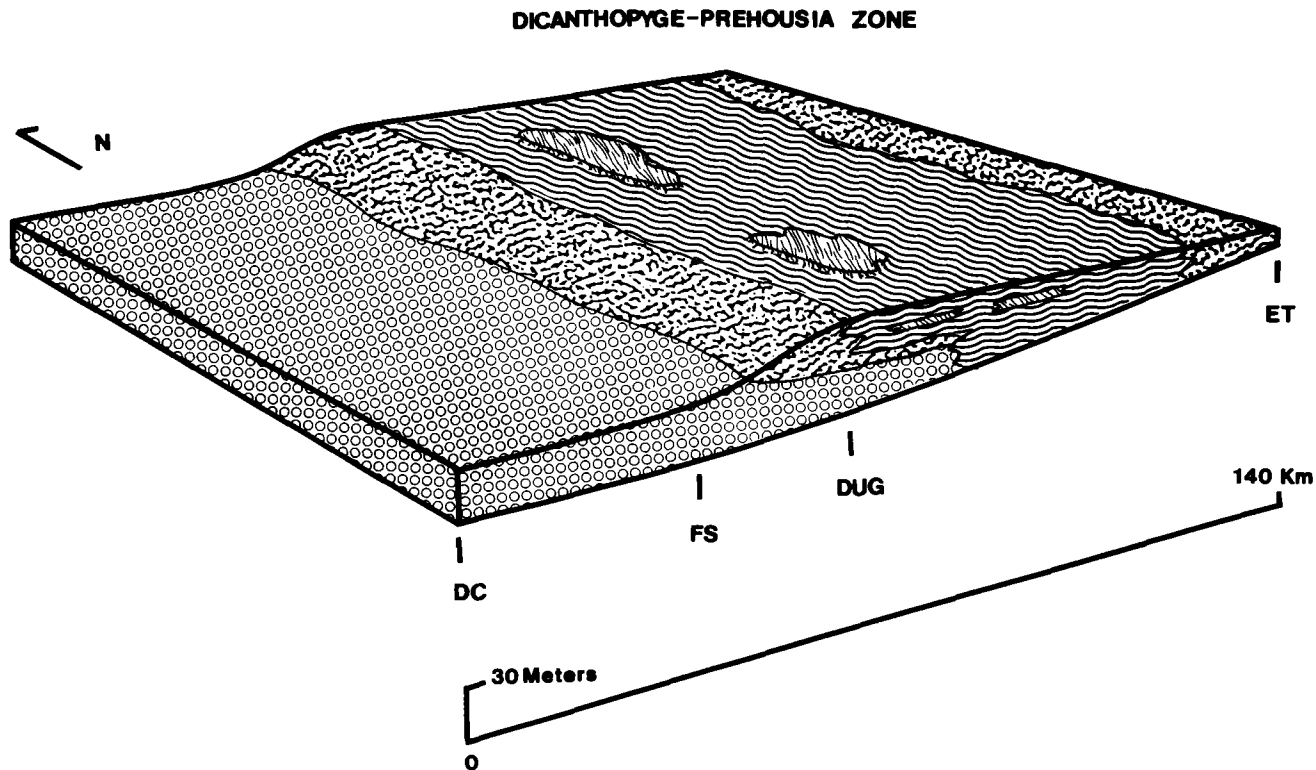
DEPOSITIONAL HISTORY

At the beginning of Pterocephaliid Biomere time, shoal water and lagoonal carbonates were deposited across the study area. During late *Aphelaspis* Zone time, marine transgression spread open-shelf carbonates and shales across the western half of the region (Text-fig. 6). Carbonates of the shoal environment persisted in the East Tintic region, and contain abundant detrital quartz reflecting proximity to the arenaceous craton margin to the east.

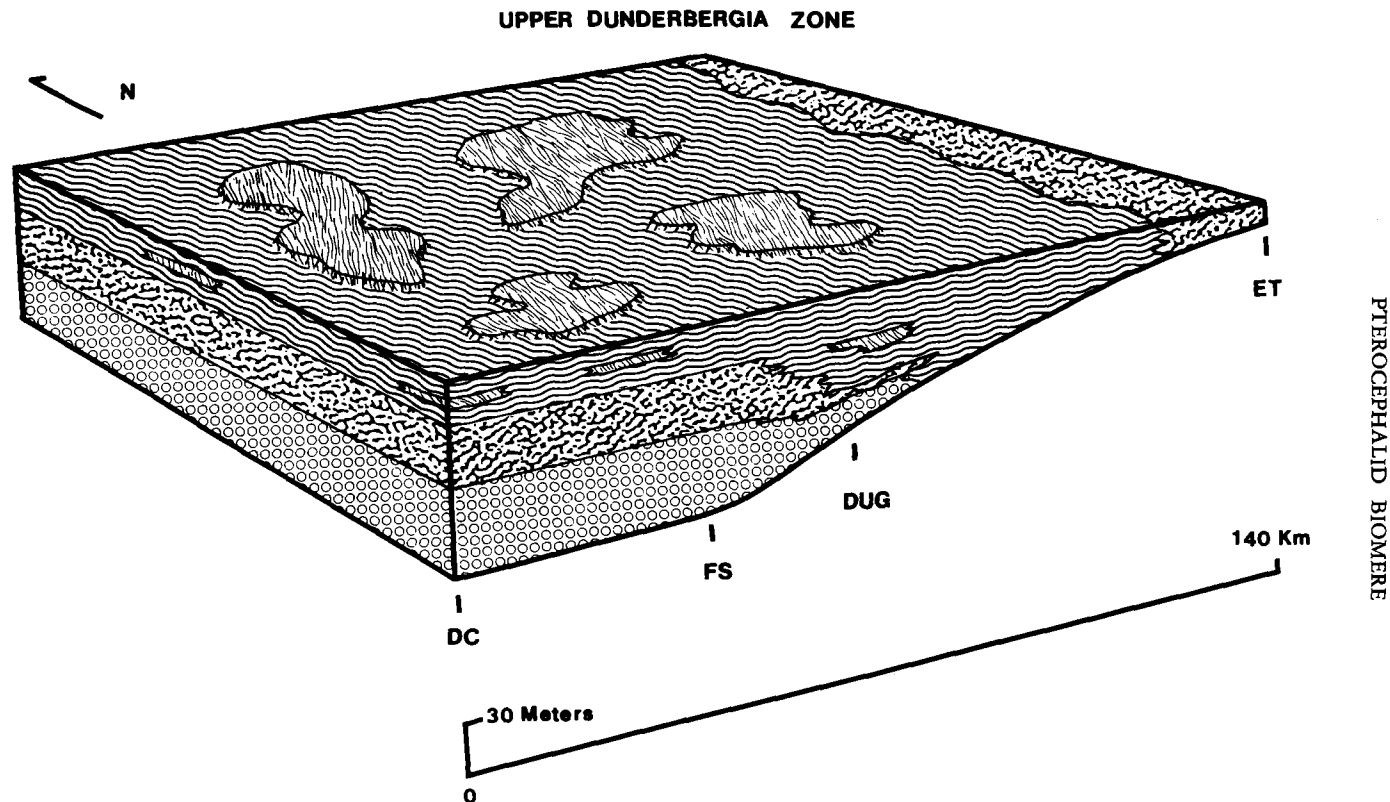
During *Dicanthopyge* Zone time (Text-fig. 7), progradation and up-building of shoal, lagoonal, and peritidal carbonates occurred in the Dugway Range area, producing a shallow-marine carbonate bank complex. Development of the carbonate bank produced a differentiated, seaward sloping, carbonate platform with fossiliferous open-shelf sediments to the west and



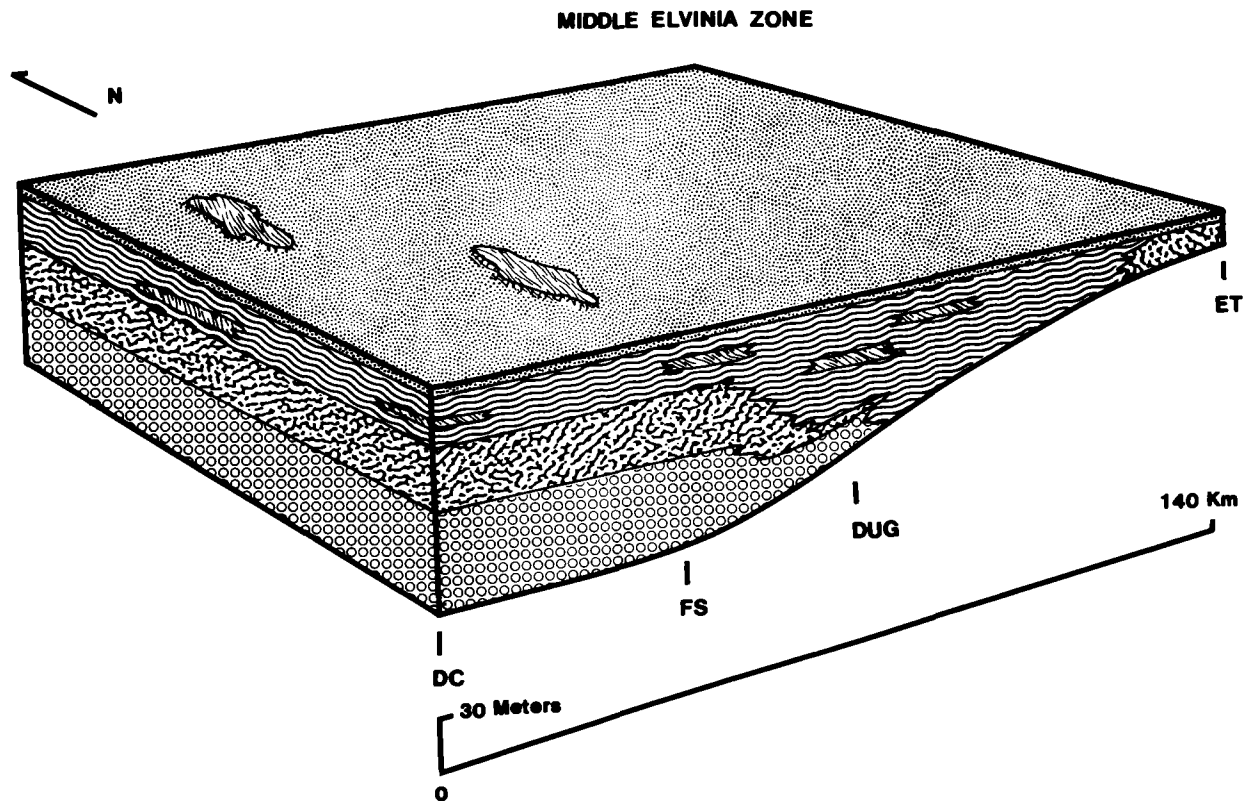
TEXT-FIGURE 6.—Block diagram depicting the distribution of depositional environments for the Upper *Aphelaspis* Zone. Positions of exposures in the study area are indicated: DC—Deep Creek Range, FS—Fish Springs Range, DUG—Dugway Range, and ET—East Tintic Mountains. Environments of deposition are indicated: irregular lined pattern—peritidal, dark wavy lined pattern—lagoonal, mottled pattern—shoal, stippled pattern—terrigenous platform, open circle pattern—open-shelf.



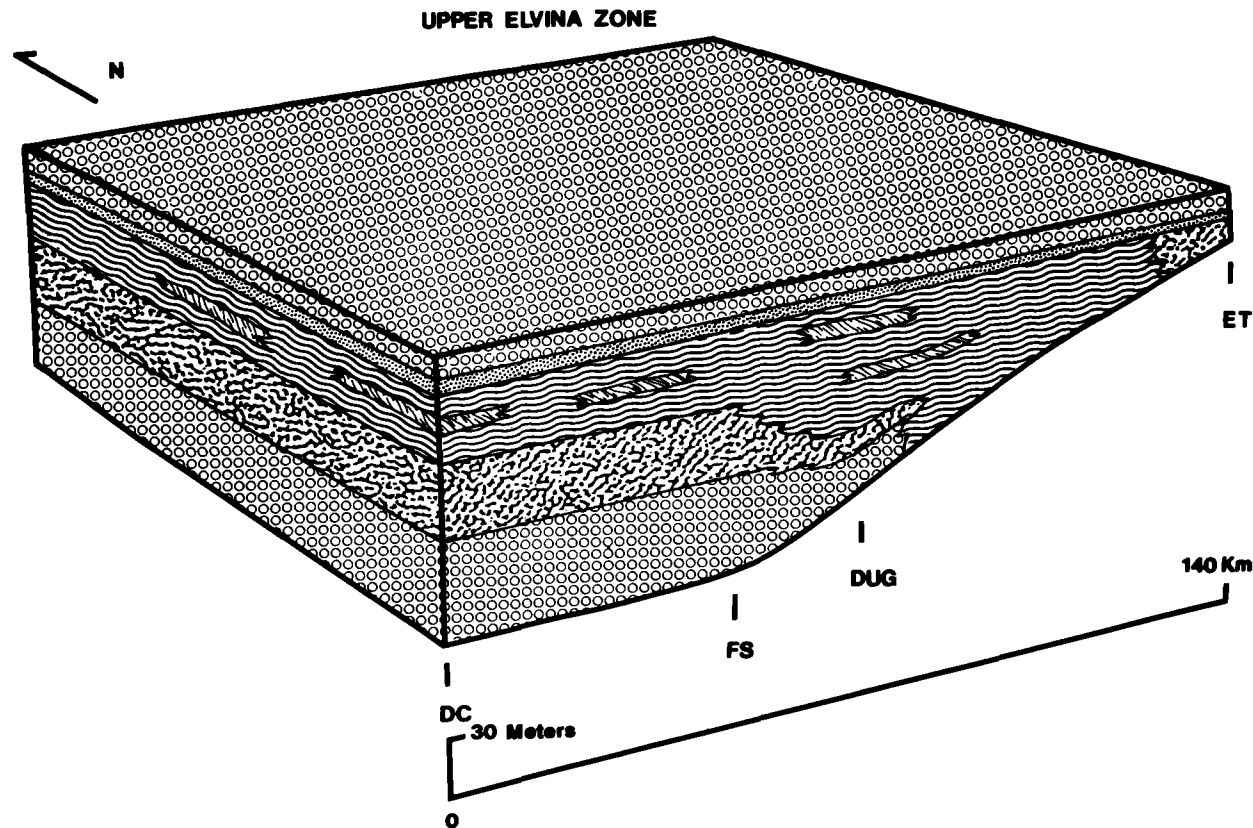
TEXT-FIGURE 7.—Block diagram depicting the cumulative depositional history through the *Prehousia* Zone. Upper surface of diagram indicates the distribution of depositional environments for the *Dicantrophyge* and *Prehousia* Zones. Explanation of symbols given in Text-figure 6.



TEXT-FIGURE 8.—Block diagram depicting the cumulative depositional history through the Upper *Dunderbergia* Zone. Upper surface of diagram indicates the distribution of depositional environments for the Upper *Dunderbergia* Zone. Explanation of symbols given in Text-figure 6.



TEXT-FIGURE 9.—Block diagram depicting the cumulative depositional history through the Middle *Elvinia* Zone. Upper surface of diagram indicates the distribution of depositional environments for the Middle *Elvinia* Zone. Explanation of symbols given in Text-figure 6.



TEXT-FIGURE 10.—Block diagram depicting the cumulative depositional history through the Upper *Elvinia* Zone. Upper surface of diagram indicates the distribution of depositional environments for the Upper *Elvinia* Zone. Explanation of symbols given in Text-figure 6.

arenaceous deposits to the east. This depositional configuration persisted through the *Prehousia* Zone and into early *Dunderbergia* Zone time.

Rapid progradation of carbonate-bank deposits during middle to late *Dunderbergia* Zone time (Text-fig. 8) displaced open-shelf sediments beyond the western edge of the study area. By early *Elvinia* Zone time, a broad, shallow-water carbonate platform consisting of a series of subtidal, lagoonal basins interspersed with areas of peritidal sedimentation was developed across the western two-thirds of the study area.

Near the end of carbonate-bank sedimentation (middle to late *Elvinia* Zone time), areas of peritidal sedimentation were substantially reduced, to be replaced by lagoonal depositional environments. Submergence of the carbonate platform resulted in elimination of peritidal deposition in the vicinity of the Dugway Range and restriction of remaining peritidal environments to local areas in the vicinity of the Deep Creek and Fish Springs ranges. However, the basin and tidal flat topography of the carbonate bank was partially retained as local shoals persisted into the succeeding clastic depositional phase (Text-fig. 9).

Carbonate sedimentation on the platform was terminated by influx of terrigenous sediments. Onset of clastic deposition marked a return to less-restricted marine conditions as gradual submergence of the platform continued. Termination of clastic sedimentation (late *Elvinia* Zone time) permitted regional deposition of open-shelf carbonates (Text-fig. 10). As a result of marine transgression, open-shelf carbonates spread to the East Tintic region, displacing arenaceous, craton-margin deposits beyond the eastern limit of the study area. Initial carbonate deposits indicate that agitated bottom conditions prevailed, reflecting the maintenance of shallow-water conditions following the terrigenous depositional phase. Shallow-water carbonate sedimentation continued for the remainder of Pterocephaliid Biomere time, although quieter water depositional conditions generally prevailed.

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REFERENCES

- Ahr, W. M., 1971, Paleoenvironment, algal structures and fossil algae in the Upper Cambrian of central Texas: *J. Sediment. Petrol.*, v. 41, p. 205-16.
- Aitken, J. D., 1967, Classification and environmental significance of cryptalgal limestones and dolomites, with illustrations from the Cambrian and Ordovician of southwestern Alberta: *J. Sediment. Petrol.*, v. 37, p. 1163-78.
- Ball, M. M., 1967, Carbonate sand bodies of Florida and the Bahamas: *J. Sediment. Petrol.*, v. 37, p. 556-91.
- Brady, M. J., and Rowell, A. J., 1975, An Upper Cambrian subtidal blanket carbonate, Eastern Great Basin: *Geol. Soc. Amer. Abst. Prog.*, v. 7, p. 1000-07.
- Carozzi, A. V., and Roache, J. E., 1968, Petrography of selected Chestrian (Visean-Namurian) biocalcarenites, type area in southwestern Illinois: *Trans. Illinois State Acad. Sci.*, v. 61, p. 182-200.

- Cook, H. E., McDaniel, P. N., Mountjoy, E. W., and Pray, L. C., 1972, Allochthonous carbonate debris flows at Devonian bank ("reef") margins Alberta, Canada: *Can. Petrol. Geol. Bull.*, v. 20, p. 439-97.
- , and Taylor, M. E., 1975, Slope environments of a Cambrian-Ordovician continental margin, Western United States: *Geol. Soc. Amer. Abst. Prog.*, v. 7, p. 1037.
- Davies, G. R., 1970, Algal-laminated sediments, Gladstone Embayment, Shark Bay, Western Australia: in Logan, B. W., and others, (eds.), *Carbonate Sediments and Environments*, Shark Bay, Western Australia: *Amer. Assoc. Petrol. Geol. Mem.* 13, p. 169-205.
- Evans, G., 1958, Some aspects of recent sedimentation in the Wash: *Eclogae Geol. Helv.*, v. 51, p. 508-15.
- Halley, R. B., 1973, Repetitive carbonate-bank development and subsequent terrigenous inundation: Cambrian Carrara Formation, Southern Great Basin: (Abs.) *Amer. Assoc. Petrol. Geol. Bull.*, v. 57, p. 782.
- Harms, J. C., Southard, J. B., Spearing, D. R., and Walker, R. G., 1975, Depositional environments as interpreted from primary sedimentary structures and stratification sequences: *Soc. Econ. Paleont. Miner. Short Course 2*, Dallas, 161 p.
- Heckel, P. H., 1972, Recognition of ancient shallow marine environments: in Rigby, J. K. and Hamblin, W. K. (eds.), *Recognition of Ancient Sedimentary Environments*: *Soc. Econ. Paleont. and Miner. Spec. Pub.* 16, p. 226-86.
- Irwin, M. L., 1965, General theory of eperic clear water sedimentation: *Amer. Assoc. Petrol. Geol. Bull.*, v. 49, p. 445-59.
- Kendall, C. G., St. C., and Skipwirth, P. A. d'E., 1969, Holocene shallow water carbonate and evaporite sediments of Khor al Bazam, Abu Dhabi, southwest Persian Gulf: *Amer. Assoc. Petrol. Geol. Bull.*, v. 53, p. 841-69.
- Kepper, J. C., 1972, Paleoenvironmental patterns in Middle to Lower Cambrian interval in Eastern Great Basin: *Amer. Assoc. Petrol. Geol. Bull.*, v. 56, p. 503-27.
- , 1974, Origin of massive banded carbonates with "bluebird structures" in the Cambrian of the eastern Great Basin: *J. Sediment. Petrol.*, v. 44, p. 1251-61.
- , 1975, Is the Middle Cambrian carbonate belt in the Basin and Range region an algal biostrome?: *Geol. Soc. Amer. Abst. Prog.*, v. 7, p. 1144.
- Koepnick, R. B., and Brady, M. J., 1973, Paleoenvironmental analysis of carbonate lithofacies in the Middle Cambrian Marjum Formation, House Range, Utah: a shelf to basin transition: *Geol. Soc. Amer. Abst. Prog.*, v. 5, p. 327-28.
- , 1974, Allochthonous carbonates of the Upper Cambrian Candland Shale Member of the Orr Formation, Fish Springs Range, Utah: *Amer. Assoc. Petrol. Geol. and Soc. Econ. Paleont. Miner. Ann. Mtg. Abst.*, v. 1, p. 54.
- , 1976, Paleoenvironmental analysis of the Upper Cambrian (Upper Dresbachian-Lower Franconian) Pteroccephaliid biomere from west central Utah: unpubl. Ph. D. thesis, University of Kansas, Lawrence, Kansas, 143 p.
- Laporte, L. F., 1971, Paleozoic carbonate facies of the central Appalachian shelf: *J. Sediment. Petrol.*, v. 41, p. 724-40.
- Lilley, W. E., Brady, M. J., and Rowell, A. J., 1974, Upper Cambrian Paleoenvironments for shelf to basinal carbonate lithofacies transitions in west central Utah and east central Nevada: *Geol. Soc. Amer. Abst. Prog.*, v. 5, p. 112-13.
- Lohmann, K. C., 1975, Carbonate platforms margin sedimentation: Dresbachian of eastern Nevada and western Utah: *Geol. Soc. Amer. Abst. Prog.*, v. 7, p. 1174.
- Matter, Albert, 1967, Tidal flat deposits in the Ordovician of western Maryland: *J. Sediment. Petrol.*, v. 37, p. 601-09.
- Meischner, K. D., 1964, Allodapische kalke, turbidite in riff-nahen sedimentationsbacken: in Bouma, A. H., and Brouwer, A. (eds.), *Developments in Sedimentology*, Elsevier, Amsterdam, v. 3, p. 156-91.
- Moore, J. N., 1975, Depositional environments of the Lower Cambrian Poleta Formation and its stratigraphic equivalents, California and Nevada: *Geol. Soc. Amer. Abst. Prog.*, v. 7, p. 1204.
- Palmer, A. R., 1965, Trilobites of the Late Cambrian Pteroccephaliid Biomere in the Great Basin, United States: *U. S. Geol. Surv. Prof. Paper* 439, 105 p.
- , 1971, The Cambrian of the Great Basin and adjacent areas, western United States: in Holland, C. H. (ed.), *Cambrian of the New World*, John Wiley & Sons, Wiley Interscience Series, New York, p. 1-78.
- Purdy, E. G., 1963a, b, Recent carbonate facies of the Great Bahama Bank: 1. Petrograph and reaction groups, 2. Sedimentary facies: *J. Geol.*, v. 71, p. 334-55, 472-97.

- Rees, M. N., Brady, M. J., and Rowell, A. J., 1974, Depositional environments of the Upper Cambrian Johns Wash Limestone Member (House Range, Utah): *Geol. Soc. Amer. Abst. Prog.*, v. 5, p. 112-13.
- , 1976, Depositional environments of the Upper Cambrian Johns Wash Limestone (House Range, Utah): *J. Sediment. Petrol.*, v. 46, p. 38-47.
- Reineck, H. E., 1967, Layered sediments of tidal flats, beaches and shelf bottoms of the North Sea: *in* Lauff, G. H. (ed.), *Estuaries*, Am. Assoc. Adv. Sci. Pub., Washington, D. C., v. 83, p. 191-206.
- Riding, R., and Toomey, D. F., 1972, The sedimentological role of *Epiphyton* and *Renalcis* in Lower Ordovician mounds, southern Oklahoma: *J. Paleont.*, v. 40, p. 507-19.
- Roehl, P. O., 1967, Carbonate facies, Williston Basin and Bahamas: *Amer. Assoc. Petrol. Geol. Bull.*, v. 51, p. 1979-2032.
- Shinn, E. A., 1968, Practical significance of birdseye structures in carbonate rocks: *J. Sediment. Petrol.*, v. 38, p. 612-16.
- , Lloyd, R. M., and Ginsburg, R. N., 1969, Anatomy of a modern carbonate tidal flat, Andros Island, Bahamas: *J. Sediment. Petrol.*, v. 39, p. 1202-25.
- Taylor, J. M. C., and Illing, L. V., 1969, Holocene intertidal calcium carbonate cementation, Qatar, Persian Gulf: *Sedimentology*, v. 12, p. 69-107.
- Tebbutt, G. E., Conley, C. D., and Boyd, D. W., 1965, Lithogenesis of a distinctive carbonate rock fabric: *in* Parker, R. B. (ed.), *Contributions to Geology*, Univ. Wyoming, Laramie, Wyo., 1-13.
- Van Straaten, L. M. J. U., 1954, Composition and structure of recent marine sediments in the Netherlands: *Liedse. Geol. Mededel.*, v. 19, p. 1-110.
- Wilson, J. L., 1974, Characteristics of carbonate-platform margins: *Amer. Assoc. Petrol. Geol. Bull.*, v. 58, p. 810-24.
- Windland, D. H., and Matthews, R. K., 1974, Origin and significance of grapestone, Bahama Islands: *J. Sediment. Petrol.*, v. 44, p. 921-27.

Outer Shelf Communities and Trophic Groups in the Upper Cambrian of the Great Basin

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ABSTRACT.—Faunal associations in the lower and middle *Dunderbergia* Zone in the central Great Basin suggest the presence of two communities; an open-shelf community living at moderate water depths under normal-marine conditions and a "shoaling" shelf community, living in somewhat shallower water, associated with the beginning of carbonate progradation during late Dresbachian time. The frequent recurrence of the same association of species supports the conclusion that in each instance the benthic organisms were living together under similar ecological conditions.

The open-shelf community is dominated by the trilobites *Cernuolimbus granulosus*, *Pseudagnostus communis*, *Apbelotoxon* sp., *Dunderbergia anyta*, *Erixanium* sp., and *Pterocephalia punctata*, in order of decreasing commonness. They are associated with abundant acrotretide and lingulide brachiopods. The problematic mollusc *Pelagiella* is rare. The shoaling shelf community is dominated by *Strigambitus utahensis*, *Strigambitus transversus*, *Dytremacephalus granulosus*, *Elburgia granulosa*, *Dunderbergia bigranulosa*, and *Homagnostus* sp., in order of decreasing commonness. Acrotretide and lingulide brachiopods are also abundant.

Differences in ornament of principal species in the two communities may be significant. Trilobites of the shoaling shelf community are granular, and the granules are typically much coarser than those present on trilobites in the open-shelf community. The granules are interpreted as coarse tubules that formed the bases of attachment for dorsal tactile setae. These setae would have aided the organisms in burrowing under a thin layer of sediment.

Fossil representatives of the two shelf communities belong to three major coexisting trophic groups of differing habit, whose distribution was controlled primarily by their own ecological requirements and tolerances. They were deposit-feeding polymeroid trilobites, suspension-feeding inarticulate brachiopods, and agnostoid trilobites of different but uncertain habit. Within the Cambrian shelf communities, competition between these trophic groups was virtually nonexistent. Although competition between the inarticulate brachiopods is believed to have been minimal, the polymeroid trilobites probably exhibited competitive behavior. Such behavior would have resulted in well-defined niches with little overlap, a conclusion that is supported by the form of the dominance-diversity curves for samples of these trilobites. Although the controls that lead to niche differentiation among polymeroid trilobites are incompletely understood, they were both stable and effective.

INTRODUCTION

The word *community* has a variety of meanings in ecological and paleoecological literature. In paleontological studies (e.g., Ziegler et al. 1968; Bretsky, 1969; Anderson, 1971), the term has been employed for recurring groups of species. In this sense, communities are regarded as temporally persistent assemblages that retain their identity throughout a stratigraphic sequence. I have adopted this concept, treating a community as a loose association of species populations occurring together, potentially interacting and responding to similar ecological conditions. I concur with Warme et al. (1974) that communities must be identified first as recurrent fossil assemblages without placing undue stress on their hypothesized habitat, trophic structure, or niche group. Once these recurrent fossil assemblages have been established, one may attempt to interpret them using analogues from community theory.

Although Cambrian faunas have been intensively studied in the past two decades, Cambrian communities as such have received little attention, and de-

tails of their composition and possible structure are essentially unknown. Berg et al. (1956) made some preliminary statements about the assemblages found in western Wisconsin and eastern Minnesota, describing both a near-shore and an offshore assemblage. The nearshore assemblage was of low faunal diversity, composed of many lingulides, acrotretides, cap-shaped univalved mollusks, and large vertical worm tubes. The offshore assemblage was characterized by diverse trilobite associations containing a few orthaceans.

This aspect of their study has been virtually the only attempt made to understand the structure of North American Cambrian communities. The majority of community-oriented paleoecological investigations have been concerned with post-Cambrian shelf faunas. Such faunas stand in marked contrast to those of the Cambrian. As is well known, Cambrian shelf faunas were dominated, in terms of biomass if not numbers, by representatives of only one phylum, the arthropods. Other phyla were present; small inarticulate brachiopods were common components of the total fauna, and echinoderms were abundant locally. Mollusks and sponges were strongly represented in a few environments. Nevertheless, typical Cambrian shelf faunas were arthropod dominated, differing in this respect from faunas characteristic of later periods.

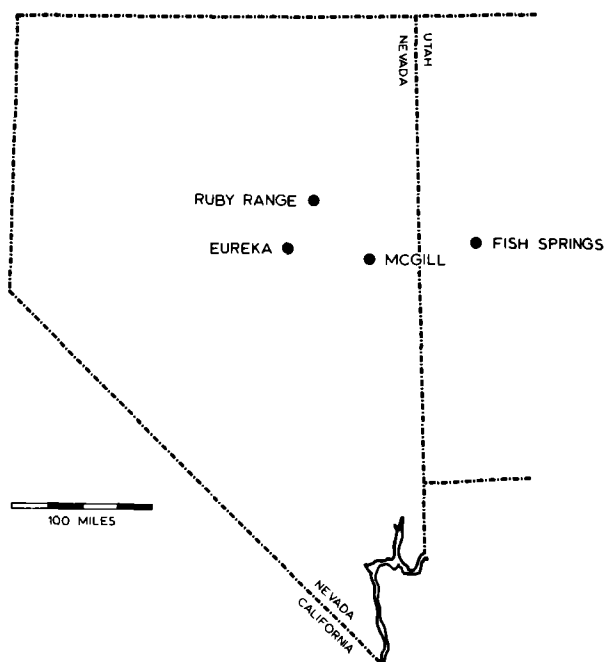
This study investigates the faunal composition of some Upper Cambrian rocks to determine if biotic communities can be identified in these relatively low-diversity faunas. The *Dunderbergia* Zone was chosen for study because, "the faunas of the *Dunderbergia* Zone are the most widespread Cambrian faunas in the Great Basin" (Palmer, 1965). Palmer (1965) recorded 61 species from this zone, 47 of which are confined to it. The systematics of the trilobites are well known (Palmer, 1960, 1965), and much recent work has been done on the brachiopods (Rowell, 1962, 1966; McBride and Rowell, 1973; McBride, 1974). The material studied is from part of the Dunderberg Formation and its lithic equivalents. These rocks are believed to have accumulated in deeper water, open-marine shelf environments that lay to the west of a belt of carbonate shoals (Palmer, 1971). In the upper part of the study interval one of these shoals, represented by the Johns Wash Member of the Orr Formation, prograded westward, forming a regressive carbonate sequence (Koepnick, 1975; Rees, 1975; Rees et al. 1976).

This paper deals with three aspects of the *Dunderbergia* Zone assemblages: (1) recognition of communities; (2) analysis of trophic groups present (insofar as this is possible); and (3) analysis and interpretation of structure within one inferred trophic group, the deposit-feeding polymeroid trilobites. The latter were chosen for detailed study because they constitute the bulk of the preserved biomass.

MATERIALS AND METHODS

Samples were collected from measured sections at each of the localities shown in Text-figure 1. A total of 41 samples were prepared, yielding some 2,600 trilobites and over 3,000 inarticulate brachiopods.

In any paleoecological study there are problems associated with sampling. These are in general well known, and the limitations that they impose are understood. Postmortem transport, when significant enough to alter faunal composition, is detectable by both faunal and sedimentological characteristics. In a few beds sampled for this study fossils are concentrated near either the



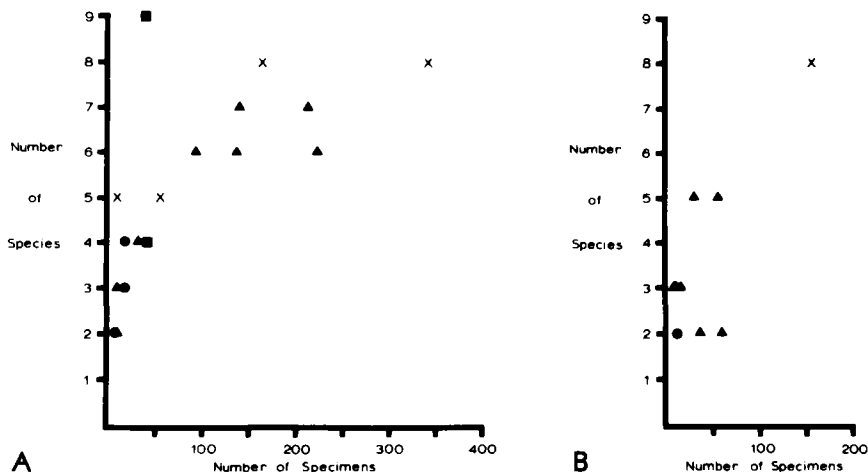
TEXT-FIGURE 1.—Locality map showing the location of measured sections used in this study. The easternmost section is in the northern Fish Springs Range, Juab County, Utah. The other three localities, near McGill, in Windfall Canyon near Eureka, and in the southern Ruby Range, are in White Pine County, Nevada.

base or the top of the unit, but generally they are found throughout. Debris flows are present at several horizons, but their fossil content is markedly different in character from that of most samples because they contain predominantly the early molt stages of polymeroid trilobites together with broken and deformed fragments of larger individuals. The majority of samples yield a wide size range of trilobites and many well-preserved inarticulate brachiopods, some of which have both valves together. The latter strongly suggest that there was little or no transport of the fossil material. Continued recurrence of the same benthic faunal associations also supports the interpretation that the elements of each assemblage were living together in the same general area. Furthermore, these regular associations are more readily explained as the remains of biologic populations than as hydrodynamic accumulations. Only samples interpreted as being essentially *in situ* were used in the study.

Even collections made from rocks whose fauna is believed to be *in situ* do not adequately reflect the composition of the original total fauna. Only under the most exceptional circumstances is there sufficient data on the soft-bodied component of the biota. Typically, one must accept the fact that detailed information about this component of the fauna is irrevocably lost, although trace fossils may provide some insight as to its importance. Given this limitation, even the most complete collection is potentially a somewhat distorted sample of the original fossilizable fauna because of the effects of differ-

ential scavenging, differential longevity, variance in the number of molt stages, and so on. This constraint must be considered in any analysis or interpretation of the data derived from the collections.

A further limitation is present but is not always considered. How large should a collection be to adequately reflect community composition of the fossils in the rock? No generalized answer is possible because it depends in large part on the frequency distribution of the various species and on the use to which the data are to be put. If one is interested only in dominant forms of common species, then large samples are not necessarily required, for these common forms will probably be adequately represented in even modest-sized samples. However, to study the details of structure within a community it becomes more important that the rarer species be represented in their proper proportions. To accomplish this much larger samples are necessary. Figure 2A is a plot of the total number of specimens versus the number of species recovered for polymeroid trilobites from the open-shelf community. The curve of points shows that in general there is a leveling off of the number of additional species found after approximately 135 specimens have been recovered. For this study, therefore, samples of 135 or more trilobites were regarded as adequate to reflect the distribution of species within fossil populations. Only these larger samples were used in the detailed study of structure within the deposit-feeding polymeroids. Text-figure 2B, which is a plot for samples assigned to the shoaling shelf community, indicates that while the samples are probably adequate for study of the common elements of the fauna, they are not sufficiently large to provide a reliable estimate of the species diversity of the total fossil fauna. The curve of points does not become asymptotic to a particular number of species after a given sample size. In the absence of evidence to the contrary, it is assumed that the curve in Text-figure 2B is essentially of the



TEXT-FIGURE 2.—A. Plot of the total number of specimens versus the number of species recovered for samples of polymeroid trilobites from the open-shelf community. B. Similar plot for samples of polymeroid trilobites from the shoaling shelf community. Triangles = samples from the Fish Springs Range. X = samples from the Ruby Range. Circles = samples from McGill. Squares = samples from Eureka.

same form as that of Text-figure 2A. The one sample of over 135 specimens from the shoaling shelf community is later compared with those of the open-shelf community in a detailed analysis of structure.

The samples used in this study were grouped together into communities based upon their dominant species. The dominant species are those that are most common in a collection. Frequently they are also the most widespread.

The descriptors of community integrity used here are those employed by Calef and Hancock (1974). Presence percentage is the number of collections in which a species occurs divided by the total number of collections and expressed as a percentage. It is a measure of the ubiquity of various taxa assigned to the community. Frequency presence, the presence percentage times average numerical abundance, is a measure of the commonness of a given taxon within the community.

RESULTS

Recognition of communities

Analysis of the faunal associations suggests the presence of two communities on the broad open shelf of the outer detrital belt during *Dunderbergia* Zone time. They are recognized here as an open-shelf community and a shoaling shelf community.

The open-shelf community (Table 1) occurs in the lower and middle part of the *Dunderbergia* Zone. This community is characterized by *Cernuolimbus granulosus*, *Dunderbergia anyta*, *Pseudagnostus communis*, *Apheletoxon* sp.,

TABLE 1
FAUNAL COMPOSITION OF THE *DUNDERBERGIA* ZONE OPEN-SHELF
COMMUNITY

Dominant Species	Presence Percentage	Presence Frequency
<i>Cernuolimbus granulosus</i>	75.0	38.50
<i>Dunderbergia anyta</i>	70.0	10.50
<i>Pseudagnostus communis</i>	55.0	21.10
<i>Apheletoxon</i> sp.	55.0	15.95
<i>Erizanium</i> sp.	30.0	2.00
<i>Pterocephalia punctata</i>	30.0	1.95
Other Species		
<i>Simulolenus wilsoni</i>	15.0	0.35
<i>Dunderbergia bigranulosa</i>	15.0	0.35
<i>Dunderbergia varigranula</i>	15.0	0.30
<i>Homagnostus</i> sp.	10.0	0.85
<i>Sigmocheilus notha</i>	10.0	0.60
<i>Elburgia granulosa</i>	10.0	0.20
<i>Cheilocephalus brachyops</i>	10.0	0.20
<i>Dytremacephalus asperaxis</i>	10.0	0.20
<i>Dytremacephalus granulosus</i>	10.0	0.10
<i>Prebousia diverta</i>	5.0	1.40
<i>Dunderbergia nitida</i>	5.0	0.05
<i>Pterocephalia concava</i>	5.0	0.05
<i>Dunderbergia polybothra</i>	5.0	0.20
Other Groups		
Lingulides	80.0	24.95
Acrotretides	85.0	115.35
<i>Pelagiella</i>	1.5	0.40

Number of collections studied = 20

Erixanium sp., and *Pterocephalia punctata*. Both acrotretide and lingulide inarticulate brachiopods are also abundant but systematic work on these forms is continuing and they are mentioned here without using specific designations. In all, 2,300 acrotretides and 500 lingulides have been recovered from seventeen samples representing this community. In addition to these, a small number of the problematic mollusk *Pelagiella* were found.

The shoaling shelf community (Table 2) occurs in the middle and upper part of the *Dunderbergia* Zone. It is characterized by *Dytremacephalus granulosus*, *Dunderbergia bigranulosa*, *Strigambitus utabensis*, *Strigambitus transversus*, *Elburgia granulosa*, and *Homagnostus* sp. Samples from this community also contain an abundance of inarticulate brachiopods.

Recognition of these assemblages as communities comes not only from their internally consistent faunal composition and occurrence, but also from the interpretation that they responded to similar environmental conditions. The open-shelf community is so named because it occurs in lime wackestones and packstones containing fossil assemblages that reflect subtidal open-marine conditions. These conditions would be expected on a broad, low-relief continental margin. The shoaling shelf community occurs in wackestones that are siltier and have different assemblages of polymeroid trilobites. In addition, the chronostratigraphic position of the shoaling shelf community corresponds with the beginning of carbonate progradation in the eastern part of the region during late Dresbachian time. The shoaling shelf community, although still indicative of subtidal shelf conditions, reflects a shallowing of the shelf waters, which had significant impact on the fauna.

One similarity between the two *Dunderbergia* Zone communities is the presence in both of *Aphelotoxon* sp. and *Erixanium* sp. These two taxa are the smallest polymeroid species that occur in the samples. Conceivably, they were relatively mobile forms: their distribution suggests that they may have been more eurytopic than the other polymeroids. Both species are more abun-

TABLE 2
FAUNAL COMPOSITION OF THE *DUNDERBERGIA* ZONE "SHOALING"
SHELF COMMUNITY

Dominant Species	Presence Percentage	Presence Frequency
<i>Dytremacephalus granulosus</i>	63.63	3.92
<i>Dunderbergia bigranulosa</i>	45.45	0.55
<i>Strigambitus utabensis</i>	36.36	15.63
<i>Strigambitus transversus</i>	36.36	4.73
<i>Elburgia granulosa</i>	36.36	2.36
<i>Homagnostus</i> sp.	27.27	0.36
Other Species		
<i>Dunderbergia nitida</i>	18.18	0.18
<i>Aphelotoxon</i> sp.	9.00	4.95
<i>Morosa extensa</i>	9.00	12.60
<i>Sigmocheilus notha</i>	9.00	9.90
<i>Erixanium</i> sp.	9.00	0.90
<i>Dunderbergia varigranula</i>	9.00	0.90
<i>Dunderbergia polybohra</i>	9.00	0.18
Other Groups		
Acrotretides	90.90	
Lingulides	81.80	

Number of collections studied = 11

dant in the open-shelf community, and were presumably somewhat better adapted to the conditions of deeper, open-shelf environments.

There is a distinct difference in the ornamentation of the polymeroid trilobites of the two communities. Trilobites of the shoaling shelf community are granular forms, and the granules are typically much coarser than those present on trilobites of the open-shelf community. When studied microscopically, many of these granules are coarse tubules. Eldredge (1970) cited the presence of canals of various types in many trilobites and reported canals of two or three different sizes on single specimens of *Phacops rana*. The structures noted by Eldredge (1970) seem to be analogous with canals recognized in modern arthropods. As discussed by Eldredge (1970), of the three types recognized in modern arthropods, one type, the minute pore canal, is involved in the secretion of cuticle. The other two types are gland ducts and canals for the sensory organs, the setae. The coarse tubules present on trilobites of the shoaling shelf community are similar to canals for the attachment of dorsal tactile setae. These setae are believed to have aided the organisms in burrowing under a thin layer of sediment in a similar manner to that described for *Limulus* (Eldredge, 1970).

Analysis of trophic groups

Detailed trophic-group analysis of ancient communities is virtually impossible. However, three broad feeding types can be discerned in the two recognized communities of the Cambrian shelf; suspension-feeding inarticulate brachiopods, deposit-feeding polymeroid trilobites, and agnostoid trilobites of different but uncertain habit.

The general framework of the community structure in *Dunderbergia* Zone shelf communities is summarized in Text-figure 3 for the open-shelf community and in Text-figure 4 for the shoaling shelf community. The figures diagram broad trophic group membership and generalized mode of life for the various faunal components. Members of the three trophic groups occupied completely different niches and therefore did not compete with one another. Likewise, available evidence suggests that no predator-prey relationships existed between these three trophic groups.

The inarticulate brachiopods were suspension feeders, filtering nutrients from the water. McCammon and Reynolds (1972) have shown that some living articulates are also capable of absorbing dissolved nutrients directly through the body wall. Cambrian forms may also have had this capability. Whether they used one or both feeding mechanisms is not known. The interpretation of inarticulate brachiopods as occupying both high and low suspension positions (Text-figs. 3 and 4) is a result of increased evidence that distribution of these forms is dependent primarily upon the availability of an attachment surface (Rowell and Krause, 1973). Although most individuals are believed to have rested directly on the substrate, others were probably attached to animals, seaweed, or floating objects. The inarticulate brachiopods are unlikely to have competed to any degree among themselves. Stanley (1973) believed that suspension-feeding animals in general are characterized by weak competition. Connell (1963) has shown that bivalve populations tend to be clumped, suggesting that they were not limited by either food or space. The work of Levinton (1974) supports this conclusion. Rowell and Brady (1976) are also of the opinion that, among Cambrian inarticulate brachiopods, the level of competitive interaction was low.

OPEN SHELF COMMUNITY						
EPIFAUNAL				INFAUNAL		
FREE		ATTACHED				
IMMOBILE	MOBILE	HIGH	LOW	IMMOBILE	MOBILE	
DEPOSIT	CERNUOLIMBUS DUNDERBERGIA APHELOTOXON ERIXANIUM PTEROCEPHALIA				"WORMS"	
	AGNOSTIDS	ACROTRETIDES LINGULIDES?	ACROTRETIDES LINGULIDES	LINGULIDES		
	PELAGIELLA ?					

TEXT-FIGURE 3.—Diagram of trophic-group membership and generalized mode of life for the open-shelf community.

"SHOALING" SHELF COMMUNITY						
EPIFAUNAL				INFAUNAL		
FREE		ATTACHED		IMMOBILE	MOBILE	
IMMOBILE	MOBILE	HIGH	LOW			
DEPOSIT		STRIGAMBITUS DYTREMACEPHALUS ELBURGIA DUNDERBERGIA APHELOTOXON ERIXANIUM				"WORMS"
SUSPENSION		AGNOSTIDS	ACROTRETIDES LINGULIDES?	ACROTRETIDES LINGULIDES	LINGULIDES	
GRAZING						

TEXT-FIGURE 4.—Diagram of trophic-group membership and generalized mode of life for the shoaling shelf community.

The agnostoids have been considered by some to be pelagic forms (cf. Robison, 1972a). Bergström (1973) has suggested that they lived in association with drifting seaweed. In any event, whatever their mode of life, major differences in the structure of the hypostoma suggest that the agnostoids differed from other trilobites in their choice of food and feeding habits (Robison, 1972b). The details of these differences are presently unknown.

Most polymeroid trilobites were probably either benthic crawlers, or else burrowed in soft sediment. The majority apparently were capable of reworking the substratum. By reworking the substratum in different ways, polymeroid trilobites were potentially able to partition available niche space. Bergström (1973) has pointed out that the smooth exterior and wide rhachis found in the illaenids and asaphids may be an adaptation toward burrowing habits. This may also be true of some Late Cambrian forms like *Pterocephalia* and *Strigambitus*. Heavy forms, like *Dunderbergia* and *Cernuolimbus*, were probably benthic crawlers that rested just below the sediment-water interface.

Still other trilobites have been interpreted as active swimmers. These forms differ from the burrowers by having more slender, lighter exoskeletons. Some of them also have enlarged eyes and reduced enrollment capacity (Bergström, 1973). In the *Dunderbergia* Zone shelf community *Simulolenus*, and possibly *Apheletoxon* and *Erixanum*, may have been partially nektonic.

Savilov (1957) pointed out that deposit feeders have relatively few options by which they can feed and thus differentiate their niches. This would imply relatively severe competition for food. Stanley (1973) has also argued that trilobites, like mammals, are characterized by relatively intense competitive behavior. He invoked such competition to explain the rapid taxonomic diversification of the group. If such a situation prevailed, niches would be narrow and well defined, and there would be little niche overlap. The available evidence, although not conclusive, is consistent with the notion that polymeroid trilobites were at least partial competitors. Although they may have competed for food, differences in other aspects of their mode of life, combined with size differences led to narrow niches. The available resources were partitioned and supported a modest diversity of taxa belonging to the same general trophic group. As discussed below, these taxa were seemingly in some general equilibrium, for their relative abundances reveal order.

Structure within the polymeroid trilobites

Polymeroid trilobites constitute the bulk of the preserved biomass of collections made for this study. Because they seemingly interacted with one another, one might anticipate that the relative abundances of taxa within a community should reveal well-organized structure. This trophic group was examined in more detail for these reasons.

In trying to identify the structure within a trophic group, it is necessary to determine the importance of various species to the community. In this discussion, we assume some correlation between three control mechanisms: the proportion of the niche hyperspace of the community that a species occupies, the amount of community resources utilized, and the proportion of community productivity a species realizes (Whittaker, 1975). Many different measurements of importance values are possible. In studies of recent communities productivity is the preferred importance value, for it expresses a species' utili-

zation of the community resources and permit comparisons of species widely differing in size and kind on a single scale.

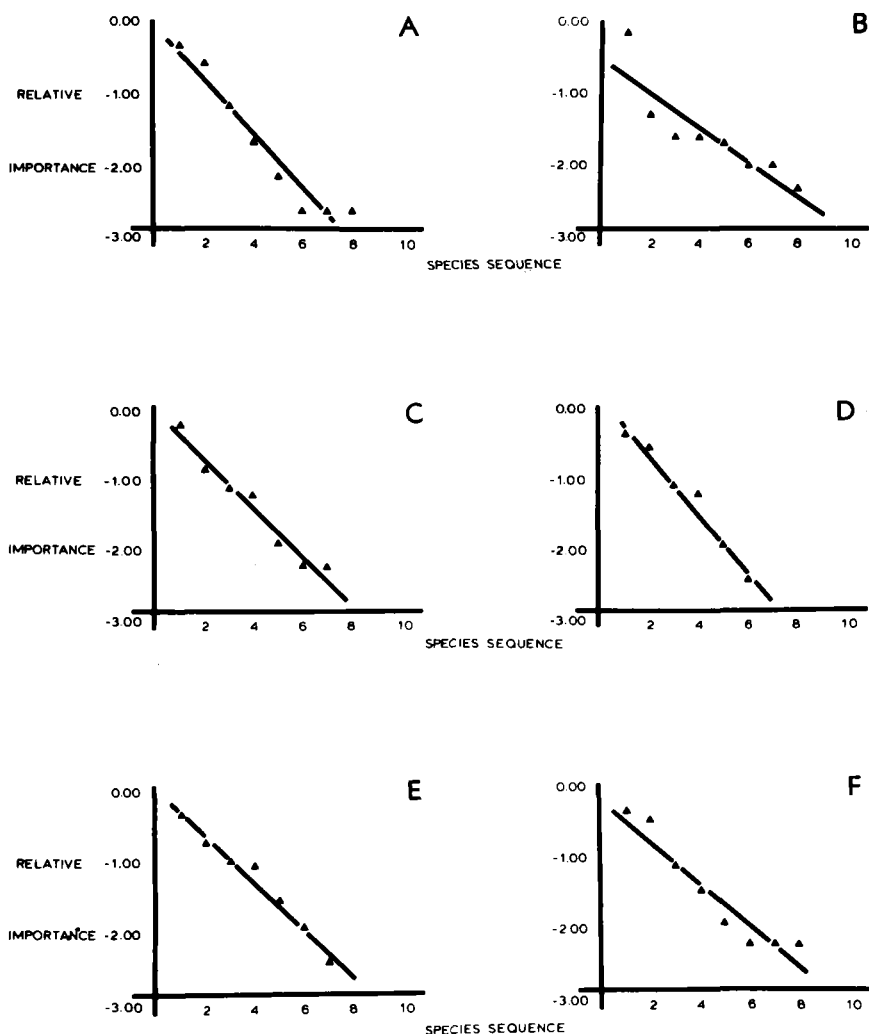
In studies of ancient communities, productivity is not readily measurable. Because polymeroids in the samples are of the same general order of size, it is possible to use relative abundance of taxa within a collection as an approximate measure of species importance. What needs to be determined is whether or not there is any systematic arrangement of relative species importance within this trophic group of the *Dunderbergia* Zone shelf communities. As discussed previously, large stable samples are needed for this type of analysis and, as determined from Text-figure 2-A, only samples with more than 135 individuals should be used. The single large sample from the shoaling shelf community is also employed for comparison.

Dominance-diversity curves (Whittaker, 1965) graphically display the relative importance of species within a trophic group. They are produced by plotting the relative abundance of each species on a logarithmic scale against its rank-order of abundance; i.e., 1, 2, 3, . . . n (Text-fig. 5). The logarithmic transformation accomplishes two purposes. It relieves the basic insensitivity of dominance measures toward rare species, for although very rare species are still likely to be inadequately represented, the addition of very rare forms will not significantly change the form of the plot. In addition, the transformation helps to reduce the effects of a modest degree of distortion in the data caused by an unequal number of molt sizes, differential predation, and so on.

A number of basically different forms of dominance-diversity curves are possible. Whittaker (1965, 1970, 1975) discussed three common ones: the MacArthur distribution, the geometric series, and the lognormal distribution. From these dominance-diversity or importance-value curves a number of hypotheses were suggested. When these hypotheses were first discussed they were treated as multiple hypotheses, one of which could be chosen on the basis of actual importance relationships between species. It is now apparent that different samples from one community and samples from different communities may fit any one of the models (Whittaker, 1975). Consequently, instead of choosing one hypothesis we need to determine what attributes of a community cause its importance values to approach those predicted by one of the models.

For the *Dunderbergia* Zone shelf communities, dominance-diversity curves of species abundance among the polymeroids form straight-line distributions (Text-fig. 5), indicating similarity to the geometric series of Whittaker (1965). The majority of distributions for the open-shelf community (Text-figs. 5A-E) have a comparable slope, but that of Text-figure 5B is anomalous. The anomaly is caused by the relative lack of abundance of the second species in the dominance sequence, an anomaly that is not understood. The dominance-diversity curve for the shoaling community (Text-fig. 5F) also displays the geometric relationship between relative species importance. The slope of the line, however, differs from that typical of open-shelf communities. The difference may reflect a real difference between the two communities, but the possibility cannot be explored further at the present time because only one large sample of the shoaling shelf community is available.

Additional order may be detected in the data, particularly for the open-shelf community (Table 3). Not only is there regularity in the distribution of the relative abundance of dominant taxa, but the same taxa tend to occupy



TEXT-FIGURE 5.—Dominance-diversity plots for all samples containing greater than 135 polymeroid trilobites. Species sequence is rank order of abundance of species. Relative importance is the logarithm of relative abundance expressed as a proportion of the total number of polymeroids. A-E are for the open-shelf community. F is from the shoaling shelf community.

the same relative major dominance positions. Thus, *Cernuolimbus granulatus* is the dominant species in eleven of the seventeen samples and either *Dunderbergia anyta* or *Aphelotoxon* sp. is the second dominant in thirteen of the samples. This relation is not so apparent in the shoaling shelf community, but its absence may be an artifact caused by the smaller average sample size of this community. Nevertheless, the data show that a species of *Strigambitus* was the dominant form in seven of nine samples (Table 4).

TABLE 3
DOMINANCE RELATIONSHIPS OF THE POLYMEROID TRILOBITES BY
SAMPLE FOR THE OPEN-SHELF COMMUNITY SHOWING THE
NUMBER OF SAMPLES IN WHICH A SPECIES OCCUPIED A GIVEN
POSITION IN THE SPECIES DOMINANCE SEQUENCE

Dominant Species	Species Sequence							
	1	2	3	4	5	6	7	8
<i>Cernuolimbus granulosus</i>	11	2			1			
<i>Dunderbergia anyta</i>	1	8	1		2	1		1
<i>Apbelotoxon</i> sp.	2	5	3					
<i>Erixanium</i> sp.			2	2	1			
<i>Pterocephalia punctata</i>	1		1	1				
Other Species								
<i>Simulolenus wilsoni</i>			1		1	1		
<i>Dunderbergia bigranulosa</i>		1		1				
<i>Dunderbergia varigranula</i>		1	3			1		
<i>Sigmocheilus notha</i>						1		
<i>Elburgia granulosa</i>					1		1	
<i>Cheilocephalus brachyops</i>						1		
<i>Dytremacephalus asperaxis</i>				1	1			
<i>Dytremacephalus granulosus</i>					1			
<i>Prebousia diverta</i>	1							
<i>Dunderbergia nitida</i>				1				
<i>Pterocephalia concava</i>	1	1						
<i>Dunderbergia polybothra</i>			1					

TABLE 4
DOMINANCE RELATIONSHIPS OF THE POLYMEROID TRILOBITES BY
SAMPLE FOR THE "SHOALING" SHELF COMMUNITY, SHOWING THE
NUMBER OF SAMPLES IN WHICH A SPECIES OCCUPIED A GIVEN
POSITION IN THE SPECIES DOMINANCE SEQUENCE

Dominant Species	Species Sequence							
	1	2	3	4	5	6	7	8
<i>Dytremacephalus granulosus</i>	1	3	2					
<i>Dunderbergia bigranulosa</i>		3		2				
<i>Strigambitus utahensis</i>	4							
<i>Strigambitus transversus</i>	3	1						
<i>Elburgia granulosa</i>		2	1	1				
Other Species								
<i>Dunderbergia nitida</i>				1		1		
<i>Apbelotoxon</i> sp.		1						
<i>Morosa extensa</i>			1					
<i>Sigmocheilus notha</i>	1							
<i>Erixanium</i> sp.						1		
<i>Dunderbergia varigranula</i>						1		
<i>Dunderbergia polybothra</i>					1			

The striking feature in comparing all the dominance-diversity curves (Text-fig. 5) is their close similarity and the regularity that this implies. Their consistency in shape would seem to suggest the operation of broadly similar control mechanisms. As Whittaker (1975) has discussed, more than one mechanism can be advanced to explain the form of any of the three common types of dominance-diversity curves. One commonly offered explanation for the straight-line or geometric series distribution is the niche preemption hypothesis (Whittaker, 1970, 1975). Niche preemption has been

recognized most frequently in plant communities and occurs where dominance by a few species is strongly developed. One or two of the most important species occupy a large fraction of the niche space and utilize a corresponding fraction of the community resources. These are the dominant species. The remaining species occupy successively smaller fractions of the niche space unoccupied by others.

Thus, if the relative importance of species within a group may be expressed by some form of geometric series, the relationship between the species may be controlled by their dependence on *some* of the same resources (Whittaker, 1975). The geometric relationship between relative importance values of polymeroid trilobites (revealed by the linear arrangement of these values on the semilogarithmic plots of Text-fig. 5) is consistent with the hypothesis that these forms were partial competitors, and that this competition for some resource, probably food, controlled the relative abundance of the species within any given community. It is quite unlikely that the regular pattern of structure within the polymeroid trilobites is an artifact. Even if further collecting produced additional rare species, the form of the major part of the dominance-diversity curve would not change significantly. Similarity of form in dominance-diversity curves between all the samples, together with a strong tendency for consistency in the relative position of any one species within the dominance sequence, suggests that the controls that led to niche differentiation, although incompletely understood, were both stable and effective.

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REFERENCES

- Anderson, E. J., 1971, Environmental models for Paleozoic benthic communities: *Lethaia*, v. 4, p. 287-302.
- Berg, R. R., Nelson, C. A., and Bell, W. C., 1956, Upper Cambrian rocks in southeastern Minnesota: in Schwartz, G. M. (ed.), *Lower Paleozoic of Upper Mississippi Valley*: Geol. Soc. Amer., Minneapolis, Guidebook, p. 1-23.
- Bergstrom, Jan, 1973, Organization, life and systematics of trilobites: *Fossils and Strata*, v. 2, p. 1-69.
- Bretsky, P. W., Jr., 1969, Evolution of Paleozoic benthic marine invertebrate communities: *Palaeogeog., Palaeoclimat., Palaeocol.*, v. 6, p. 45-59.
- Calef, C. E., and Hancock, N. J., 1974, Wenlock and Ludlow marine communities in Wales and the Welsh Borderland. *Paleont.*, v. 17, p. 779-810.

- Connell, J. H., 1963, Territorial behavior and dispersion in some marine invertebrates: *Res. Popul. Ecol.*, v. 2, p. 87-101.
- Eldredge, Niles, 1970, Observations on burrowing behavior in *Limulus polyphemus* (Chelicerata, Merostomata), with implications on the functional anatomy of trilobites: *Amer. Mus. Novitates*, No. 2436, 17 p.
- Koepnick, R. B., 1975, Depositional history of the Upper Cambrian Pterocephaliid Biomere from west central Utah: *Geol. Soc. Amer. Abst. Prog.*, v. 7, p. 1149.
- GEOLOGY 41 41 19573
- Levinton, J. S., 1974, Trophic group and evolution in bivalve molluscs: *Paleont.*, v. 17, p. 579-85.
- McBride, D. J., 1974, Phenetic variation and inferred cladistic pathways in the *Apsotreta*-*Linnarssonella* complex (Brachiopoda, Upper Cambrian): unpub. M. S. thesis, Univ. Kansas, 150 p.
- , and Rowell, A. J., 1973, Phenetic variation and inferred cladistic pathways in the *Apsotreta*-*Linnarssonella* complex (Brachiopoda, Upper Cambrian): *Geol. Soc. Amer. Abst. Prog.*, v. 5, p. 335.
- McCammon, H. M., and Reynolds, A. W., 1972, Geologic implication of the brachiopod lophophore as an organ of nutrient assimilation: *Geol. Soc. Amer. Abst. Prog.*, v. 7, p. 587.
- Palmer, A. R., 1960, Trilobites of the Upper Cambrian Dunderberg Shale, Eureka district, Nevada: *U. S. Geol. Surv. Prof. Paper* 334-C, p. 53-109.
- , 1965, Trilobites of the Late Cambrian Pterocephaliid Biomere in the Great Basin, United States: *U. S. Geol. Surv. Prof. Paper* 493, 105 p.
- , 1971, The Cambrian of the Great Basin and adjacent areas, Western United States: in Holland, C. H. (ed.), *Lower Paleozoic rocks of the World*: v. 1, Cambrian of the New World, Wiley-Interscience, New York, p. 1-78.
- Rees, M. N., 1975, Evolution of an oolite shoal complex: Upper Cambrian Johns Wash Limestone (House Range, Utah): *Geol. Soc. Amer. Abst. Prog.*, v. 7, p. 1240.
- , Brady, M. J., and Rowell, A. J., 1976, Depositional environments of the Upper Cambrian Johns Wash Limestone (House Range, Utah): *J. Sediment. Petrol.*, v. 46, p. 38-47.
- Robison, R. A., 1972a, Mode of life of agnostid trilobites. 24th Int. Geol. Congr., *Proc.*, Sect. 7, p. 33-40.
- , 1972b, Hypostoma of agnostid trilobites: *Lethaia*, v. 5, p. 239-48.
- Rowell, A. J., 1962, The genera of the brachiopod superfamilies Obolidae and Siphonotretacea: *J. Paleont.*, v. 36, p. 136-52.
- , 1966, Revision of some Cambrian and Ordovician inarticulate brachiopods: *Univ. Kansas Paleont. Contr.*, Paper 7, 36 p.
- , and Brady, M. J., 1976, Brachiopods and Biomes: in Robison, R. A., and Rowell, A. J. (eds.), *Paleontology and depositional environments: Cambrian of western North America*: Brigham Young Univ. Geol. Stud., v. 23, pt. 2.
- , and Krause, F. F., 1973, Habitat diversity in the Acrotretacea (Brachiopoda, Inarticulata): *J. Paleont.*, v. 47, p. 791-800.
- Savilov, A. I., 1957, Biological aspect of the bottom fauna groupings of the North Okhotsk Sea: in Nikitin, B. N. (ed.), *Marine Biology: Trans. Inst. Oceanology*, p. 67-136.
- Stanley, S. M., 1973, Effects of competition on rates of evolution, with special reference to bivalve mollusks and mammals: *Syst. Zool.*, v. 22, p. 486-506.
- Warne, J. E., Ekdale, S. F., and Ekdale, A. A., 1974, Interpretation of fossil communities based on modern marine benthic studies: *Geol. Soc. Amer. Abst. Prog.*, v. 6, p. 1000.
- Whittaker, R. H., 1965, Dominance and diversity in land plant communities: *Science*, v. 147, p. 250-60.
- , 1970, *Communities and ecosystems*: MacMillan Co., New York, 158 p.
- , 1975, *Communities and ecosystems*: Second ed., MacMillan Co., New York, 385 p.
- Ziegler, A. M., Cocks, L. R. M., and Bambach, R. K., 1968, The composition and structure of Lower Silurian marine communities: *Lethaia*, v. 1, p. 1-27.

Upper Cambrian Subtidal Blanket Carbonate of the Miogeocline, Eastern Great Basin

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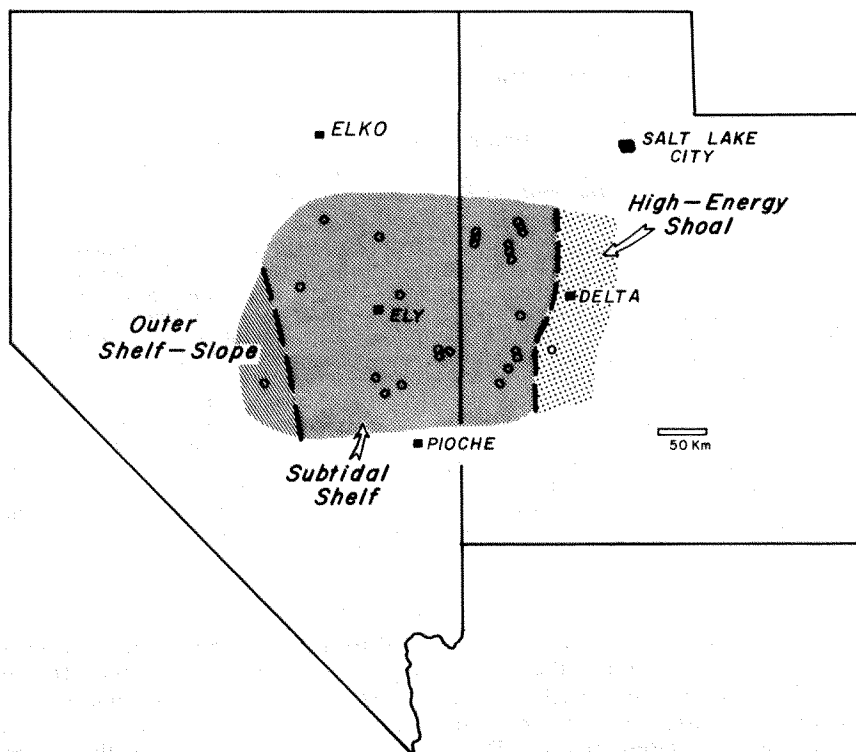
ABSTRACT.—Blanket carbonate deposition spread across the Cordilleran Miogeocline of the eastern Great Basin during middle-late *Elvinia* time. The miogeocline was characterized by a broad subtidal shelf which developed over much of west central Utah and east central Nevada; a narrow high-energy shoal existed along its landward (eastern) edge. Lime wackestones containing a "normal marine" assemblage dominated by trilobites, echinoderms, inarticulate brachiopods and sponges were deposited on the shelf, which lay below normal wave base in water in the range of a hundred meters deep. The remarkable uniformity of these rocks over more than 40,000 km² reflects the low-energy, but well-circulated conditions that prevailed on the almost featureless shelf. Laminated lime mudstones and alldapic grainstones accumulated in the deeper water slope environment just seaward of the shelf. The general lack of shoal-water carbonates and terrigenous deposits on the shelf and slope during middle-late *Elvinia* time contrasts with the more variable depositional patterns of the miogeocline earlier in the Middle and Late Cambrian. The existence of at least two other types of shelves in these older rocks clearly indicates that no single depositional model can be applied to the interpretation of the miogeocline.

INTRODUCTION

Two tectonic models have been proposed for the lower Paleozoic Cordilleran Geosyncline (Stewart and Poole, 1974, Fig. 14): A marginal sea and offshore island arc system (Burchfiel and Davis, 1972; Churkin, 1974), and, a stable continental margin with a broad shelf separated from an oceanic basin by a continental rise (Burchfiel and Davis, 1972; Stewart, 1972). In both of these models the miogeocline is situated at the edge of the main continental mass and it is in this setting that our studies of the Middle and Upper Cambrian in the Great Basin have been concentrated.

The existence of a north-trending miogeoclinal "carbonate belt" approximately paralleling the continental margin throughout much of the Cambrian has been known for some time (Palmer, 1971); however, details of the paleoenvironments represented by rocks comprising the belt are still being deciphered. Already, it is apparent that the nature of the environments which characterized the miogeocline was not always the same, particularly in the continental shelf setting.

Shoal-water conditions prevailed over the "carbonate belt" during the Middle Cambrian (Brady and Koepnick, 1973; Kepper, 1972, 1975) and also during deposition of the Upper Cambrian Johns Wash Limestone (Rees et al., 1976). Lagoonal and peritidal environments covered most of the bank interiors while bioclastic and oolitic grainstones were deposited along the margins in the zone of maximum wave action. Relief at the edges of the carbonate banks ranged from a few tens of meters during deposition of the Johns Wash Limestone (Rees et al., 1976) to possibly a few hundreds of meters during deposition of the Middle Cambrian Marjum Formation (Brady and Koepnick, 1973). Without exception, the shoal-water rocks of these "carbonate belts" pass westward into shales and thin-bedded limestones of the outer shelf and slope.

MIDDLE - LATE ELVINIA ZONE

TEXT-FIGURE 1.—Paleoenvironmental map of the miogeocline during middle-late *Elvinia* Zone. Control points shown by circles.

A marked change in the sedimentary pattern of the miogeocline occurred with the onset of middle *Elvinia* Zone carbonate deposition. The influx of terrigenous sediment onto the miogeoclinal shelf was abruptly terminated and, for the first time, carbonate deposition spread across the entire shelf and into the slope environment as the "carbonate belt" expanded to completely encompass the miogeocline (Text-fig. 1). Another striking difference in the shelf during this time was the general absence of shoal-water environments. Except for a narrow zone along its landward edge, the miogeocline lay entirely below normal wave base in water that must have been in the range of a hundred meters deep. Monotonously uniform blanket carbonates accumulated on this broad, low-relief shelf in contrast to the varied shoal-water and outer shelf lithologies of the earlier shelves.

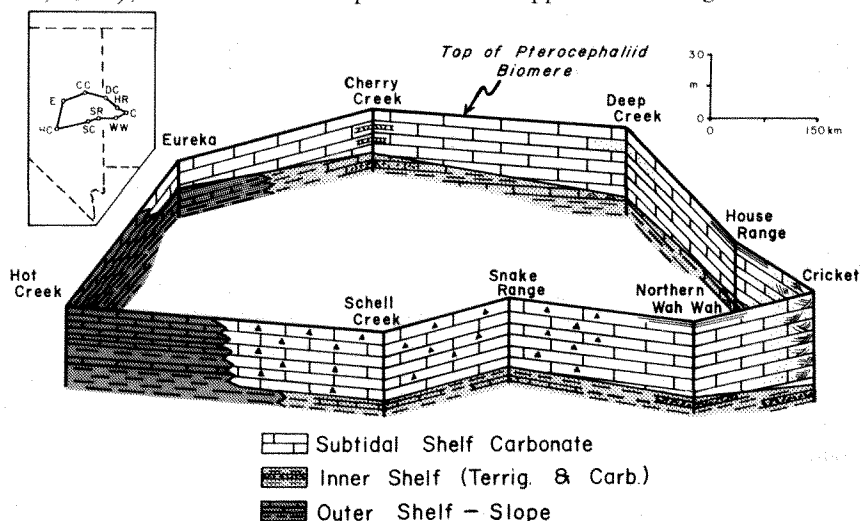
In this paper we examine the miogeocline of the middle and late *Elvinia* Zone by first discussing the rock types representative of the various environments, with emphasis on the subtidal shelf, and then summarizing our interpretation of the paleogeographic setting. We also briefly describe the environmental conditions that existed at the top of the *Elvinia* Zone in relation to the Pteroccephaliid/Ptychaspid Biome boundary. Finally, we wish to compare the shelf setting during middle-late *Elvinia* time with two different shelf

types that we have examined, which are represented by the Marjum Formation and the Johns Wash Limestone.

STRATIGRAPHIC RELATIONS

Approximately 30 meters of shelf carbonates were deposited in the miogeocline of the eastern Great Basin during middle-late *Elvinia* time. The top of this interval coincides with the upper boundary of the Pterocephaliid Biome. Rock stratigraphic units representative of the shelf include the Sneakover Member of the Orr Formation, and the Barton Canyon Member of the Windfall Formation, and their equivalents (Palmer, 1965). The top of the interval in contemporaneous outer shelf and slope deposits exposed in the Hot Creek Range of Nevada (Text-fig. 2) is in the basal Hales Limestone. The lower boundary has not been precisely determined in these deeper water equivalents, but it most likely occurs within the upper part of the Dunderberg Shale.

Throughout most of west central Utah and east central Nevada, the shelf carbonates are underlain by argillaceous shales and thin-bedded limestones of the Corset Springs and upper Dunderberg Shales. The limestones of these underlying units contain a marine faunal assemblage dominated by echinoderms and trilobites, and locally thicken with the presence of domal stromatolites. Also present are flat-pebble limestone conglomerates containing many clasts, which appear to have been rounded by wave action prior to reaching their final site of deposition. The stromatolites, conglomerates, and echinoderm-trilobite grainstones all indicate that at least periodic shoal-water conditions existed on the inner shelf during deposition of the Corset Springs Shale (Koepnick, 1976), and easternmost exposures of the upper Dunderberg Shale. Rocks



MIDDLE - LATE *ELVINIA* ZONE

TEXT-FIGURE 2.—Fence diagram illustrating facies relationships across the miogeocline during middle-late *Elvinia* time. Rock units representative of the environments include: subtidal shelf (Sneakover and Barton Canyon Limestones); inner shelf (Corset Springs Shale and easternmost exposures of upper Dunderberg Shale); outer shelf-slope (basal Hales Limestone, upper Dunderberg Shale).

of these units grade westward into the somewhat deeper water shales and dark thin-bedded, lime mudstones of the upper part of the Dunderberg Shale underlying the outer shelf and slope deposits (Text-fig. 2)

Limestones of the Ptychaspid Biomere overlie upper *Elvinia* Zone carbonates on the eastern portion of the shelf. Cook and Taylor (1975) found that the Whipple Cave Formation of eastern Nevada is composed of shoal-water carbonates which change facies westward into the deeper water deposits of the middle and upper Hales Limestone exposed in the Hot Creek Range.

MIDDLE-LATE *ELVINIA* ZONE SHELF ENVIRONMENTS

We interpret the carbonates of this interval to have been deposited in three distinct depositional environments: 1) a high-energy shoal; 2) a broad subtidal shelf; and, 3) an outer shelf-slope (Text-fig. 1). The rocks representative of each of these environments exhibit criteria which enable one to make a paleoenvironmental reconstruction of the miogeocline during middle-late *Elvinia* time.

High-energy Shoal

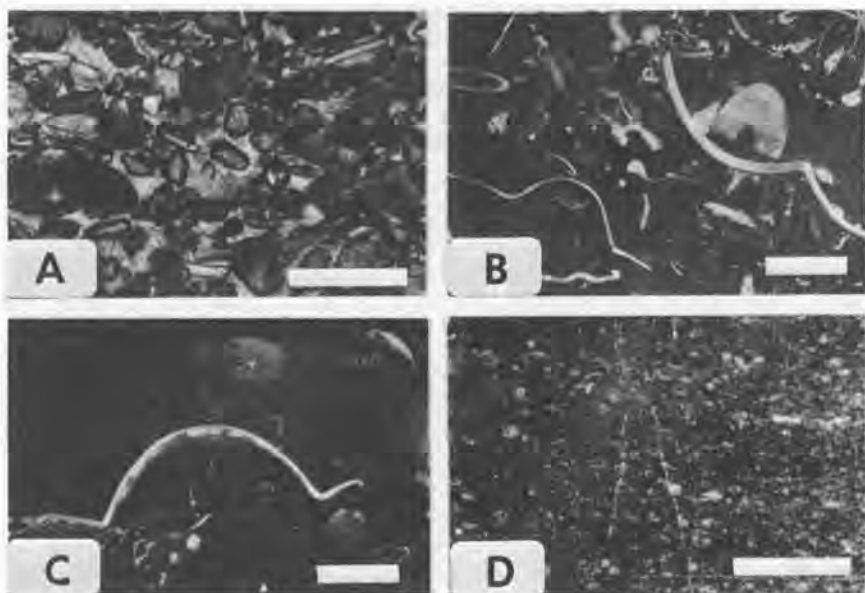
The high-energy shoal portion of the shelf lay along its eastern margin (Text-figs. 1, 2), its position being largely determined by the depth of normal wave base. Rocks representative of this environment are exposed in the Cricket Range of west central Utah and are described in a stratigraphic section measured by Hintze (1973). They consist of medium- to thick-bedded, light to medium grey limestones which commonly exhibit medium-scale trough cross-stratification. Grainstones containing abundant trilobites, echinoderms, and intraclasts are the dominant rock type (Text-fig. 3A). All of the bioclasts in the grainstones have been fragmented and they are generally well rounded, as are the intraclasts. The grains range from fine to medium sand and are commonly well sorted.

Associated with the grainstones are less common beds of trilobite-echinoderm packstones and wackestones. The bioclasts in these muddier carbonates are often unbroken and poorly sorted. *Chancelloria* and other sponge spicules, together with pellets are also quite common in these rock types, while intraclasts are relatively rare. Many of the wackestone units are burrow mottled with a few 0.2–1.0 cm diameter burrows preserved.

The well-washed grainstones are an obvious reflection of the high-energy conditions which existed on the shoal. The rounded and well-sorted nature of both the bioclasts and intraclasts indicates they were shaped in a wave-agitated environment as tidal or other near-shore currents piled the sediment into dunes on the surface of the shoal. Muddier carbonate sediments accumulated within embayments or on the lee side of the shifting dune system; these fine-grained sediments were the source of intraclasts for successive grainstone units formed by migration of the dune complex over the low-energy areas. The seaward edge (western) of this high-energy shoal extended to the point where normal wave base intersected the bottom.

Subtidal Shelf

This environment was the most extensive of the miogeocline, covering a large part of east central Nevada and west central Utah (Text-fig. 1). Rocks that were deposited on the subtidal shelf are remarkably uniform over the en-



TEXT-FIGURE 3.—(A) Intraclastic trilobite-echinoderm grainstone of the high-energy shoal. (B) Pelleted trilobite-echinoderm wackestone typical of the subtidal shelf. Note the unbroken nature of fragile bioclasts in contrast to abraded grains shown in (A). (C) Burrowed trilobite-sponge spicule wackestone from near top of *Elvinia* Zone in Wah Wah Mountains, Utah. (D) Laminated mudstone-wackestone of the slope environment. Bar scales equal 2 mm.

tire area situated between the high-energy shoal to the east and the outer shelf and slope environments to the west.

Light to medium gray, medium- to thick-bedded limestones are typical of this portion of the shelf. They are generally highly burrowed and exhibit essentially no primary sedimentary structures; burrows are commonly replaced by either rust-colored chert or dolomite. Pelletal wackestones containing trilobites, echinoderms and sponge spicules are the dominant rock type (Text-fig. 3B). The bioclasts lack orientation, are unsorted and unbroken, indicating that the organisms lived where they were deposited and were not affected by wave or current activity.

Occasional coated bioclastic grainstones and even intraformational conglomerates occur in this interval in exposures in the Cherry Creek and Deep Creek Ranges (Text-fig. 2). We interpret these higher-energy deposits to be the result of wave action washing mud from the sediment on slightly positive areas on an otherwise nearly featureless shelf.

Dark gray, nodular chert is present throughout the subtidal-shelf limestones in the Schell Creek and Snake Ranges (Text-fig. 2). The rocks of these localities are also somewhat thinner bedded and darker gray; however, they are very similar in composition to rocks on other parts of the shelf and were probably deposited in only slightly deeper water.

A sharp lithologic change occurs near the top of the *Elvinia* Zone in the vicinity of the northern Wah Wah Mountains and the House Range. Here the thick-bedded, light gray limestones are replaced vertically by thin- to medium-bedded, dark gray limestones (Text-fig. 3C). These dark units are unlike the typical subtidal-shelf carbonates in that they contain no echinoderms and have more abundant sponge spicules and lingulide brachiopods. They reflect either restriction or deepening of this portion of the shelf near the close of the *Elvinia* Zone.

The environment of the deposition of all these rocks was that of a low-relief, open shelf lying just below normal wave base. The diverse faunal assemblage and abundance of carbonate mud are evidence of a stable low-energy setting, but nonetheless one having good circulation. There was no influx of terrigenous sediment; pure carbonate deposition prevailed on the shelf. These environmental conditions are analogous to those described by Irwin (1965) in the open sea, low energy zone (Zone X, Fig. 3, p. 450), of his epeiric sea model. Although Irwin's model was intended for epeiric sea sedimentation, the shallow, low-energy conditions with unrestricted circulation over an area of many thousands of square kilometers is comparable to that of the broad middle-upper *Elvinia* Zone continental shelf, which bordered western North America. Similar rocks also occur in the Kalkberg facies of the Lower Devonian Helderberg Group in the northern Appalachians, which consists largely of skeletal wackestones deposited on an open, well-circulated, shallow shelf (Laporte, 1969). Again, this is an epeiric sea setting, but nonetheless is very similar to this Upper Cambrian subtidal shelf. This type of shelf contrasts with more steeply sloping, higher relief, or narrower, high-energy shelves where energy conditions and water circulation are not nearly so uniform and abrupt facies changes are the rule (Brady and Ward, 1973; Wilson, 1974, 1975).

Outer Shelf-Slope

The subtidal-shelf carbonates pass westward into deeper water lithologies of the outer shelf and slope. Rocks representative of these environments are found in the upper Dunderberg Shale and basal Hales Limestone exposed in the Hot Creek Range of central Nevada (Text-figs. 1, 2).

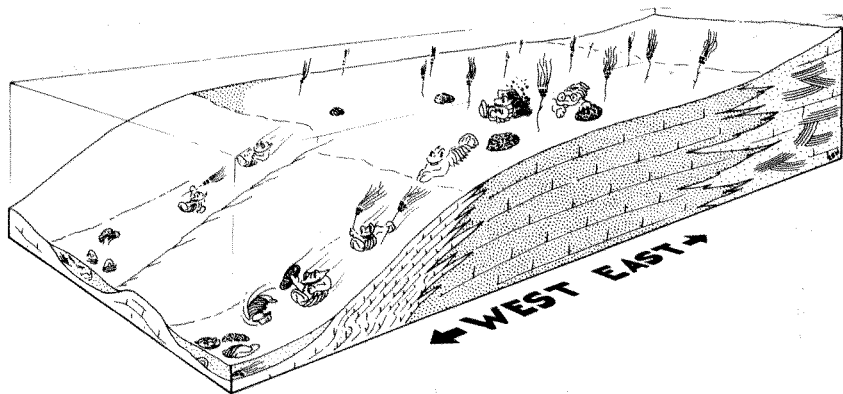
The deep-water character of the middle and upper Hales limestone immediately overlying rocks of the *Elvinia* Zone in this area has been nicely documented by Cook and Taylor (1975). Except for the presence of slump structures and allochthonous conglomerates, these deposits are very similar to those of basal Hales Limestone and we support their interpretation of a slope setting. Thin-bedded, dark gray lime mudstones and wackestones are the dominant rock types. These rocks are commonly finely laminated, have microscale cut-and-fill, and contain abundant sponge spicules (Text-fig. 3D). Associated with these fine-grained rocks are allodapic grainstones composed mainly of echinoderm and trilobite debris. Cook and Taylor (1975) found that the trilobites in similar units higher in the Hales Limestone are markedly different than those present in the *middle* fine-grained deposits. They concluded that the trilobites in the grainstones represent an assemblage displaced from the carbonate shelf into the deeper water slope environment. The presence of abundant echinodermal debris, ubiquitous in rocks of the subtidal shelf but restricted to grainstone units of the slope, further supports the interpretation of the allodapic nature of these coarse-grained carbonates. It is evident that substantial

paleoslopes existed in this part of the miogeocline, in sharp contrast to the very gentle relief of the subtidal-shelf environment.

PALEOGEOGRAPHIC SETTING

Text-figure 4 depicts our interpretation of the paleogeography of this segment of the miogeocline during middle-late *Elvinia* time. On the eastern edge of the continental shelf, in the zone of maximum wave and current action, cross-bedded, bioclastic grainstones accumulated on a high-energy shoal. Seaward of the shoal a broad (greater than 200 km wide) subtidal part of the shelf lay just below normal wave base. Burrowed, light gray, trilobite-echinoderm wackestones were deposited in this stable, low-energy environment. Water depths, although relatively shallow, had to have been great enough to maintain good water circulation over such a large area. Lack of tidal flat features or other evidence of subaerial exposure, and general absence of wave and current structures suggests water depths in the range of a hundred meters. A significant increase in paleoslope in central Nevada marked the boundary between the shelf and the deeper water slope deposits to the west. Laminated, dark gray, lime mudstones and wackestones dominate the slope environment. However, interspersed among these muddy carbonates are coarse allodapic grainstones made up largely of bioclastic debris transported from the shelf by gravity-flow mechanisms. Our paleogeographic interpretation is comparable to the ramp model described by Ahr (1973), in which grainstones are deposited near the surf zone adjacent to the mainland, and the sediments become muddier in a seaward direction. Ahr points out that this is opposite to the typical shelf model in which the landward facies are muddy and pass seaward into shelf-margin grainstones and boundstones.

The shelf-edge apparently stayed essentially in the same position into the Lower Ordovician (Cook and Taylor, 1975), and except for later deposition of coarse allochthonous conglomerates and the occurrence of slump structures, the slope environment appears to have remained constant. However, Cook and Taylor (1975) found evidence that following *Elvinia* time, shoal water and even tidal flat conditions developed over extensive areas of the previously subtidal shelf.



TEXT-FIGURE 4.—Cartoon depicting paleogeography of the miogeocline during middle-late *Elvinia* Zone. Broad subtidal shelf separating high-energy shoal to the east from slope environment just seaward of western shelf-margin. Not to scale.

SEDIMENTOLOGY OF THE PTEROCEPHALIID/PTYCHASPID
BIOMERE BOUNDARY

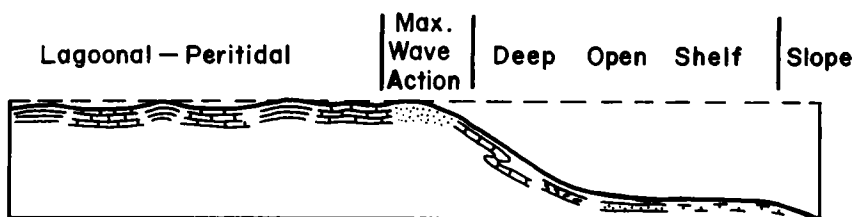
The top of the *Elvina* Zone coincides with the close of the Pterocephalid Biome, which is marked by the abrupt nonevolutionary extinction of several polymeroid trilobite species (Palmer, 1965). If the extinction of the trilobites was related to a major regressive phase as proposed by Lockman-Balk (1970) one would expect to find some manifestation of the change in environments preserved in the sedimentological record, particularly in deposits of the shoal-water shelf environments. However, we found a general lack of evidence for major changes in depositional environments at the Pterocephalid/Ptychaspid Biome boundary. Rather, it was not uncommon for the boundary to occur within what appeared to be a lithologically homogeneous unit.

Some deepening of the water is indicated near the top of the *Elvina* Zone in the vicinity of the House Range and northern Wah Wah Mountains (Text-fig. 2), where the rocks become darker and thinner bedded, and echinoderms decrease in abundance and are replaced by sponge spicules. This lithofacies change in the late *Elvina* Zone is approximately coincident with the appearance of the *Irvingella major* fauna, but precedes rather than coincides with the abrupt change in trilobite fauna at the top of the Pterocephalid Biome. However, upon examining the boundary at several other localities (Text-fig. 1) we found that it was not normally associated with an abrupt lithofacies change. Whatever the reason for the trilobite extinctions it did not noticeably affect the associated sediments. Therefore, we currently believe that the most likely cause of such a mass extinction would be modest reduction in temperature (Rowell and Brady, 1976). This could drastically affect the organisms without appreciably altering the nature of the accumulating sediments.

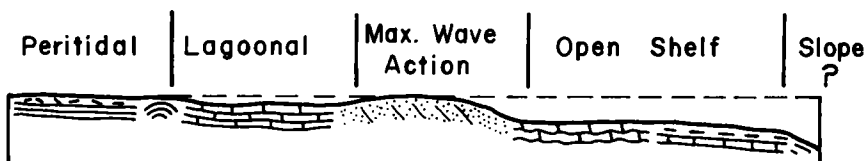
COMPARISON WITH SOME OTHER CAMBRIAN SHELVES
OF THE GREAT BASIN

It has become apparent that the nature of the environments which characterized the Cambrian miogeocline was not always the same, particularly in the continental shelf setting of which the low-relief open shelf of the middle and upper *Elvina* Zone is but one type (Text-fig. 5C). Detailed discussion of the different shelf models which have evolved from paleoenvironmental investigations in the Great Basin is beyond the scope of this paper; however, some general comparisons of them are worthy of mention.

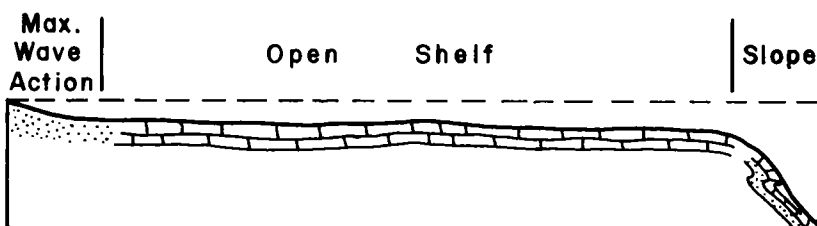
Brady and Koepnick (1973) interpreted the Middle Cambrian Marjum Formation exposed in the House Range of west central Utah as having been deposited on a relatively high-relief shelf (Text-fig. 5A). Algal laminated and pelleted dolomitic mudstones, many of which exhibit fenestral fabrics and contain intraformational conglomerate lenses, were deposited in the lagoonal and peritidal environments which dominated much of the shoal-water portion of the shelf. Wave ripples and desiccation features associated with these lithologies are further evidence of their shoal-water origin and periodic exposure. Cross-bedded, coated-grain packstones and grainstones accumulated on the edges of the shoals in the zones of maximum wave action. In the area of the House Range, these higher-energy deposits pass laterally into deeper water bioclastic wackestones and laminated mudstones with interbedded shales, which were deposited below normal wave base. The presence of sponge spicules, small-scale cross laminations, and microscopic cut-and-fill structures is typical of the dark, thin-bedded limestones of this environment. Relatively high depositional



A. HIGH RELIEF SHELF



B. LOW RELIEF SHELF



C. LOW RELIEF OPEN SHELF

TEXT-FIGURE 5.—Shelf types of the Middle and Upper Cambrian.

- (A) High-relief shelf—Marjum Formation of House Range, west central Utah.
- (B) Low-relief shelf—Johns Wash Limestone of eastern Great Basin.
- (C) Low-relief open shelf—Sneakover and Barton Canyon Limestone, eastern Great Basin.

slopes at the margins of the shoals are indicated by penecontemporaneous slump structures and debris lenses deposited by submarine slides. In a generally similar setting, but on a more regional scale, Kepper (1972) found evidence of a north-trending shoal separating a deeper water open shelf from a shallow shelf-lagoon during the Middle and early Late Cambrian in the eastern Great Basin.

Yet another type of miogeoclinal shelf is manifest in the Johns Wash Limestone exposed throughout much of west central Utah and east central

Nevada. Rees and others (1976) interpreted the Johns Wash Limestone of the House Range as reflecting deposition on a broad shelf on which an oolite shoal separated a shallow lagoon from a more open-marine environment to the west (Text-fig. 5B). Peritidal carbonates accumulated on an extensive tidal flat landward of the lagoon. Westerly progradation of these environments over a low-relief shelf resulted in the regressive carbonate sequence of the Johns Wash Limestone. Koepnick (1976) and Lilley (1976) have shown that the nature of the shelf throughout much of the eastern Great Basin during deposition of the Johns Wash Limestone was essentially the same as described by Rees and others (1976).

Thus, a minimum of the three types of shelves were developed in the miogeocline during the Middle and Late Cambrian. One was a high-relief shelf of which the Marjum Formation in the House Range is an example (Text-fig. 5A), the second was a low-relief shelf represented by the Johns Wash Limestone (Text-fig. 5B), and the third was the middle and upper *Elvinia* Zone low-relief open shelf characterized by widespread, blanket-like, subtidal carbonates (Text-fig. 5C). It is then readily apparent that whatever the tectonic setting of the Cordilleran miogeocline, no single depositional model can be universally applied to its interpretation.

ACKNOWLEDGMENTS

We wish to express our appreciation to R. B. Koepnick, W. W. Lilley, D. J. McBride, and M. N. Rees who worked with us in the Great Basin and helped formulate many of the ideas presented in this paper. We gratefully acknowledge the financial support of the National Science Foundation, Earth Science Section, for NSF grant GA-39692. We appreciate the support of the Wallace E. Pratt Fund provided to the University of Kansas by the Exxon USA Foundation. M. J. Brady also acknowledges the financial support of General Research Fund grants 3456-5038 and 3233-5038 of the University of Kansas. Roger B. Williams, Assistant Editor, *Treatise on Invertebrate Paleontology*, University of Kansas, kindly sketched the cartoon shown in Text-figure 4.

REFERENCES

- Ahr, W. M., 1973, The Carbonate Ramp: An alternative to the Shelf Model: Gulf Coast Assoc. Geol. Soc., Trans., v. 23, p. 221-25.
- Brady, M. J., and Ward, W. C., 1973, Carbonate facies of the northeastern Yucatan Shelf, Mexico: *The Mountain Geologist*, v. 11, p. 41-42.
- , and Koepnick, R. B., 1973, Transition from shelf to basinal carbonates in Middle Cambrian Marjum Formation of House Range, Western Utah—Paleoenvironmental analysis: *Amer. Assoc. Petrol. Geol. (abstr.)*, v. 57, p. 771.
- Burchfiel, B. C., and Davis, G. A., 1972, Structural framework and evolution of the southern part of the Cordilleran orogen, western United States: *Amer. J. Sci.*, v. 272, p. 97-118.
- Churkin, Michael, Jr., 1974, Paleozoic marginal ocean basin volcanic arc systems in the Cordilleran fold belt: in Dott, R. H., Jr., and Shaver, R. H. (eds.), *Modern and ancient geosynclinal sedimentation*: Soc. Econ. Paleont. Miner. Spec. Pub. 19, p. 174-92.
- Cook, H. E., and Taylor, M. J., 1975, Early Paleozoic continental margin sedimentation, trilobite biofacies, and the thermocline, western United States: *Geology*, v. 3, p. 559-62.
- Hintze, L. F., 1973, Geologic history of Utah: Brigham Young Univ. Geol. Studies, v. 20, pt. 3, no. 8, 181 p.
- Irwin, M. L., 1965, General theory of epeiric clear water sedimentation: *Amer. Assoc. Petrol. Geol. Bull.*, v. 49, p. 445-59.

- Kepper, J. C., 1972, Paleoenvironmental patterns in Middle to Lower Upper Cambrian interval in eastern Great Basin: *Amer. Assoc. Petrol. Geol. Bull.*, v. 56, p. 503-27.
- , 1975, Is the Middle Cambrian carbonate belt in the Basin and Range Region an algal biostrome?: *Geol. Soc. Amer. Abst. Prog.*, v. 7, p. 1144.
- Koepnick, R. B., 1976, Depositional history of the Upper Cambrian Pterocephaliid Biomere from west central Utah: *in* Robison, R. A., and Rowell, A. J. (eds.), *Paleontology and depositional environments: Cambrian of western North America: Brigham Young Univ. Geol. Stud.*, v. 23.
- Laporte, L. F., 1969, Recognition of a transgressive carbonate sequence within an epeiric sea: Helderberg Group (Lower Devonian) of New York State: *Soc. Econ. Paleont. Miner. Spec. Pub.* 14, p. 98-119.
- Lilley, W. W., 1976, Stratigraphy and paleoenvironments of the Pterocephaliid Biomere (Upper Cambrian) of western Utah and eastern Nevada: unpub. Ph.D. dissertation, University of Kansas, 151 p.
- Lochman-Balk, Christina, 1970, Upper Cambrian faunal patterns on the Craton: *Geol. Soc. Amer. Bull.*, v. 81, p. 3197-224.
- Palmer, A. R., 1965, Trilobites of the Late Cambrian Pterocephaliid Biomere in the Great Basin, United States: *U. S. Geol. Surv. Prof. Paper* 493, 105 p.
- , 1971, The Cambrian of the Great Basin and adjacent areas, western United States: *in* Holland, C. H. (ed.), *Cambrian of the New World*, Wiley Interscience, New York, p. 1-78.
- Rees, M. N., Brady, M. J., and Rowell, A. J., 1976, Depositional environments of the Upper Cambrian Johns Wash Limestone (House Range, Utah): *J. Sediment. Petrol.*, v. 46, p. 38-47.
- Rowell, A. J., and Brady, M. J., 1976, Anatomy of a biomere boundary. 25th Int. Geol. Cong. Proc., (in press).
- Stewart, J. H., 1972, Initial deposits in the Cordilleran geosyncline: evidence of a late Precambrian (< 850 m.y.) continental separation: *Geol. Soc. Amer. Bull.*, v. 83, p. 1345-60.
- , and Poole, F. G., 1974, Lower Paleozoic and uppermost Precambrian Cordilleran Miogeocline, Great Basin, western United States, *in* Dickinson, W. R. (ed.), *Tectonics and sedimentation: Soc. Econ. Paleont. Miner. Spec. Pub.* 22, p. 28-57.
- Wilson, J. L., 1974, Characteristics of carbonate-platform margins: *Amer. Assoc. Petrol. Geol. Bull.*, v. 58, p. 810-24.
- Wilson, J. L., 1975, Carbonate facies in geologic history: Springer-Verlag, New York-Heidelberg-Berlin, 471 p.

Brachiopods and Biomes

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ABSTRACT.—Inarticulate brachiopods of the Cambrian Pteropaliid Biome of the Great Basin are relatively abundant in limestones deposited in open-marine environments, but are rare or absent in rocks representing carbonate shoals and lagoons. Maximum species diversity of the brachiopods occurs in the *Dunderbergia* Zone; the pattern of chronological species diversity fluctuation is similar to that of the trilobites, but is nearly always substantially lower. In part, this difference in diversity may be a reflection of different degrees of competitive interaction, low among the brachiopods, substantially higher among the polymeroid trilobites. The same factor may explain the difference in the patterns of changing generic diversity between the two groups. The brachiopods were not markedly affected by the environmental crisis that was responsible for the nearly complete extinction of the shelf polymeroid trilobites of North America at the end of the biome, and we are unable to distinguish a brachiopod biome comparable to that in the trilobites. It is possible to recognize five brachiopod zones and subzones in the Pteropaliid interval. Their resolving power, relative to the trilobite zonal system, is variable, but is lower than that of the trilobite system below the *Dunderbergia* Zone, comparable to that of trilobites in the *Dunderbergia* Zone, and somewhat finer than it in the *Elvinia* Zone. Although it is possible by use of brachiopods to make gross time-correlation with the cratonic sequences to the east, the relatively low diversity in cratonic brachiopod assemblages precludes complete utilization of the zonal system available for the Great Basin. However, there is evidence to suggest that the base of the trilobite *Elvinia* Zone may be diachronous.

INTRODUCTION

The stratigraphic distribution of polymeroid trilobites in Upper Cambrian rocks of North America shows the effect of three biomes. Within each biome (Palmer, 1965a), the polymeroids are characterized by progressive evolutionary development and diversification followed by their abrupt extinction at the end of the biome. The succeeding trilobite fauna, at the beginning of the next biome, was seemingly established by immigration and was not closely related to that of the immediately underlying beds. Stitt (1971) has commented on the close similarity in the patterns of changing species diversity and species longevity in the three documented examples of a biome. He interpreted the patterns within each biome as a reflection of an adaptive radiation of an immigrant population and recognized four sequential stages in its development.

More recently, the factors influencing the geographical distribution of polymeroid trilobites have been studied. The most abrupt change in composition of contemporaneous faunas is seemingly related to the position of the animals relative to the permanent thermocline (Cook and Taylor, 1975). Trempealeauan trilobites of Asiatic type are inferred to have existed on the continental slope of western North America. They are markedly different taxonomically from the trilobites that occurred on the shelf to the east. Even on the shelf itself, there are conspicuous differences in the composition of the trilobite faunas. The forms that lived in outer shelf sites were commonly distinct from those that inhabited the carbonate-shoal areas and the inner shelf regions (Robison, 1975; Palmer and Campbell, 1975). Subtle changes in taxonomic composition of outer shelf faunas may be related to inferred periods of shallowing (McBride, 1975). Although a few shelf polymeroid trilobites were widely distributed, it is apparent

that the geographic distribution of many of them, even within an area as small as the Great Basin, was rather closely circumscribed by physical and, probably, biological environmental factors. Such restricted distribution may be regarded as a convenient, but rather crude, measure of degree of stenotopism. In this sense many of the polymeroid trilobites were relatively stenotopic.

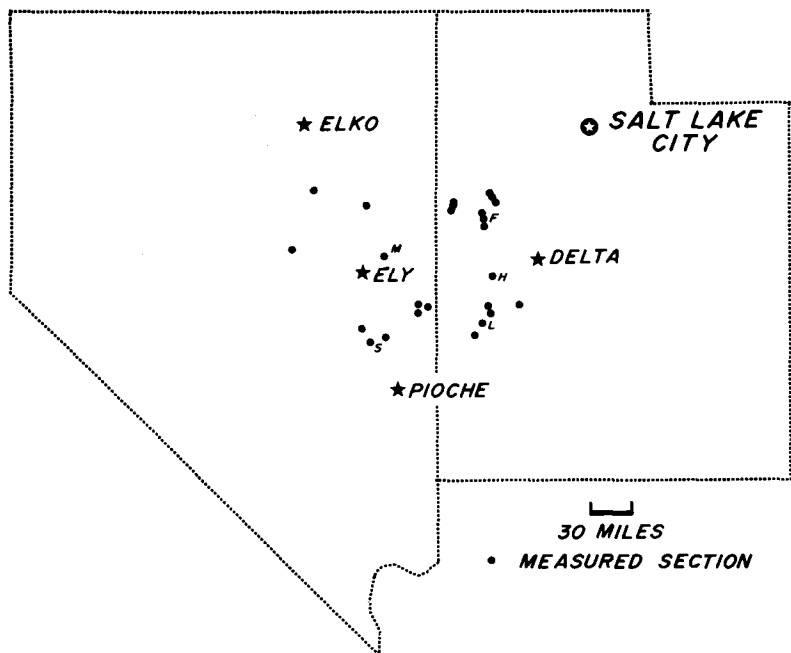
Previous studies by Palmer in Texas (1954), Grant in Montana (1965), and Kurtz in Missouri (1971) have documented the stratigraphic occurrence of brachiopods in the Upper Cambrian, but they have all been concerned with relatively low diversity, cratonic assemblages. Howe et al. (1972) and Kurtz et al. (1975), however, have very successfully demonstrated the stratigraphic utility of brachiopods in correlation, particularly with material derived from cores. In this paper, we wish to examine the geographical distribution of Cambrian inarticulate brachiopods in a miogeoclinal setting and to relate the pattern to that of the principal sedimentary environments as inferred from study of the containing rocks. Furthermore, we wish to discuss the fluctuations in brachiopod diversity within the bioterm and compare them with those of the polymeroid trilobites. Finally, we shall pursue some of the problems in biostratigraphy that arise from a comparison of brachiopod and trilobite distributions between the miogeocline and the craton.

For this study, we have chosen to utilize the brachiopods of the Pterophaeliid Bioterm in what one may regard at its type area, the Great Basin. Brachiopods are relatively abundant in carbonate rocks within the miogeocline and their species diversity is much higher than that of the cratonic sequences. Many of the taxa that occur in the region are new and are being described by Rowell and McBride. Details of their taxonomy, however, are of relatively little consequence in the ensuing discussion.

DEPOSITIONAL FRAMEWORK

Although inarticulate brachiopods are common fossils in the Cambrian of the Great Basin, they are not ubiquitous and their distribution is nonrandom. To appreciate the broad factors controlling their geographic (and stratigraphic) distribution, it is necessary to digress briefly and summarize some aspects of the results of our studies, and those of our student colleagues, on the major depositional environments that prevailed during the late Dresbachian and early Franconian of the Great Basin, the time interval spanning the Pterophaeliid Bioterm. These studies are based on field data and petrologic examination of material from 25 measured sections distributed in a generally east-west transect across western Utah and eastern Nevada (Text-fig. 1). Details of them are available elsewhere (Rees et al., 1976; Brady and Rowell, 1976; Koepnick, 1976; Lilley, 1976), but the changing patterns of depositional environments may be readily summarized as in Text-figure 2.

We believe that the sediments were deposited on a gently westward sloping shelf. Terrigenous clays were deposited over much of the area during *Aphelaspis*-*Prehousia* time, and in the western part of the region, clay deposition continued until late *Elvinia* time. During this interval, carbonates accumulated episodically and the resulting rock sequence consists of alternations of shales and limestones. The boundary between inner and outer shelf sediments of Text-figure 2 is rather arbitrary. The limestones of the inner shelf facies tend to be cleaner, with less mud. Thin beds of stromatolitic limestone and flat pebble conglomerate are moderately common in this facies. During most of the interval from *Aphelaspis* to early *Elvinia* time, a carbonate platform complex occurred in the region.

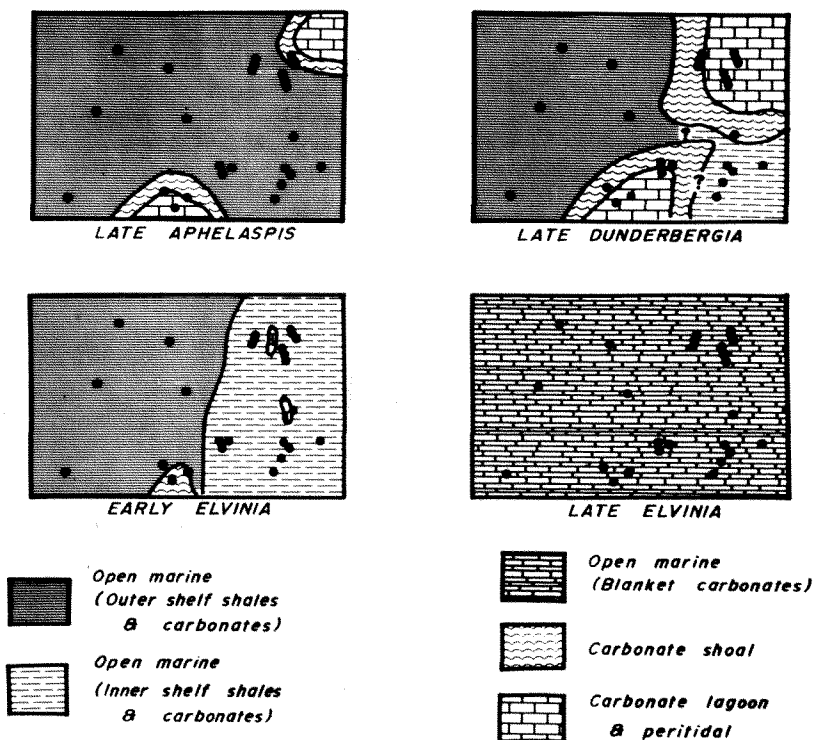


TEXT-FIGURE 1.—Location of measured sections of the Pterocephaliid Biome. F—Fish Springs Range, H—House Range, L—Lawson Cove, M—McGill, and S—Shingle Pass.

It was a relatively minor feature until late *Dunderbergia* time (Text-figs. 2A and 2B) when extensive progradation markedly increased its area. A diversity of lithologies occurs in the carbonate complex, but for our immediate purposes we may simplify the pattern by recognizing two major facies. One is a shoal-water facies in which grainstones, commonly oolitic, are predominant, and the other is a combined lagoonal-peritidal facies characterized by pelletoidal mudstones, fenestral mudstones, and stromatolitic boundstones. The platform complex was terminated over most of the area in early *Elvinia* time by an influx of clay, which, together with thin limestone beds, forms the Corset Spring Shale and its lithic equivalents. This was the last major incursion of terrigenous material into the region during the Cambrian. By the middle of *Elvinia* time, carbonate was being deposited across the entire width of the miogeocline. This carbonate belt was both structurally and environmentally quite unlike that which occurred earlier in the bioterm (Brady and Rowell, 1976); not only was it much more extensive and homogenous, but it was also entirely subtidal in origin.

FACTORS CONTROLLING BRACHIOPOD DISTRIBUTION

Text-figure 3 shows diagrammatically the stratigraphic sequence of inferred depositional facies at five localities in the region, together with the location of samples that were processed for inarticulate brachiopods. The sections were selected to give some appreciation of the variability in the sequences, but this

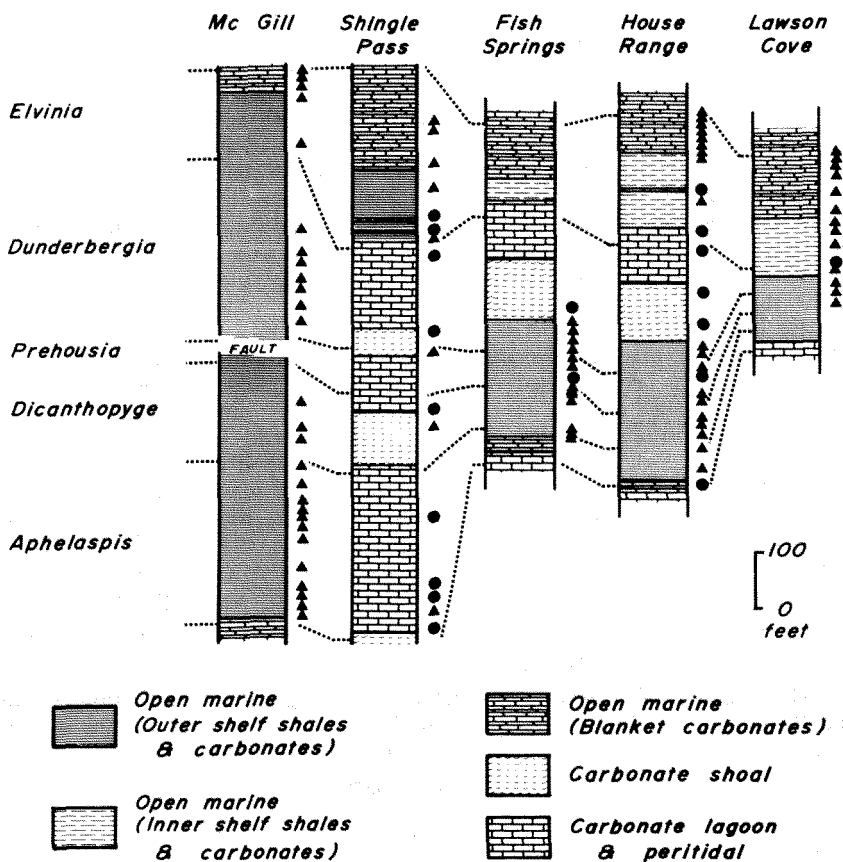


TEXT-FIGURE 2.—Inferred depositional environments during the Pteroecephaliid Biomere. Control points shown by black dots.

point is not critical to the subsequent discussion. It is apparent, merely by inspection of the diagram, that brachiopods are absent or poorly represented in both the shoal-water and lagoonal-peritidal deposits. They are commonly absent from the former even when trilobites are present.

The abundant trilobite and brachiopod faunas that occur in the carbonates of the outer and inner shelf, shale-carbonate sequences, and in the subtidal carbonates at the top of the biomere suggest that those rocks accumulated under normal-marine conditions with good circulation. Such a view is consistent with their sedimentological characteristics. If one groups together the samples from these three environments and compares them for presence/absence of brachiopods with the samples from both the shoal water and lagoonal-peritidal deposits, the resulting χ^2 value of 52.79 is highly significant ($p < .005$). The statistic merely confirms the result of inspecting the figure. It does not imply that there is a direct causal relationship between the inferred depositional environment and the relative absence of brachiopods, although it does provide a license to seek such a relationship.

Kepper (1974) has previously noted the antipathetic relationship between trilobites and stromatolites and inferred that the activities of the animals inhibited the establishment of a persistent algal mat. He believed that well



TEXT-FIGURE 3.—Location of samples in five stratigraphic sections. Samples yielding brachiopods shown by triangles, samples processed but lacking brachiopods or containing only abraded fragments shown by circles. Location of sections shown in Text-fig. 1.

developed stromatolites could form only when environmental conditions were such that burrowing or grazing animals were unable to survive, probably because of elevated salinity. Although the inarticulate brachiopods themselves would probably not have had deleterious effects on the algal mats, Kepper's model would predict the observed rarity of brachiopods associated with the carbonate platform complex. There are certainly indications that, over much of its extent, the platform was a high-stress environment. In the Johns Wash Limestone of the House Range (Rees et al., 1976), for example, the lagoonal deposits of the platform, although pelleted, are virtually devoid of body fossils. The pelletoids are possibly of fecal origin, although other methods of formation could be invoked, but given the general regional setting of the beds, the absence of recognizable fossils can be most readily explained by postulating abnormal salinity or temperature fluctuation or both in the waters of the lagoon. That brachiopods are absent in the peritidal deposits of the carbonate platform

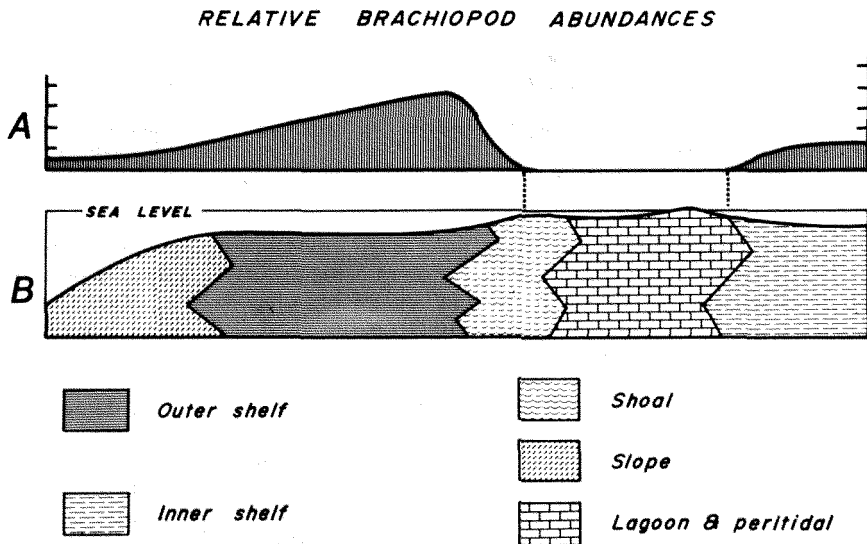
is hardly surprising. Intertidal brachiopods, although known, are relatively rare. Supratidal forms have never been recorded and from what is understood of the physiological requirements of members of the phylum it is unlikely that they ever invaded this environment.

The relative absence of brachiopods from deposits of the shoal-water environment of the platform is probably to be correlated more with the lack of substrate stability rather than with high salinity or temperature fluctuation. The majority of the inarticulate brachiopods are small; maximum length is commonly between 1 and 2 mm. Such animals would find difficulty as an epifauna attached to ooids of comparable dimension in a relatively high-energy environment. Occasional individuals did become established, presumably on more sheltered parts of the shoal, because rare, well-preserved specimens, usually lingulides, occur in acid residues of rocks from this depositional site. More commonly, brachiopod material consists of comminuted fragments that are inferred to have been washed onto the shoal and buried, rather than being subsequently washed off it.

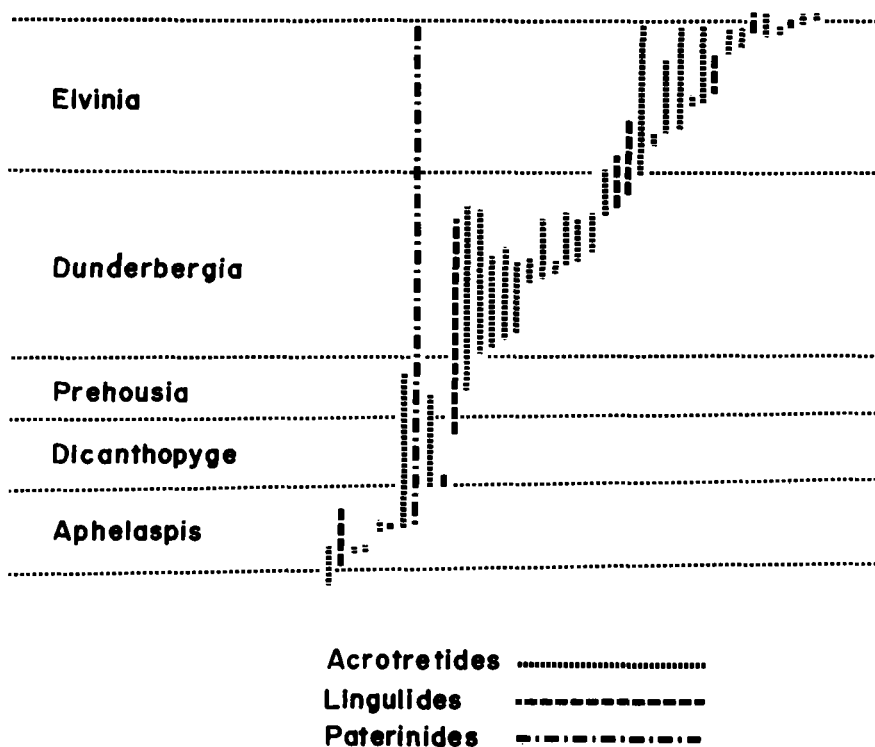
Text-figure 4 summarizes rather subjectively and diagrammatically our impression of the distribution of inarticulate brachiopod abundances across the shelf. They are typically most abundant in outer shelf sites, but our very limited data from the Hot Creek Range of Nevada suggest that abundance declines markedly in the deeper water slope region (Taylor, 1975). This distribution pattern is not unlike that of the agnostid trilobites (Robison, 1975), but inarticulate brachiopods tend to occur more abundantly than agnostids on inner shelf sites.

STRATIGRAPHIC DISTRIBUTION

The pattern of inarticulate brachiopod stratigraphic distribution within the Pterocephaliid Biome is shown in Text-figure 5. Acrotretaceans are the dominant component of the fauna, but lingulides are also common. The majority



TEXT-FIGURE 4.—Diagrammatic reconstructed cross-section (B) and related subjective impression of relative brachiopod abundances (A).



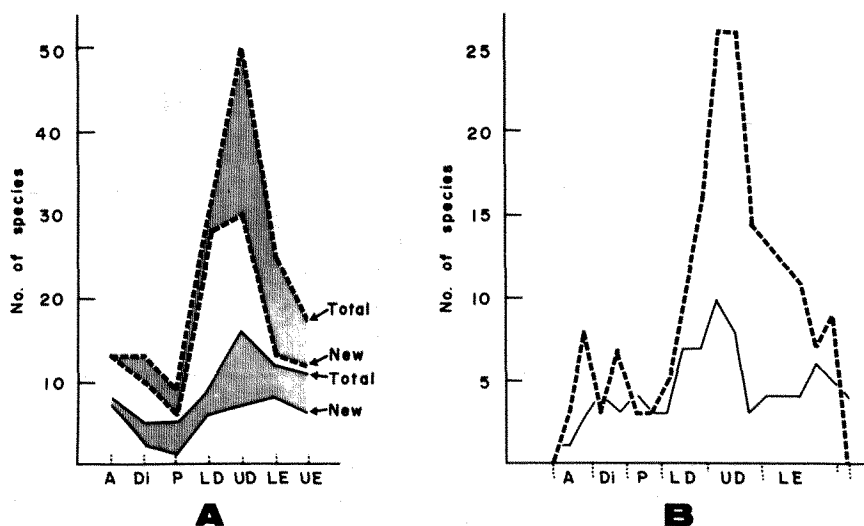
TEXT-FIGURE 5.—Composite stratigraphic range chart of inarticulate brachiopod species within the Pteroccephaliid Biome of the Great Basin.

of the lingulides are best referred to *Lingulella*, but two other genera occur, one of which is new. Siphonotretaceans are relatively rare, but two genera are represented. The only other order of inarticulates present is the Paterinida. A species of *Micromitra* ranges throughout most of the biome, and a second form, referred to *Dictyonina*, occurs in the lower part.

Details of the biostratigraphy, together with a systematic account of the taxa involved, will be presented in a monograph currently in preparation by Rowell and McBride. Several aspects of more general stratigraphic and paleobiological interest are, however, noteworthy.

Fluctuation of brachiopod diversity within the biome

The changing pattern of brachiopod species diversity (Text-fig. 5) shows many similarities with that of the polymeroid trilobites (Palmer 1965b, plate 21). The similarities are more apparent when the data are recast. Text-figure 6A was compiled from the corresponding composite range charts and shows both the total number of species recorded from each time-span interval and the number of taxa that are first recorded in that interval. The time spans used are the *Aphelaspis*, *Dicanthopyge*, and *Prehousia* Zones together with Lower and Upper *Dunderbergia* Zones and Lower and Upper *Elvinia* Zones. One



TEXT-FIGURE 6.—(A) Total number and number of new species of polymeroid trilobites (broken line) and inarticulate brachiopods (solid line) appearing within the seven trilobite zones and subzones of the Pterocephaliid Biome.

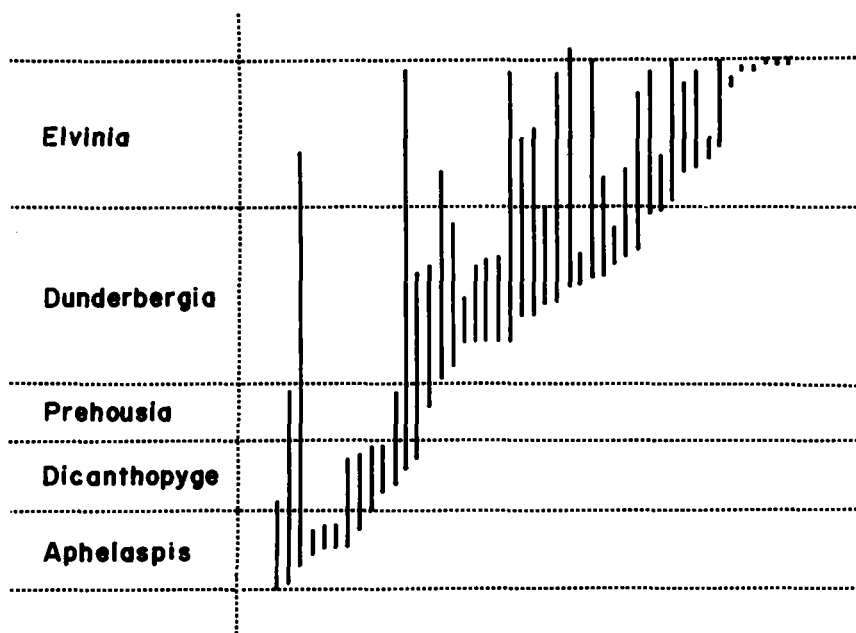
(B) Number of species of polymeroid trilobites (broken line) and inarticulate brachiopods (solid line) present at 19 equally spaced transects across respective composite range charts (see text). A—*Apbelaspis* Zone, D—*Dicanthopyge* Zone, P—*Prebousia* Zone, LD—Lower *Dunderbergia* Zone, UD—Upper *Dunderbergia* Zone, LE—Lower *Elvinia* Zone, UE—Upper *Elvinia* Zone.

cannot claim that each of these intervals represents an equivalent period of time; therefore some caution is required in interpreting the figure. This is a problem that has been discussed by several authors, most recently by Harper (1975) and Boucot (1975). It is obvious, however, both from Text-figure 5 and Text-figure 6B, that maximum species diversity occurs in the *Dunderbergia* Zone. Text-figure 6B was compiled from species counts along 19 equally spaced transects across the composite range charts for polymeroid trilobites and inarticulate brachiopods of the biome. Although these 19 transects are equally spaced in the figure, they are, of course, nonmetric. Fluctuations in the brachiopod and trilobite species diversity of this figure are correlated: the Spearman rank correlation of 0.4 is significantly different from zero ($0.05 > p > 0.01$). Raup et al. (1973) have warned of the dangers of over-interpreting diagrams of this type and their advice is timely. However, in this particular case, the similarity in species diversity patterns of the trilobites (Stitt, 1971) of all known biomes suggests that some underlying nonstochastic casual mechanism may be operative, as suggested by Bretsky and Lorenz (1970). The behavior of the brachiopods supports this view, for although the polymeroids were undergoing a major adaptive radiation (Stitt, 1971), the brachiopods were not. Many of their genera were extant long before the beginning of the biome.

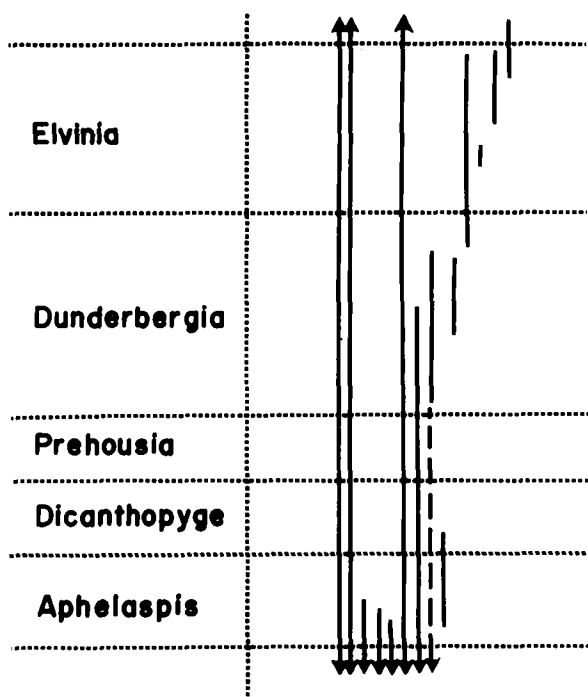
Although much remains to be learned about the feeding habits of Paleozoic brachiopods and trilobites, our present understanding suggests that brachiopods were either filter feeders, or fed on dissolved nutrients, or possibly utilized both mechanisms (McCammon, 1969; Cowan, 1971; Suchanek and Levinton,

1974). In contrast, the majority of the shelf polymeroid trilobites were probably detritus feeders, although others may have been hunters (Bergström, 1973). If this is the case, some generalizations concerning the relationship between trophic groups and evolutionary turnover rate are in need of modification. Levinton (1974) has recently argued that the evolutionary turnover rate for suspension feeders should be greater than that of detritus feeders. The statement is perhaps true of the bivalves with which he worked, but is inconsistent with our data. Text-figure 6A shows that the advent of new species of trilobites into the biomere in the Great Basin, which must have been a function of speciation, was typically two or three times higher than for the brachiopods. Furthermore, the mean generic longevity of the trilobites was substantially less than that of the brachiopods (Text-figs. 7 and 8) during this interval. Neither result would be predicted by the Levinton model.

Stanley (1974) has discussed the effects of differences in intensity of competition on rates of adaptive radiation. The essence of his argument is that forms exhibiting low levels of competition would diversify slowly and substantial niche overlap could occur, whereas forms which had intense competitive interactions would radiate rapidly and have narrowly defined, clearly demarcated niches. He believed that animals, like the bivalves, which are characterized by weak competition would show "... primitive, inflexible behavior; uncrowded, sedentary modes of life; generalized feeding habits; the ability to withstand long periods of near-starvation; and limitation of population size by predation and physical environmental factors so that food is seldom in short supply." (Stanley, 1974, p. 502). In contrast, intense competitive interactions might be anticipated in mobile animals that had developed



TEXT-FIGURE 7.—Composite stratigraphic range chart of polymeroid trilobite genera of the Pterocephaliid Biomere of the Great Basin (derived from Palmer, 1965b).



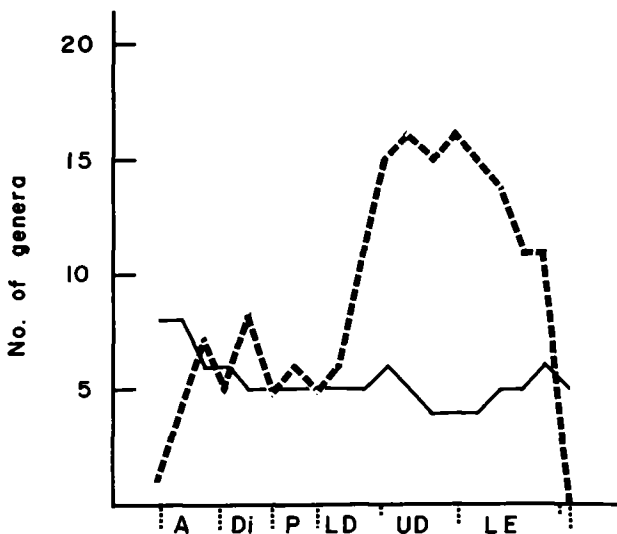
TEXT-FIGURE 8.—Composite stratigraphic range chart of the inarticulate brachiopod genera of the Pterocephaliid Biome of the Great Basin.

complex behavior patterns, had rather specialized feeding habits and were food limited. There is little direct information on the level of competition in either the inarticulate brachiopods or the trilobites. Stanley (1974, p. 502) has previously discussed some of the limited indirect evidence to support the view that trilobites competed. By analogy with many living crustaceans (Crane, 1975), he believed that they probably exhibited territorial behavior. Levinton (1974, p. 581) concluded that deposit feeders in general would tend to compete and be niche specific as a response to the relative stability of their trophic resources. The arguments that have been advanced to regard the bivalves as forms in which competitive interactions were minimal (Stanley, 1974) apply, to a considerable extent, to the brachiopods. Competition for space may have been intense in some of the reef-dwelling forms like the lytoniaceans and richthofeniaceans, as it probably was for the rudist bivalves. In general, however, competition for space was probably not a major factor, and the mean level of competitive interaction was probably low. The difference in rate of speciation shown in Text-figure 6A could be explained in this manner: the available data are consistent with Stanley's thesis, although the level of corroboration is not high.

Difference in level of competitive interaction may explain another enigma in the data. Although the patterns of species diversity in trilobites and brachiopods are similar (Text-fig. 6B), those of the comparable generic diversities

are quite different (Text-fig. 9). Text-figure 9 was produced in the same manner as Text-figure 6B from the composite generic range charts of Text-figures 7 and 8. The diversity of trilobite genera shows basically the same pattern as that of the trilobite species, reaching a maximum in the *Dunderbergia* Zone. The brachiopod generic curve, in contrast, is completely different, and for most of the bioterm, oscillates between 4 and 6 genera, giving the impression of being in equilibrium. It is probable that the inferred higher level of competition between trilobite species led to a greater adaptive shift per speciation event, which, in turn, was expressed as a greater mean morphological divergence at speciation. If competitive interactions between brachiopod species were low, greater niche overlap could be tolerated and adaptive displacements could be modest. These differences would be reflected in current taxonomic practice by recognizing more genera of trilobites than of brachiopods. Only rarely would the adaptive displacement at speciation in the latter group produce a morphological displacement of sufficient magnitude to merit the erection of a new genus. This rationale is basically the same as that advanced by Stanley (1974, p. 498) to explain the different frequencies of sibling species in the Mollusca and Vertebrata that had previously been noted by Mayr (1963), but, in this instance, it is applied to a higher taxonomic category.

It is also possible that the difference in generic diversity patterns is caused, in part, by difference in the relative position of the two groups in their radiation and the intensity of the radiations. The earliest stage of the inarticulate brachiopod radiation is as yet unknown, but must have occurred in the early Early Cambrian. By the middle Early Cambrian, regional diversity was typically in the order of 4 or 5 genera (Rowell, 1976). Data are sparse, but the value would appear to rise to a maximum of 8 genera present at any given



TEXT-FIGURE 9.—Number of genera of trilobites (broken line) and inarticulate brachiopods (solid line) at 19 equally spaced transects across respective composite range charts (Text-figs. 7 and 8). Abbreviations as Text-fig. 6.

moment in the middle Late Cambrian, and have fluctuated between this and 4 or 5 genera throughout the remainder of the period. Thus, by the beginning of the Pterocephaliid Biomere, the first phase of radiation of the inarticulate brachiopods was essentially complete and the total number of genera, if it was rising at all, was doing so very slowly. The radiation of the polymeroids was markedly different; at the family group level, virtually the entire radiation occurred during the time span of the Pterocephaliid Biomere. Consequently, one observes a rapid buildup in the number of genera and an equally dramatic decrease at the close of the biomere, for only one polymeroid genus, *Simulolenus*, is known to range into the overlying Ptychaspid Biomere.

Fluctuations of the brachiopod fauna at and close to the upper biomere boundary

Stitt (1971) observed that in the three documented examples of a biomere there was a notable phase of polymeroid extinction near the end of the biomere (the end of his stage 3), followed by a brief stage of diversification that ended in the final extinction phase which terminated stage 4. This final crisis is not detectable in the brachiopods; three of the four species that occur immediately below the biomere boundary are present in beds immediately above it. All four of the genera that occur at the top of the Pterocephaliid Biomere are found in younger rocks. The situation at the base of the Pterocephaliid Biomere is comparable in that eight genera found in its basal beds all cross the biomere boundary and are known in the underlying "*Crepicephalus*" Zone.

The extinction at the end of Stitt's stage 3 does, however, appear to be expressed in the brachiopods. Six acrotretides occur in the upper part of stage 3 of the Pterocephaliid Biomere, but none of them have been found in the *Irmigella major* beds of stage 4, nor have they been recorded in the basal strata of the Ptychaspid Biomere (Text-fig. 5). The brachiopods of the Ptychaspid Biomere of the Great Basin are not well known and it is possible that some of the six species may reappear above the basal beds. However, comparable forms have not been recorded elsewhere from rocks of this age and their extinction appears to be real. Of the four genera involved, two undoubtedly persist into younger beds, the third is a new siphonotretacean which is known at present only from the *Elvinia* Zone, and the fourth is *Linnarssonella*. *Linnarssonella* is abundant in the *Elvinia* Zone of North America, but has not been found in younger strata.

The only other nontrilobite component of the fauna whose stratigraphic distribution throughout a biomere is reasonably well known are the conodonts of the Ptychaspid Biomere (Miller, 1975). Their behavior relative to the trilobite faunal crisis at the ends of stages 3 and 4 is comparable to those of the brachiopods in the underlying biomere. Significant extinction occurs at the close of stage 3, immediately beneath the *Corbima apopopsis* Subzone, but the terminal biomeric extinction at the end of stage 4 is not reflected in the conodonts. Although additional data are required, it begins to appear that the extinction at the close of stage 3 of a biomere was more pervasive than that of stage 4, in that other elements of the total fauna were affected.

Comparison of brachiopod species diversity between the miogeocline and the craton

The contrast in diversity of inarticulate brachiopod species between the miogeocline and the localities on the craton is marked, particularly in the *Dunderbergia* and *Elvinia* Zones. In the *Dunderbergia* Zone of the Great Basin,

for example, we presently recognize some 16 species of inarticulates, 12 of them acrotretides, whereas only three acrotretides have been recorded from the beds of comparable age in Missouri (Kurtz, 1971; Kurtz et al., 1975). The recorded diversity of the "post-*Aphelaspis*" Zone beds of Texas is similar to that of Missouri; five inarticulate brachiopod species have been noted, three of them acrotretides (Palmer, 1954). In part, this difference between miogeoclinal and craton may be a reflection of the poor representation of the *Dunderbergia* Zone on the craton and the magnitude of pre *Elvinia* erosion. However, this is clearly not the complete explanation, for the same distinction in diversity is apparent in the *Elvinia* Zone, which is well represented in both tectonic sites. Seventeen inarticulate brachiopod species of this age are known from the Great Basin in contrast to five from Montana, one from Texas, and four from Missouri (Grant, 1965; Bell and Ellinwood, 1962; Kurtz, 1971; Kurtz et al., 1975).

It is difficult to isolate the factors responsible for the observed difference in diversity. It is possible that the miogeoclinal region offered a greater variety of habitats than did the craton, but the mean within-habitat diversity of the miogeoclinal region is greater than that of the craton, so this again is not the entire explanation. It seems probable that the closer proximity of the miogeoclinal region to the open ocean may have been the primary factor. In this setting, the water of the miogeoclinal region would have been readily buffered, both physically and biologically, by oceanic water masses. Salinity and temperature fluctuations would, on average, have been less in the miogeoclinal region and nutrient supply would probably have been more stable than in the cratonic interior. All of these are factors that have been claimed to lead to increased biotic diversity (Sanders, 1969). At the present time, it is not possible to say which of them was the most significant in its effects, but their combined action was probably responsible for both the higher species diversity in the miogeoclinal region, and the location of the area of maximum brachiopod abundance within it, which has been previously discussed.

Biostratigraphic outline and problems

Within the Great Basin, it is possible to recognize five brachiopod assemblage zones and subzones in the Pterocephaliid Biome, but neither the base nor the top of the biome exactly coincides with the boundary of a brachiopod zone. The stratigraphic resolution of the zones relative to the existing trilobite zonal system is variable. The lowermost zone is large and spans all of the *Prehousia* and *Dicanthopyge* zones together with much of the *Aphelaspis* Zone. The succeeding zone almost exactly coincides with the trilobite *Dunderbergia* Zone (as used in the Great Basin) and, like it, is divisible into two subzones. The upper two zones are equivalent to the *Elvinia* Zone below the *Irvingella major* faunule.

This brachiopod zonal system can be fully utilized only within the Great Basin. A few species are very widespread and have been recorded wherever Cambrian rocks of the appropriate age have been investigated. *Linnarssonella girtyi* is probably the most conspicuous example (Bell, 1941), but forms belonging to its putative ancestral group, the *Apsotreta expansa* species complex, occur in most Late Dresbachian sequences. With the usual assumptions, widespread taxa such as these allow approximate time-correlation between the miogeoclinal succession and the cratonic sequences to the east. The low diversity of the cratonic faunas, however, does not allow complete recognition of all the biozones and subzones that are recognizable in the Great Basin. For example, the taxa which permit recognition of two brachiopod zones, that

are approximately equivalent to the *Elvinia* Zone, are presently unknown in the cratonic areas and technically these biozones are absent on the craton.

There is one conspicuous and significant chronostratigraphic problem that arises in a comparison of the brachiopod and trilobite sequences of the Great Basin with those of Missouri. In both regions, species of the *Apsotreta expansa* complex are followed stratigraphically by forms referred to *Linmarssonella*. It is usually argued that the two groups are phylogenetically related (Kurtz, 1971) and all available evidence corroborates the implied hypothesis. *Apsotreta expansa* is followed by populations of somewhat similar gross morphology, but many of its individuals have a low dorsal median ridge, and all possess grooved dorsal propareas. Kurtz (1971) has termed such forms *Linmarssonella costa*. This latter species is morphologically intermediate between *A. expansa* and the younger *Linmarssonella girtyi* in the form of the median septum. It is a blade in *A. expansa*, a low ridge in most individuals of *L. costa*, and absent in *L. girtyi*. The first appearance of *L. costa* in this lineage might reasonably be taken as defining a chronohorizon. However, in the Great Basin, the oldest *L. costa* occur in the late *Dunderbergia* Zone, for example, they are in association with trilobites characteristic of this zone some 40 feet below the first appearance of the *Elvinia* Zone fauna at Cherry Creek, Nevada. In contrast, Kurtz et al. (1975) have recorded *A. expansa* from the early *Elvinia* Zone of Missouri and specimens referred to *L. costa* make their first appearance some 5 feet above the base of the *Elvinia* Zone. There is no overwhelming evidence to suggest that the first appearance of either *L. costa* or *Elvinia roemeri* is isochronous, but clearly both cannot be so. Details of the phylogeny of *Elvinia* are less well known. Unlike *L. costa*, one cannot recognize with any confidence the putative ancestor of *Elvinia roemeri*. As Palmer (1975, personal communication) has commented, it seems unlikely that the speciation event that produced *L. costa* was of long duration and perhaps the first appearance of this form is a better indicator of an event than the initial appearance of *Elvinia* in any one section. Whatever the correct explanation, it is apparent that the difference in the velocities of the signal (in the sense of Kitts, 1966) was not zero. The difference between the two is hardly spectacular; nonetheless, it sounds a note of caution, and reminds us of the assumptions that are implicit in chronostratigraphic correlation.

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REFERENCES

- Bell, W. C., 1941, Cambrian brachiopods from Montana: *J. Paleont.*, v. 15, p. 193-255.
- , and Ellinwood, H. L., 1962, Upper Franconian and Lower Trempealeuan trilobites and brachiopods, Wilberns Formation, central Texas: *J. Paleont.*, v. 36, p. 385-423.
- Bergström, J., 1973, Organization, life, and systematics of trilobites: *Fossils and Strata*, v. 2, p. 1-69.
- Boucot, A. J., 1975, Standing diversity of fossil groups in successive intervals of geologic time viewed in the light of changing levels of provincialism: *J. Paleont.*, v. 49, p. 1105-11.
- Brady, M. J., and Rowell, A. J., 1976, An Upper Cambrian subtidal blanket carbonate, eastern Great Basin: in Robison, R. A., and Rowell, A. J. (eds.), *Paleontology and depositional environments: Cambrian of western North America*: Brigham Young Univ. Geol. Studies., v. 23, pt. 2.
- Bretsky, P. W., and Lorenz, D. M., 1970, Adaptive response to environmental stability: a unifying concept in paleoecology. *N. Amer. Paleont. Conv.*, Chicago, 1969, Proc. E, p. 522-50.
- Cook, H. E., and Taylor, M. J., 1975, Early Paleozoic continental margin sedimentation, trilobite biofacies, and the thermocline, western United States: *Geology*, v. 3, p. 559-62.
- Cowen, R., 1971, The food of articulate brachiopods—a discussion: *J. Paleont.*, v. 45, p. 137-39.
- Crane, J., 1975, Fiddler crabs of the world (*Ocypodidae*: Genus *Uca*): Princeton University Press, Princeton, 736 p.
- Grant, R. E., 1965, Faunas and stratigraphy of the Snowy Range Formation (Upper Cambrian) in southwestern Montana and northwestern Wyoming: *Geol. Soc. Amer.*, Mem. 90, 171 p.
- Harper, C. W., Jr., 1975, Standing diversity of fossil groups in successive intervals of geologic time: a new measure: *J. Paleont.*, v. 49, p. 752-57.
- Howe, W. B., Kurtz, V. E., and Anderson, K. H., 1972, Correlation of Cambrian strata of the Ozark and upper Mississippi Valley regions. *Missouri Geol. Surv. and Water Resources*, Dept. of Investigations, No. 52, 60 p.
- Kepper, J. C., 1974, Antipathetic relation between Cambrian trilobites and stromatolites: *Amer. Assoc. Petrol. Geol. Bull.*, v. 58, p. 141-43.
- Kitts, D. B., 1966, Geologic time: *J. Geol.*, v. 74, p. 127-46.
- Koepnick, R. B., 1976, Depositional history of the Upper Cambrian Pterocephaliid Biome from west central Utah: in Robison, R. A., and Rowell, A. J. (eds.), *Paleontology and depositional environments: Cambrian of western North America*: Brigham Young Univ. Geol. Stud., v. 23, pt. 2.
- Kurtz, V. E., 1971, Upper Cambrian Acrotretidae from Missouri: *J. Paleont.*, v. 45, p. 470-76.
- , Thacker, J. L., Anderson, K. H., and Gerdemann, P. E., 1975, Traverse in Late Cambrian strata from the St. Francis Mountains, Missouri to Delaware County, Oklahoma: *Missouri Dept. of Natural Resources, Rept. of Inv.*, no. 55, 112 p.
- Levinton, J. S., 1974, Trophic group and evolution in bivalve molluscs: *Paleont.*, v. 17, p. 579-85.
- Litley, W. W., 1976, Stratigraphy and paleoenvironments of the Pterocephaliid biome (Upper Cambrian) of western Utah and eastern Nevada: unpub. Ph.D. thesis, University of Kansas.
- Mayr, E., 1963, *Animal species and evolution*. Harvard University Press, Cambridge, 797 p.
- McBride, D. J., 1975, Cambrian communities: competition or coexistence?: *Geol. Soc. Amer. Abstr. Prog.*, v. 7, p. 1193.
- McCammon, H., 1969, The food of articulate brachiopods: *J. Paleont.*, v. 43, p. 976-85.

- Miller, J. F., 1975, Conodont faunas from the Cambrian and lowest Ordovician of western North America: Geol. Soc. Amer. Abst. Prog., v. 7, p. 1200-01.
- Palmer, A. R., 1954, The faunas of the Riley Formation in Central Texas. J. Paleont., v. 28, p. 709-86.
- , 1965a, Biomere—a new kind of stratigraphic unit: J. Paleont., v. 39, p. 149-53.
- , 1965b, Trilobites of the Late Cambrian Pteroccephalid Biomere in the Great Basin, United States. U. S. Geol. Surv. Prof. Paper 493, 105 p.
- , and Campbell, D. P., 1975, Biostratigraphic implications of trilobite biofacies: *Albertella* Zone, Middle Cambrian, western United States: Geol. Soc. Amer. Abst. Prog., v. 7, p. 1222-23.
- Raup, D. M. S., Gould, S. J., Schopf, T. J. M., and Simberloff, D. S., 1973, Stochastic models of phylogeny and the evolution of diversity. J. Geol., v. 81, p. 525-42.
- Rees, M. N., Brady, M. J., and Rowell, A. J., 1976, Depositional environments of the Upper Cambrian Johns Wash Limestone (House Range, Utah): J. Sediment. Petrol., v. 46, p. 38-47.
- Robison, R. A., 1975, An alternate Middle Cambrian trilobite zonation for the Great Basin: Geol. Soc. Amer. Abst. Prog., v. 7, p. 1249-50.
- Rowell, A. J., 1976, Early Cambrian Brachiopods from the southwestern Great Basin of California and Nevada: J. Paleont., (in press).
- Sanders, H. L., 1969, Benthic marine diversity and the stability-time hypothesis: Brookhaven Symposium Biol., v. 22, p. 71-80.
- Stanley, S. M., 1974, Effects of competition on rates of evolution, with special reference to bivalve molluscs and mammals. Syst. Zool., v. 22, p. 486-506.
- Stitt, J. H., 1971, Repeating evolutionary pattern in Late Cambrian trilobite biomes. J. Paleont., v. 45, p. 178-81.
- Suchanek, T. H., and Levinton, J., 1974, Articulate brachiopod food: J. Paleont., v. 48, p. 1-5.
- Taylor, M. E., 1976, Upper Cambrian of western North America. Trilobite biofacies, environmental significance, and biostratigraphic implication in Kaufman, E. G., and Hazel, J. E. (eds.), Concepts and methods in biostratigraphy. Soc. Econ. Paleontologists and Mineralogists, (in press).

Continental Shelf and Slope Facies in the Upper Cambrian and Lowest Ordovician of Nevada

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ABSTRACT.—Integrated paleontological and sedimentological analysis of the Upper Cambrian-lowest Ordovician Whipple Cave Formation and lower House Limestone of eastern Nevada, and coeval parts of the Hales Limestone of central Nevada suggests that a change exists in depositional regime from shoal-water shelf to deeper water slope.

The Whipple Cave Formation contains about 600 m of biostromal and biohermal lenses of algal stromatolites, fenestral limestone, flat-pebble conglomerate, lime grainstone, and other carbonate rocks normally associated with shoal-water environments. In contrast, 170 km to the west, the coeval part of the Hales Limestone is only a third to a quarter as thick and consists of dark hemipelagic limestone and interbedded debris and turbidity-flow deposits. The mass-flow deposits reflect mobilization of slumps and sediments from both slope and shelf-margin sites to the east, and redeposition in deeper water environments to the west.

Trilobites in debris-flow deposits derived from the shelf show strong taxonomic differences from those in *in situ* slope deposits. Redeposited trilobites have affinities with faunas from shoal or higher slope habitats typical of areas of carbonate deposition in North America. *In situ* trilobite assemblages from slope sediments resemble those assemblages in deeper water deposits of southeastern Asia, but not those in shallow-water deposits of either North America or Asia.

A paleogeographic model is developed for the shelf-to-slope transition in Nevada on the basis of analogy with Holocene shelf-margin and slope sedimentation and biofacies patterns.

INTRODUCTION

Traditionally, studies of the North American Cambrian have concentrated mainly on the use of trilobites as tools for stratigraphic correlation. Pioneer work by Wilson (1957), Lochman-Balk and Wilson (1958), and Palmer (1960, 1971) has recognized the importance of major biofacies "realms" or "belts," and Palmer (1965a, b; 1973) has stressed the importance of trilobite biofacies in both temporal and paleozoogeographic distribution studies. Most studies have been based principally on an inductive analysis of large amounts of taxonomic and stratigraphic data. Results have provided understanding of the broader patterns of Cambrian history and, in large part, have provided the conceptual framework for most subsequent North American Cambrian research. However, most biofacies models have been of limited usefulness for making comparisons with models for other geologic systems, or for comparison with taxonomic groups other than trilobites. In contrast, our approach is to pose questions that are amenable to an integrated paleontological and sedimentological analysis. Interpretations are compared with Holocene models of faunal distribution and sedimentary processes. Results provide implications for biological and physical processes that were operating during the Late Cambrian and earliest Ordovician. Thus, an integrated sedimentological and paleontological approach may have a synergistic effect. We hope this procedure will yield information that can be more readily compared with biofacies analyses of other geologic systems.

GEOLOGICAL FRAMEWORK

The broad classification of lower Paleozoic rocks of the Great Basin by Roberts and others (1958) includes an eastern assemblage of miogeosynclinal carbonate rocks, a western assemblage of eugeosynclinal siliceous rocks, and a transitional assemblage of intermediate composition. More recent syntheses have compared these facies assemblages with Holocene tectonic and depositional models. The paleogeographic model that emerges is one in which lower Paleozoic rocks of the Great Basin reflect a broad continental shelf and either an adjacent marginal ocean-basin and volcanic-arc system (Burchfiel and Davis, 1972; Churkin, 1974) or an adjacent open oceanic basin (Dietz and Holden, 1966; Stewart, 1972; Stewart and Poole, 1974).

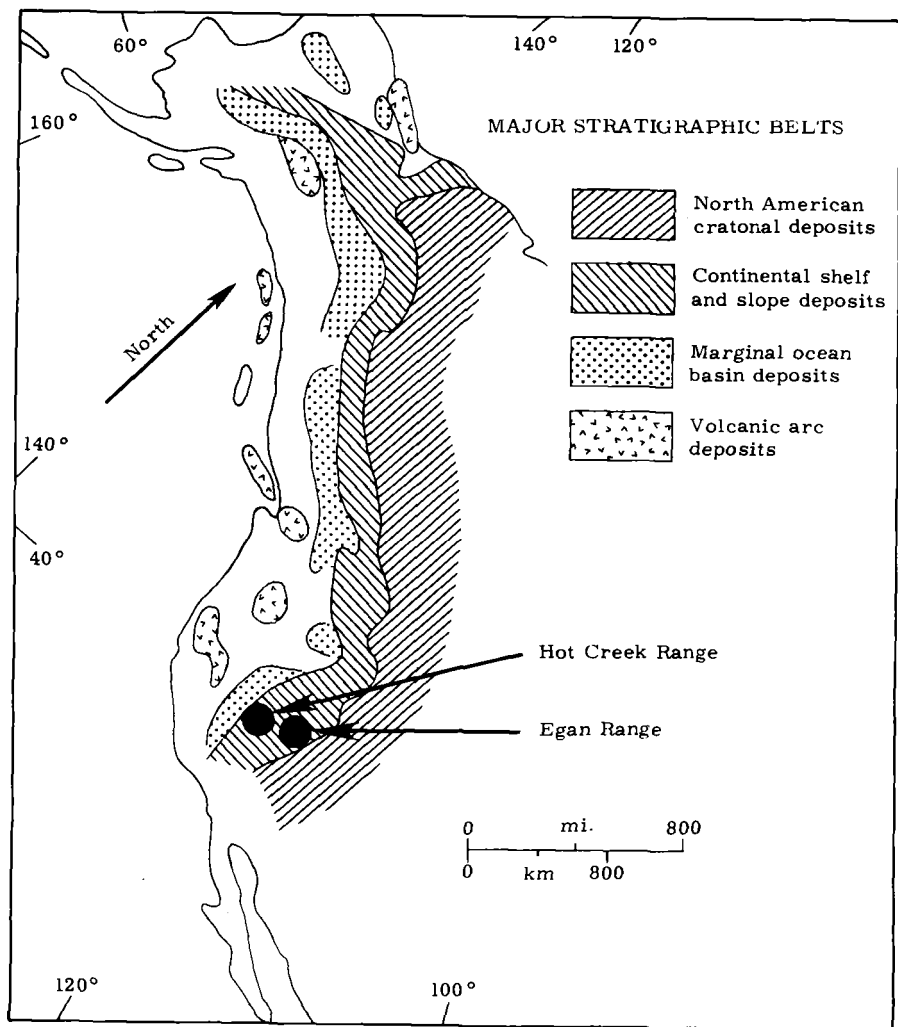
Our objectives are to better understand the paleogeographic significance of the "eastern assemblage" thick carbonates and the "transitional assemblage" thin carbonates and shales, and to relate them to proposed paleogeographic models. Two sections of Upper Cambrian and lowermost Lower Ordovician rocks were selected for detailed study: (1) the Whipple Cave Formation of Kellogg (1963) and the lower House Limestone in the central Egan Range of eastern Nevada, which represent the eastern assemblage carbonates; and (2) the Hales Limestone in the Hot Creek Range of central Nevada, which represents the transitional assemblage. Text-figure 1 shows the general location of the Egan and Hot Creek sections in relation to major stratigraphic belts in western North America.

In an earlier summary paper (Cook and Taylor, 1975), we concluded that the Whipple Cave Formation and lower House Limestone of the Egan Range represent shoal-water deposition on a shallow carbonate shelf, whereas the Hales Limestone in the Hot Creek Range represents deeper water depositional environments on an ocean-facing slope. Detailed systematic analysis of the trilobite faunas is under study or reported elsewhere (Taylor, 1971 and other unpubl. data; Taylor, 1976a). Here we present data on the lithologic characteristics of the shelf and slope rocks, taphonomic characteristics of the entombed fossils, and some aspects of the trilobite faunas that bear on paleogeographic significance of the shelf-to-slope transition in the Great Basin.

SHOAL WATER ENVIRONMENTS—CENTRAL EGAN RANGE

The Whipple Cave Formation of Kellogg (1963) and the lower part of the House Limestone comprise about 650 m of marine carbonate rocks, deposited in environments ranging from shallow subtidal to supratidal (Text-fig. 2). From the base of the section upward, the sedimentation history is one of progressively shallowing water, which records a westerly seaward progradation of the carbonate platform.

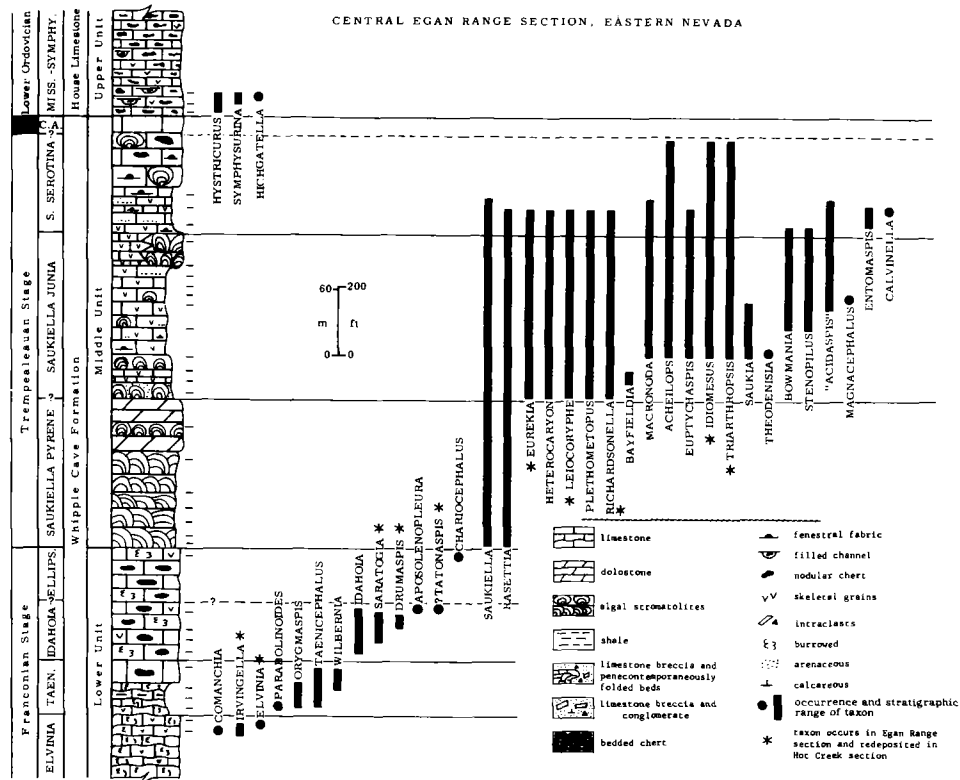
For convenience of discussion, the central Egan Range section is here divided into three informal units (Text-fig. 2) based on lithologic and faunal characteristics considered to have environmental significance. The lower unit consists of the lower 200 m of the Whipple Cave Formation. It is composed primarily of argillaceous limestone in 1- to 2-cm-thick beds that form recessive slopes. This interval is characterized by wavy bedding surfaces, sedimentary boudinage (Text-fig. 3), patchy and unevenly distributed clay mudstone lenses (Text-fig. 4), and abundant bioturbation (Text-fig. 5). Texturally the rocks are mudstone and wackestone. The main fabric constituents are trilobites, possible sponge spicules, lime mud, and peloids. The lower unit probably



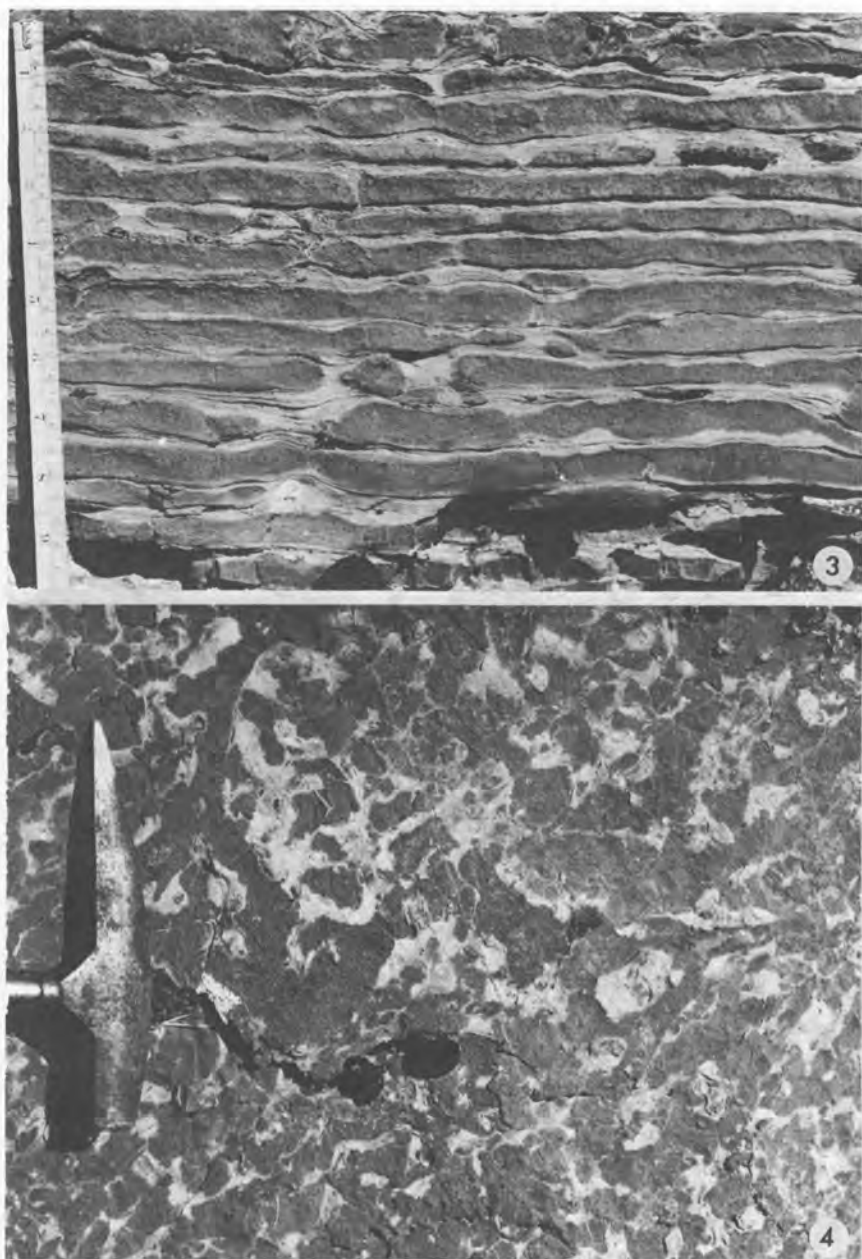
TEXT-FIGURE 1.—General location of sections in the Hot Creek Range and central Egan Range, Nevada, in relation to major regional stratigraphic belts. Map generalized from Churkin (1974).

represents deposition on a shallow subtidal, low-energy open shelf seaward of algal banks and tidal flats with little influence by wave action. The dominant faunal elements are parabolinoïdids and other trilobites typical of the North American Faunal Province.

We concur with Wilson (1969, p. 17) that the kind of sedimentary boudinage common in the lower unit suggests deposition in shallow subtidal shelf waters below active wave base but within well-oxygenated water. It is not a rock fabric typically seen either in deeper water carbonate settings or in shelf

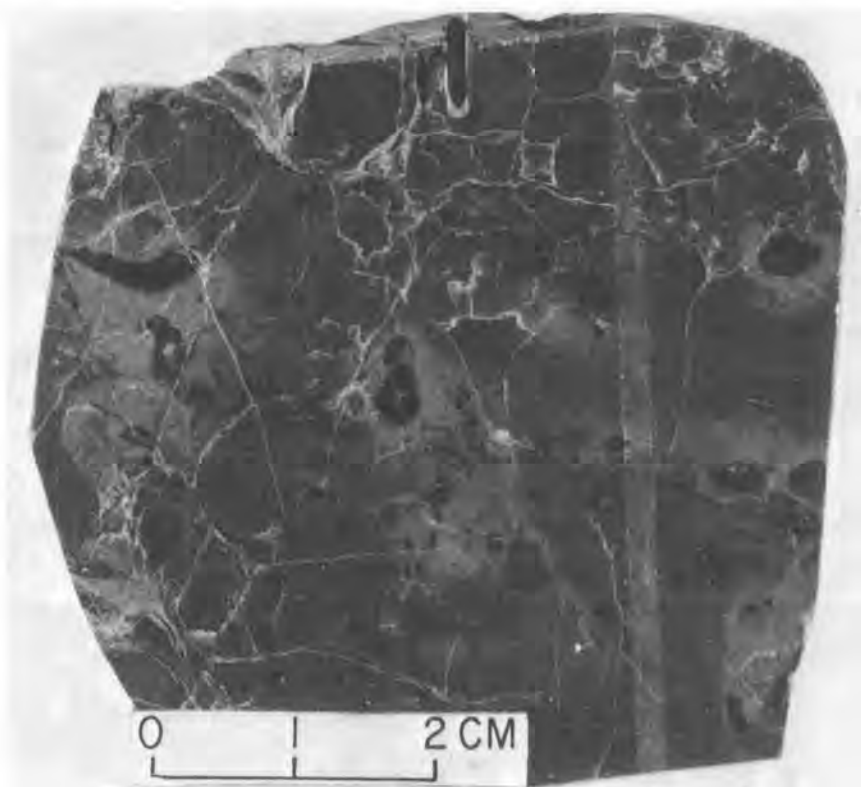


TEXT-FIGURE 2.—Range of polymeroid trilobite genera recognized from the Whipple Cave Formation and lower House Limestone in the central Egan Range, Nevada. The section was measured on the west face of the Egan Range near Lund, Nevada. *C.A.*, *Corbinia apopsis* Subzone of *Saukia* Zone; not recognized in measured section, but known to occur 170 km north in Cherry Creek Mountains. Dashes on right side of column show position of fossil samples.



TEXT-FIGURE 3.—Lower unit of Egan Range section. Dark gray argillaceous lime mudstone and wackestone showing typical sedimentary boudinage bedding. Light-colored irregular lenses contain more abundant clayey material than do darker beds.

TEXT-FIGURE 4.—Bedding-plane view of same beds shown in Text-fig. 3.



TEXT-FIGURE 5.—Polished slab of lime wackestone from lower unit, Egan Range section. Note abundant bioturbation and lighter-colored burrow linings. View parallel to bedding.

lagoon or tidal flat environments. This interpretation is further strengthened by the stratigraphic position of the unit directly below and gradational with rocks having distinctive shoal water features, and by its field characteristics that clearly contrast with those of contemporaneous sediments deposited farther oceanward.

The upper 380 m of the Whipple Cave Formation constitutes the middle unit, which crops out as light-colored resistant cliffs along the west face of the central Egan Range. These rocks have characteristics that indicate shallow subtidal to supratidal deposition. Much of this interval contains algal buildups composed of laterally linked hemispheroids. Individual algal heads are as much as 30 cm in diameter (Text-fig. 6). Three types of buildups occur. The most common one is sheetlike and ranges from 1 to 2 m in thickness and 75 m or more in length. Also common are pillow-shaped buildups about 2 m thick and 5 m long (Text-fig. 7). Total areal extent of both types is unknown. A third, less common type consists of single isolated stromatolites as much as 20 cm high and 50 cm long. Total relief on any of these algal buildups probably did not exceed more than a few tens of centimeters at any



TEXT-FIGURE 6.—Bedding-plane view of algal stromatolites from middle unit of Egan Range section.

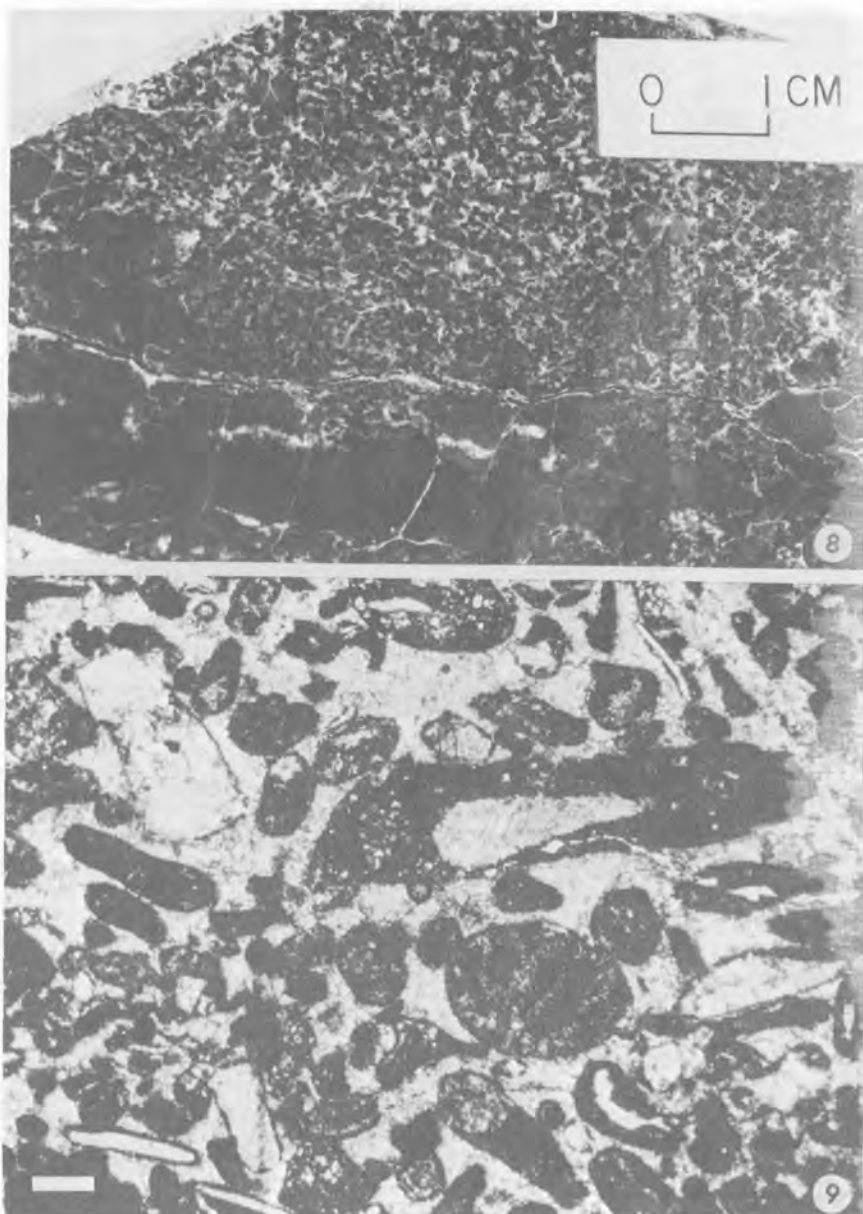
one time. In cross section, the buildups can be seen to interfinger with centimeter-thick beds of clastic limestone (Text-fig. 7). Also, on bedding-plane surfaces the tops of laterally linked algal heads have no more than a few centimeters of relief which is in-filled with clastic limestone debris.

Sediment types interfingering and interbedded with algal buildups consist of fenestral limestone and ribbon limestone (lime mudstone interbedded with lime packstone and grainstone in centimeter-thick beds). Grain-supported fabrics are composed of skeletal grains of echinoderms, gastropods, trilobites, the possible-alga *Ninia*, and peloids and oncolites (Text-figs. 8, 9, 10). Ribbon limestones have scour and fill features, cross-bedding, and occasional pebble-sized intraclasts of lime mudstone.

Depositional environment of the middle unit is inferred to have been one of moderately high energy where algal mats flourished in peritidal habitats. Fenestral or birdseye fabrics suggest intertidal environments (Shinn, 1968), as does ribbon limestone (Ebanks, 1967). Ribbon limestone, scour and fill, and cross-bedding indicate a moderate amount of current activity. Lime mud was not removed from this environment but was selectively winnowed and alternately deposited with grain-supported beds to form the ribbon limestones. Thus, a supply of lime mud was available for the stromatolites to trap and bind. At times, small phototrophic algal hemispheroid mounds were subjected to adverse conditions and ceased to grow. These conditions probably occurred during storms when sudden influxes of sediment buried the algal



TEXT-FIGURE 7.—Algal buildups in middle unit of Egan Range section. Light-colored massive lenses in upper part of photograph are composed of coalescing hemispherical algal stromatolites. Thinly bedded lime grainstone layers lap over and interfinger with algal buildups. Lime grainstone is composed of peloids and skeletal grains of trilobites, gastropods, echinoderms, and the possible-alga *Nuia*. Bar scale equals approximately 1 m.



TEXT-FIGURE 8.—Lime grainstone interbedded with algal stromatolites from middle unit of Egan Range section. Sand-sized grains are composed of *Nuia*, echinodermal plates, and peloids. Large dark-colored pebbles are lime mudstone.

TEXT-FIGURE 9.—Photomicrograph of lime grainstone shown in Text-fig. 8. Most grains are *Nuia* and coated echinodermal grains. Middle unit, Egan Range section. Bar scale equals 0.2 mm.



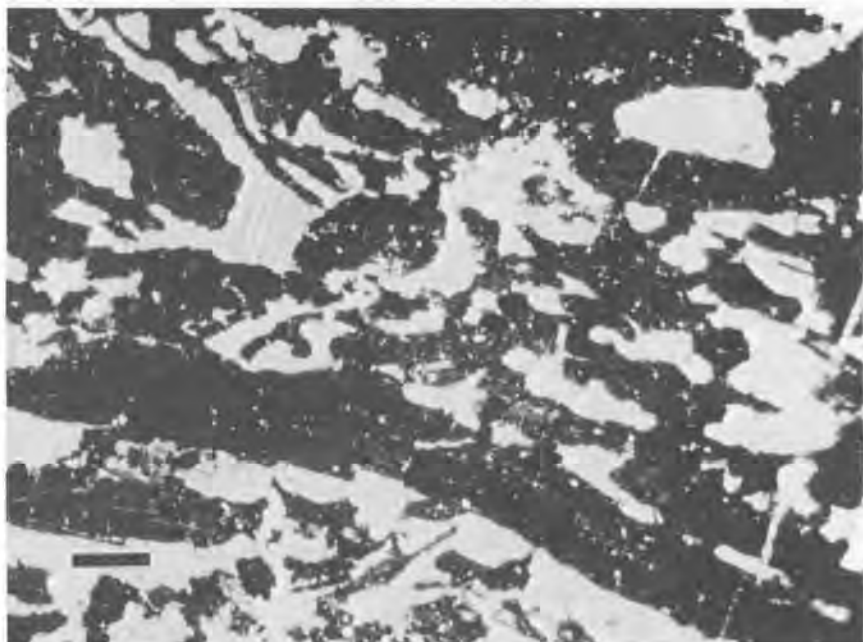
TEXT-FIGURE 10.—Bedding-plane view of lime packstone-grainstone associated with algal buildups in middle unit of Egan Range section. Bed contains abundant hyolithoid, gastropod, and trilobite skeletal debris.

mats. This is suggested by normally graded grainstone and wackestone in beds as much as 20 cm thick that occasionally are draped over the stromatolite heads without any evidence of upward algal growth through the bed.

The upper unit consists of the lower 50 m of the House Limestone, and contains abundant beds of flat-pebble breccia and conglomerate that alternate with dolomitic lime mudstone and fenestral limestone (Text-fig. 11). Scattered throughout the unit is light-brown and pink chert in lenses and complexly interconnected nodules. Breccia and conglomerate commonly fill shallow channels (Text-fig. 12) or form thin sheets having essentially flat-parallel lower and upper contacts (Text-fig. 13). Clasts in the breccia are lime mudstone or dolomitized lime mudstone fragments (Text-fig. 14). Skeletal debris and trace fossils are less common in the upper unit. The lower House Limestone in this area is interpreted to represent deposition on tidal flats. This environment commonly contains flat pebbles, channels, laminated lime mudstone, and early-dolomitized lime mudstone (Roehl, 1967; Shinn, 1968; Shinn and others, 1969; Bathurst, 1971; Cook, 1972).

DEEPER WATER ENVIRONMENTS—HOT CREEK RANGE

The Hales Limestone in the Hot Creek Range, central Nevada, contains vastly different rocks and faunas from those in the coeval Whipple Cave and lower House formations 170 km to the east (Text-figs. 2 and 15). Stratigraphic



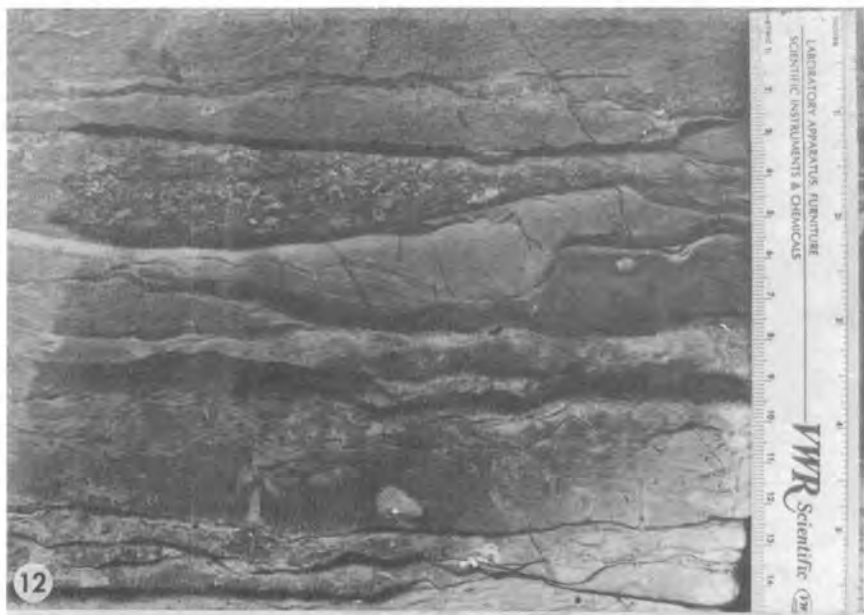
TEXT-FIGURE 11.—Photomicrograph showing fenestral fabric in limestone from upper unit of Egan Range section. Bar scale equals 0.5 mm.

correlation between the two areas is complicated by strong biofacies differences (Taylor, 1976a).

The lower 200 m of the Hales Limestone (Text-fig. 15) consists of rocks interpreted as slope deposits. Dark fine-grained hemipelagic limestone is interbedded with numerous gravity-flow debris deposits derived from both shallow-shelf and higher slope settings to the east. Criteria for the recognition of coarse-grained allochthonous carbonate deposits in deeper water environments have been summarized by Cook and others (1972). Most of the rocks in the Hot Creek section are dark gray to black shaly lime mudstone and wackestone, interpreted as *in situ* slope deposits (Text-figs. 16, 17). These sediments are characterized by millimeter-thick parallel laminae and only rare evidence of burrowing (Text-fig. 16). The associated fauna consists of pervasive sponge spicules and trilobites unknown from either the shallow-shelf environments in the Egan Range, or elsewhere in the North American Faunal Province.

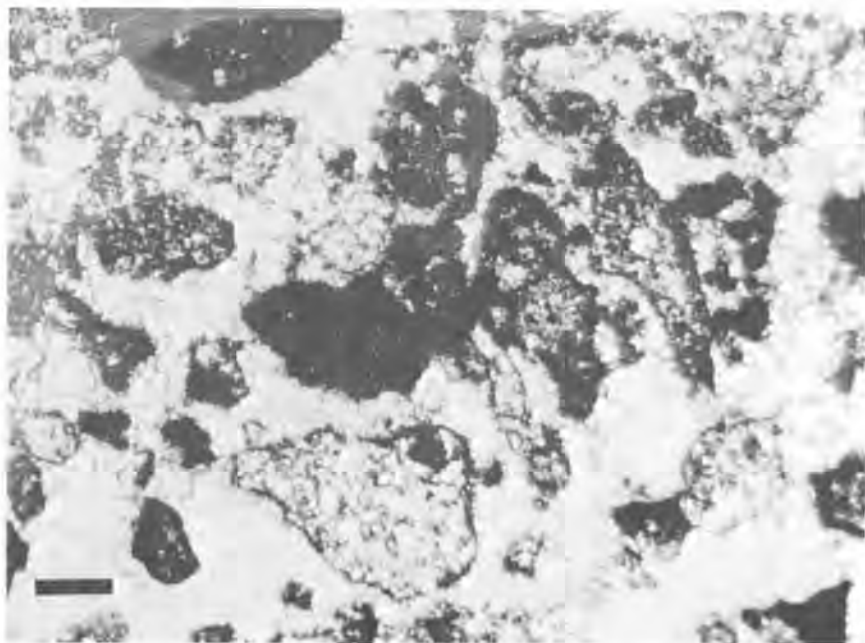
A large proportion of the dark laminated spicular lime mudstones show different degrees of slumping and transformation into debris and turbidity-flow deposits. Slope-derived slump and debris-flow units range from a few centimeters to 10 m in thickness (Text-figs. 18, 19). Intraclasts range from pebble size to boulders 2' x 3 m across. In these debris beds, both intraclasts and matrix were derived from deeper water sources.

Some debris-flow beds consist of sheetlike and channel-form deposits containing intraclasts of both shoal- and deeper water origin (Text-fig. 20). These beds reach a maximum thickness of one meter. Interclast matrix (Text-



TEXT-FIGURE 12.—Channel-form deposits of partly dolomitized limestone from upper unit of Egan Range section.

TEXT-FIGURE 13.—Partly dolomitized flat-pebble conglomerate and lime grainstone matrix from upper unit of Egan Range section.



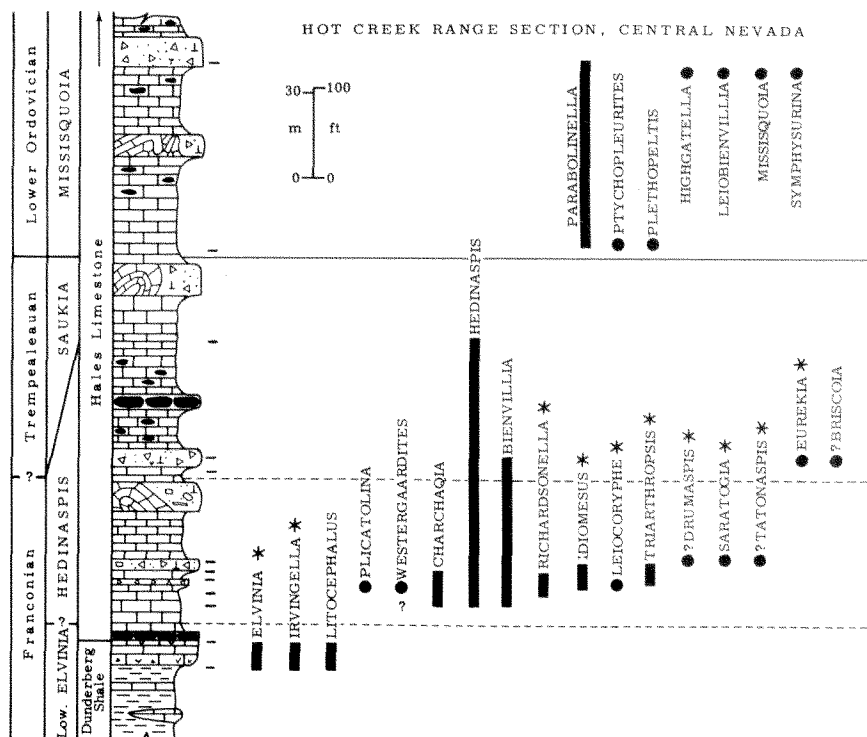
TEXT-FIGURE 14.—Photomicrograph of bed shown in Text-fig. 13. Rock is a mixture of dolomitic limestone clasts (light colored with dark rims) and limestone clasts (dark colored). Bar scale equals 0.5 mm.

fig. 21) is composed of skeletal debris consisting of *Ninia* grains, echinodermal plates, and other skeletal material similar to that found commonly in the coeval shoal-water rocks of the Egan Range. The shoal-water grains are admixed with spicular lime mudstone and trilobite debris. Normal grading of intra-clasts is common (Text-fig. 20); beds show abundant tabular shaped intra-clasts, some of which are imbricated (Text-fig. 22). In addition, coarse-textured debris-flow beds are occasionally capped by planar- and cross-laminated sand-sized skeletal and lithic grains (Text-fig. 22). In some instances, mass-flow beds are only a few centimeters thick and contain only trilobites that have affinities with shoal-water faunas typical of the North American Faunal Province (Text-fig. 23).

CORRELATION

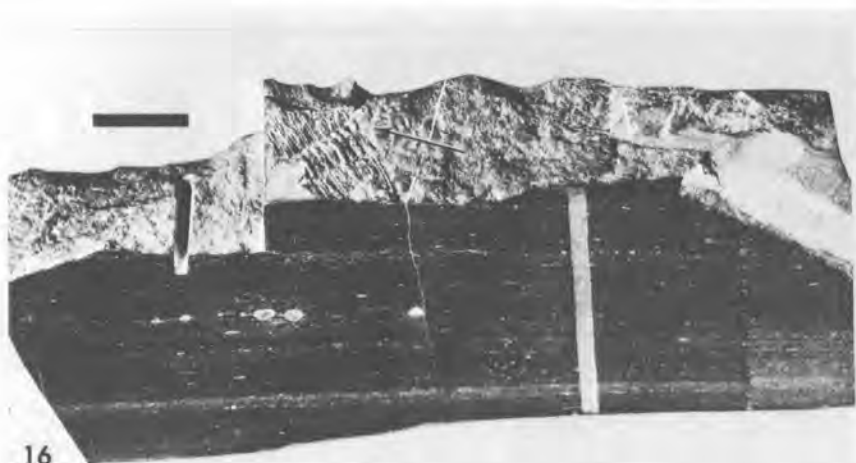
The occurrence of shoal-water trilobite taxa typical of the Egan Range section in allochthonous debris-flow deposits of the Hales Limestone provides a basis for correlation (Text-fig. 24).

Correlation of the Franconian-Trempealeuan boundary in the Hales presents problems in part because of the strong biofacies differences. Emphasis is placed on the occurrence of *Eurekia* above beds containing *?Drumaspis*, *Saratogia*, and *?Tatonaspis* (Taylor, 1976a). Because all four taxa occur in allochthonous debris-flow beds, their occurrences are, at best, an imprecise basis for recognizing the Franconian-Trempealeuan boundary.



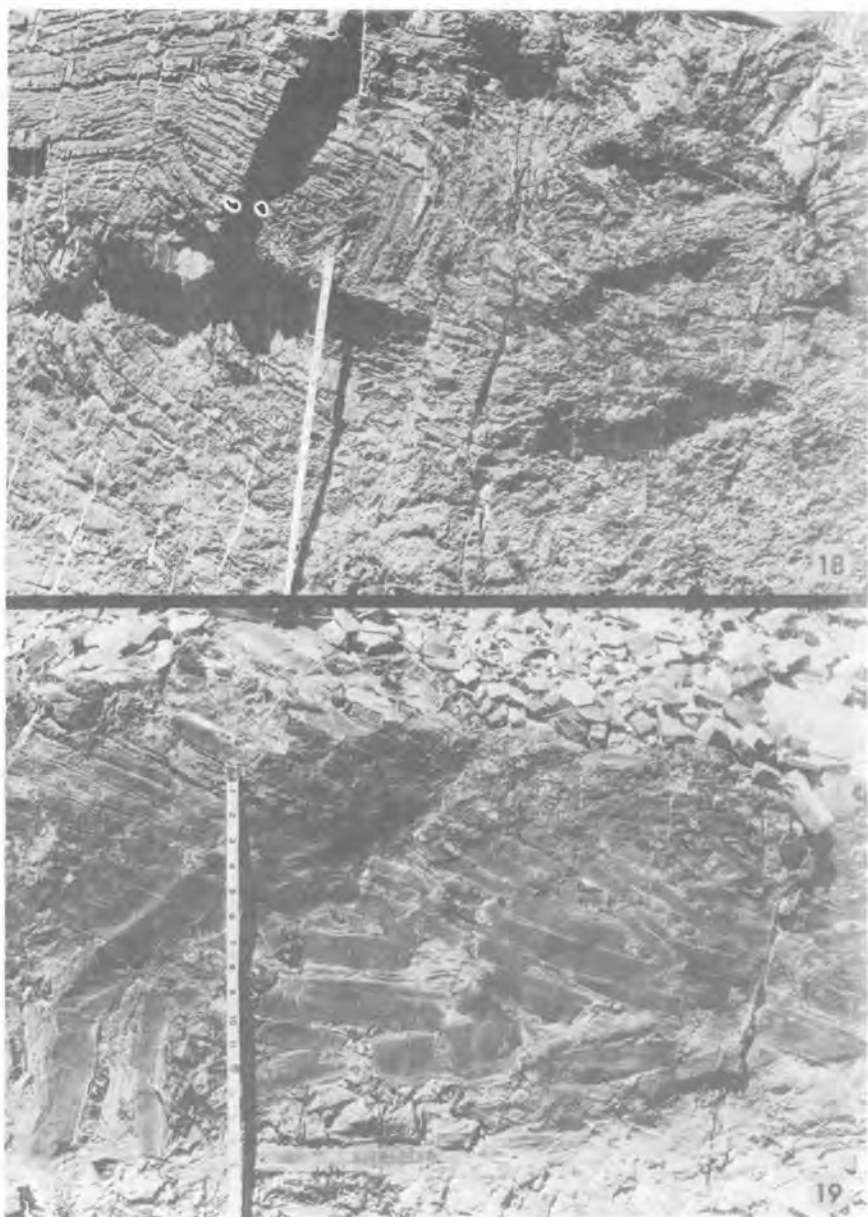
TEXT-FIGURE 15.—Range of polymeroid trilobite genera from the lower part of the Hales Limestone in the Hot Creek Range, Nevada. Section measured on north side of Tybo Canyon at Tybo. More detailed taxonomic data are given in Taylor (1976a). Explanation of lithologic symbols given in Text-fig. 2. Dashes on right side of column show position of fossil samples.

Several genera from allochthonous debris-flow deposits assigned to the upper Franconian are known in the Egan Range only from rocks assigned to the Trempealeauan Stage. The genera include *Richardsonella*, *Idiomesus*, *Leiocoryphe*, and *Triarthropsis*. *Idiomesus* and *Triarthropsis* are represented by different species in each section. However, *Leiocoryphe* sp. A (of Taylor, 1976a) occurs in both the Hot Creek and Egan sections. These observations



TEXT-FIGURE 16.—Oblique view of polished slab from Hot Creek section, showing (arrow) articulated specimen of *Hedinaspis regalis* (Troedsson, 1937) and fabric of entombing deeper water sediment. Note finely laminated parallel bedding, and pervasive sponge spicules in black mud matrix. Larger white-appearing spherules are authigenic pyrite. Bar scale equals 1 cm.

TEXT-FIGURE 17.—*In situ* slope deposits of black, shaly, lime mudstone and wackestone of the Hales Limestone, Hot Creek section.



TEXT-FIGURE 18.—Thin-bedded lime mudstone and wackestone showing soft-sediment slumping in Hales Limestone. Semiconsolidated beds were lithified after breaking up into individual intraclasts.

TEXT-FIGURE 19.—Same stratigraphic interval as Text-fig. 18. Here the sheer strength of a slump mass was exceeded, and the mass became mobile and was transformed into a highly viscous sediment gravity-flow with a distinct clastic texture.



TEXT-FIGURE 20.—Allochthonous debris bed approximately 50 cm thick in Hales Limestone. The bed shows normal grading of clasts and a mixture of clasts derived from shoal- and deeper water environments.

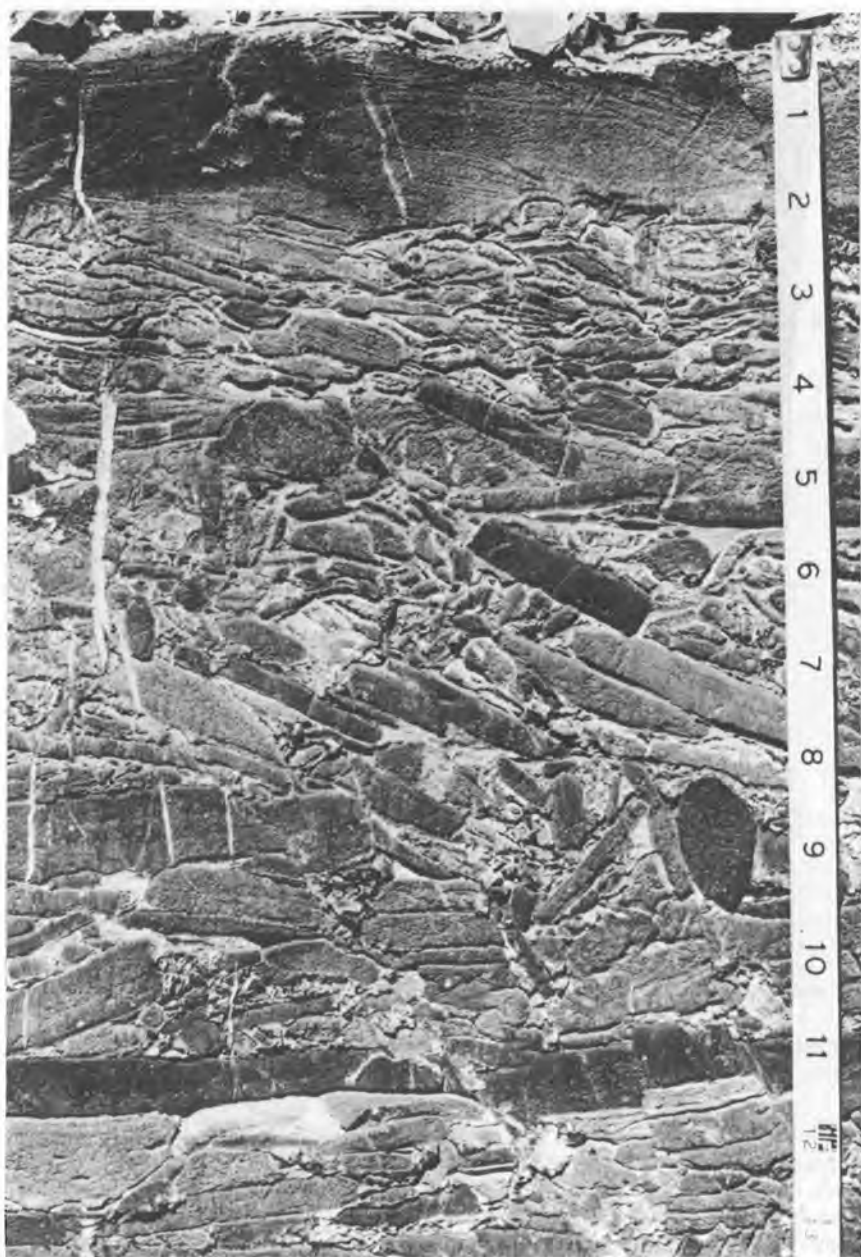


TEXT-FIGURE 21.—Photomicrograph showing matrix of debris-flow bed in Text-fig 20. The matrix contains abundant shoal-water-derived skeletal grains of *Nuia*, echinoderms, and trilobites in dark lime mudstone matrix. Bar scale equals 0.5 mm.

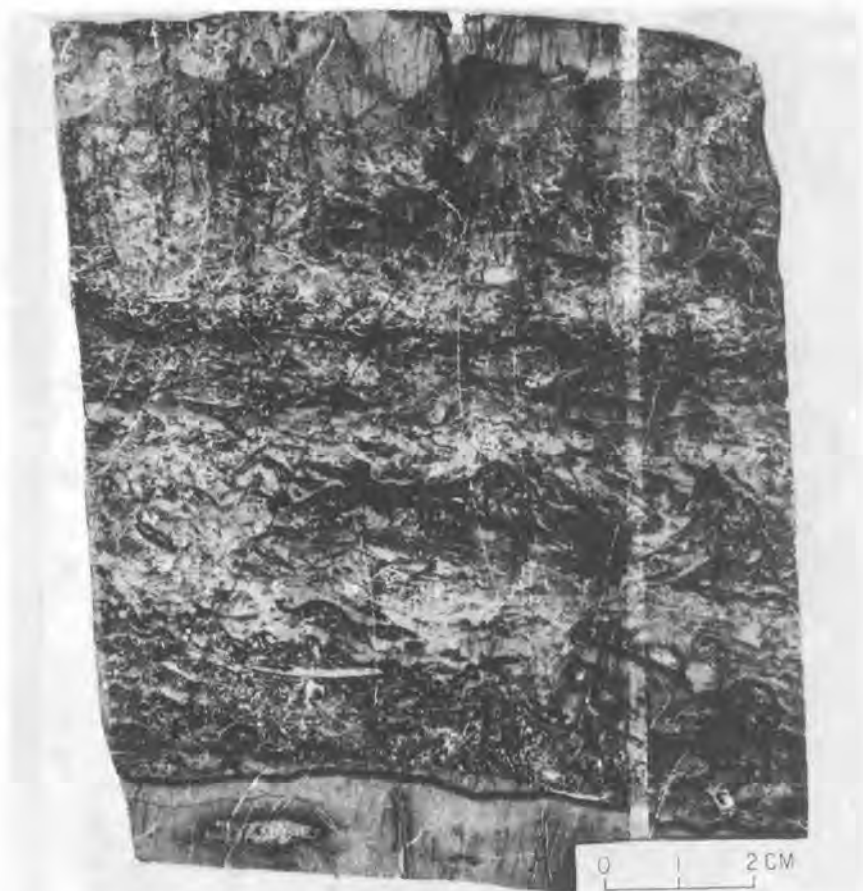
suggest that the Franconian-Trempealeau boundary in the Hales could alternatively be drawn approximately 38 m lower in the section.

The Cambrian-Ordovician boundary is currently under review by a working group of the International Stratigraphic Commission. Pending outcome of their deliberations, we provisionally recognize the boundary as being at the base of the *Missisquoia* Zone (Taylor and Halley, 1974, p. 8). The *Missisquoia* Zone is recognized in the Hot Creek section by the association of *Parabolinella*, *Ptychoplenrites*, and *Plethopeltis*. The association is similar to assemblages in central Texas (Winston and Nicholls, 1967) and Oklahoma (Stitt, 1971). It is especially similar to an assemblage assigned to the *Missisquoia depressa* Subzone of the *Missisquoia* Zone in the Wichita Mountains by Stitt (1976). Fossils indicative of the *Missisquoia* Zone and the uppermost Cambrian *Corbinia apopsis* Subzone have not been found in the central Egan Range section, although they are well represented in the Cherry Creek Mountains about 115 km to the north. In the Egan Range section, an assemblage from the lower House Limestone contains *Highgatella*, *Symphysurina*, and *Hystriacus*. The assemblage is probably younger than the *Missisquoia depressa* Subzone assemblage in the Hot Creek section and may be as young as the *Symphysurina* B Zone of Ross (1951) and Hintze (1952).

In relation to the objectives of this study, these correlation problems are minor and do not affect the conclusions drawn here. Further discussion of



TEXT-FIGURE 22.—Upper part of a normally graded debris bed from Hales Limestone showing rounded and tabular clasts of dark, deeper water, spicular mudstone and light-colored, shoal-water grainstone. The capping bed is composed of planar- to cross-laminated *Nuia* grainstone and spicular mudstone.



TEXT-FIGURE 23.—Polished slab of allochthonous debris bed from lower part of Hales Limestone, showing skeletal debris dominated by trilobites derived from shoal or higher slope habitats. Contacts with enclosing *in situ* slope rocks can be seen at bottom and top.

regional biostratigraphic correlation is presented elsewhere (Taylor, 1976a and in preparation).

DEPOSITIONAL MODEL

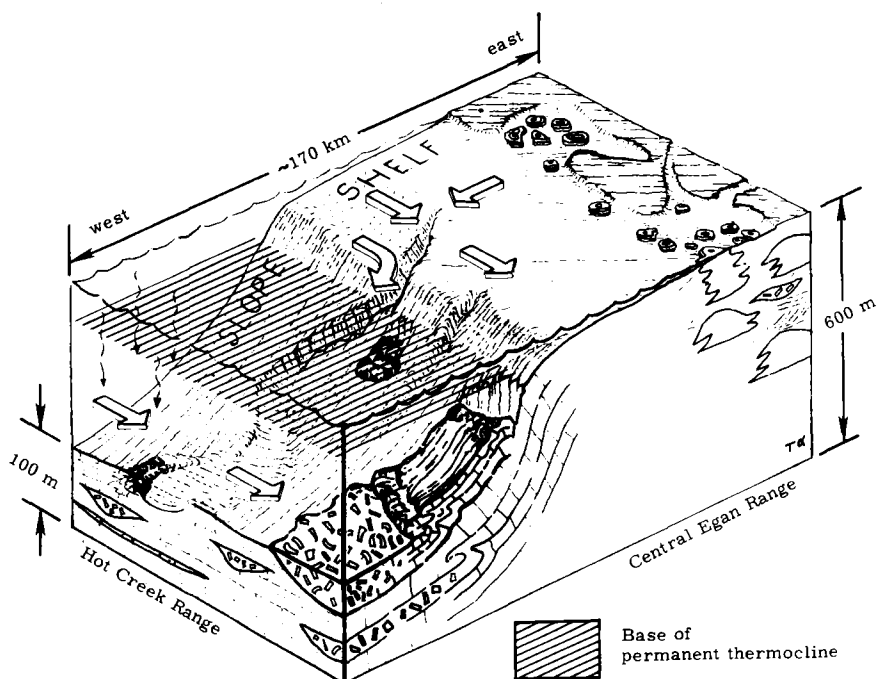
Major facies changes occur between coeval "eastern assemblage" rocks in the central Egan Range and "transitional assemblage" rocks in the Hot Creek Range. Sediment thickness decreases oceanward by a factor of three to four; dark laminated, spicule-rich lime mudrocks prevail oceanward, whereas light-colored, grain-supported and stromatolitic fabrics dominate in the shoalward rocks. As much as 40 percent of the deeper water section consists of slump masses and sediment gravity-flow deposits.

We suggest a model that includes shoal-water carbonate environments in eastern Nevada representing the "eastern assemblage" of Roberts and others

S E R I E S	Stage	BIOSTRATIGRAPHIC UNITS	
		Slope Biofacies (Hales Limestone)	Shelf Biofacies (Whipple Cave Formation)
Lower Ordovician		MISSISQUOIA Zone	
Upper Cambrian	Trempealeuan	?	SAUKIA Zone
		?	
Upper Cambrian	Franconian	HEDINASPIS Local Range Zone	ELLIPSOCEPHALOIDES Zone
		?	IDAHOIA Zone
		?	TAENICEPHALUS Zone
		?	Upper ELVINIA Zone
			Lower ELVINIA Zone

TEXT-FIGURE 24.—Biostratigraphic classification of slope and shelf biofacies. Arrows show inferred source of fossils used in correlation. Modified from Taylor (1976a, Text-fig. 4).

(1958), and slope environments in central Nevada representing the "transitional assemblage" (Text-fig. 25). Shallow-subtidal to peritidal environments in the central Egan Range seem well established. Sediments deposited under these conditions are well documented throughout the geologic column from many parts of the world. An excellent comparative analysis between modern



TEXT-FIGURE 25.—Graphic model of inferred shelf-slope transition in the Upper Cambrian-lowest Ordovician of Nevada. See text for discussion. Not drawn to scale. Modified from Cook and Taylor (1975, Fig. 2). Drawn by Tau R. Alpha.

and ancient shoal-water carbonate environments has been given by Roehl (1967).

Interpretation of a slope environment of deposition for the Hales Limestone is based on integration of the regional geologic framework (Roberts and others, 1958; Kellogg, 1963; Burchfiel and Davis, 1972; Stewart, 1972; Churkin, 1974; Stewart and Poole, 1974), comparison with other ancient deeper water environments (Garrison and Fischer, 1969; Thompson and Thomasson, 1969; Wilson, 1969; Cook, 1972; Cook and others, 1972; Mutti and Ricci-Lucchi, 1972; Walker and Mutti, 1973; Reinhardt, 1974), and comparison with modern continental margin transitions (Uchupi and Emery, 1963; Worzel, 1968; Stanley and Silverberg, 1969; Rona, 1970; Stanley and Unrug, 1972; Lewis, 1971).

Features of the Hales Limestone that suggest a slope rather than subtidal open shelf, base of slope, or submarine-fan environment include abundant slump masses involving stratigraphic thicknesses as great as 10 m, numerous debris-flow deposits as much as 10 m thick containing clasts as large as several meters across, and an extremely attenuated section when compared with the coeval shoal-water section in the Egan Range. Thus, if the shoal-water-derived debris and turbidity deposits are discounted, sediment accumulation rate for *in situ* hemipelagic sediments would be less than one-fifth that of the Egan Range section.

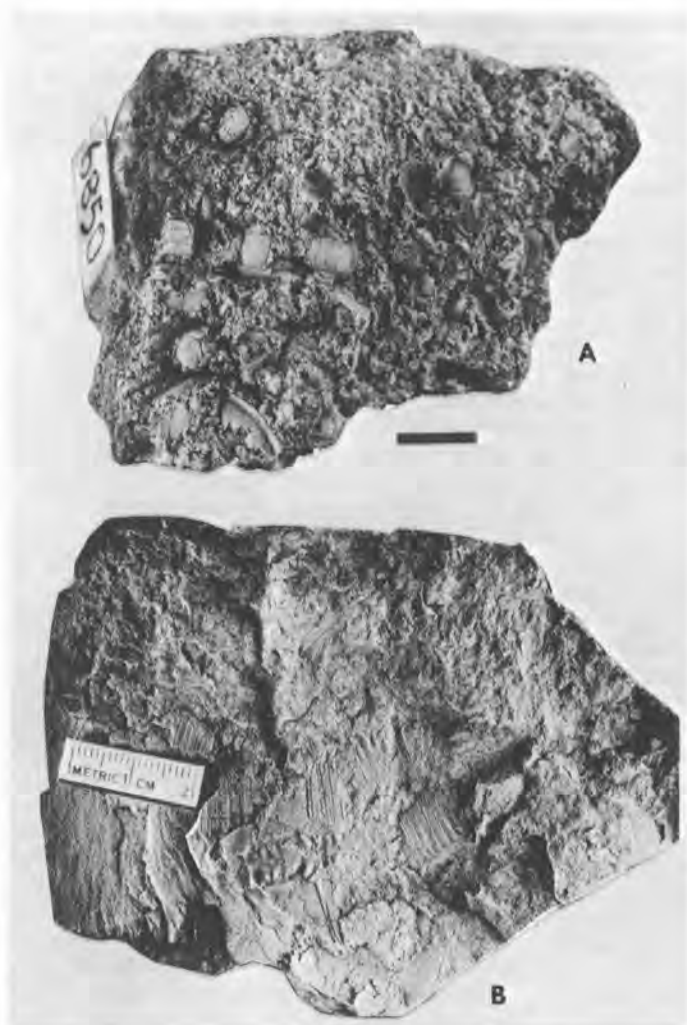
Mutti and Ricci-Lucchi (1972) and Walker and Mutti (1973) summarized characteristics of facies changes between slope, continental rise, and outer submarine-fan environments in ancient rocks. Stanley and Unrug (1972) and Lewis (1971) present lithologic and geophysical data for the nature of modern continental slope and base-of-slope environments. The characteristics of the lower Hales Limestone are in general accord with a slope environment of deposition.

Factors influencing slope sedimentation in the Hot Creek Range involve an interplay between depositional and erosional processes. The dark laminated, spicule-rich mudrocks largely represent hemipelagic sedimentation by suspension and other normal pelagic processes. Submarine gravity movements, although not of a large scale, were a dominant process in the development of the slope facies. Almost half the section is composed of gravity-flow and slumped sediments. Transportation by gravity slumping probably ranged from relatively short distances for slump masses that retain their stratigraphic identity to greater distances where shear strengths were exceeded and slump masses were transformed into highly viscous debris and turbidity flows. These types of slumps and flows originated and were deposited in a deeper water environment. Other types of submarine debris and turbidity flows, characterized by a mixture of shoal-water and deeper water constituents, had a more complex origin. This kind of flow apparently originated in a shoal-water setting and incorporated a variety of material during transport oceanward.

Although a significant change in depositional regime took place between the near-sea-level environments of the Egan Range section and the slope environments of the Hot Creek section, water depth of the slope environment is not known. However, depth can be estimated if certain assumptions are made. Palinspastic reconstructions by Stewart and Poole (1974) suggest that the Egan and Hot Creek sections are in original spatial relationship to each other. Modern continental shelves are inclined seaward at an average angle of approximately $0^{\circ} 07'$ (Shepard, 1973, p. 277). A uniform inclination of this magnitude between the Egan and Hot Creek sections would yield a depth of approximately 300 m. This calculated depth assumes that the Hot Creek section was fortuitously located at the shelf-slope break and the Egan section was near the seaward margin of shoal-water deposition. Thus, 300 m is probably a minimum estimate, and actual depth may have been greater. Perhaps a more realistic estimate of depth can be calculated by assuming a shelf-slope break midway between the Egan and Hot Creek sections. The inclination of the continental slope may not necessarily have been great. Slumping on modern continental slopes inclined at 1° to 4° is probable (Lewis, 1971), and transport of thick boulder-sized debris can be initiated and sustained across low-angle lime mud bottoms (Cook and others, 1972). Therefore, if an angle of $0^{\circ} 07'$ is assumed for the shelf part, and an angle of 1° (a conservative estimate) for the slope part, then a calculated depth would be approximately 1600 m. In any case, water depth over the slope was very likely greater than that necessary for development of a permanent thermocline, a conclusion supported independently by faunal evidence.

TAPHONOMY

Two kinds of trilobite assemblages can be recognized in the Hales Limestone on the basis of taphonomic characteristics (Taylor, 1972). Text-figure 26



TEXT-FIGURE 26.—Modes of occurrence of trilobites in the Hales Limestone, Hot Creek section. A) Redeposited trilobites; lime packstone containing disarticulated, broken, and abraded skeletal debris consisting of genera typical of the North American Faunal Province. USGS locality 6850-CO. Bar scale equals 2 cm. B) *In situ* trilobites; dark lime mudstone containing thin articulated exoskeletons of species that show affinities with those of southeastern Asia. USGS locality 7522-CO. Both views are parallel to bedding.

shows two pieces of rock broken parallel to bedding. They are examples of transported and *in situ* accumulations of trilobite debris. The transported type consists of disarticulated, broken, and abraded trilobite debris in lime grainstone beds of allochthonous debris-flow origin. The fauna consists of representatives of the Ptychaspidae, Dikelocephalidae, Parabolinoidea, Catilli-

cephalidae, and other trilobite families that are known mostly from sites of shallow-water shelf deposition in North America.

The second type of trilobite occurrence consists of articulated and fragile adult and immature dorsal exoskeletons that are usually found parallel to bedding in black lime mudstone of slope origin. An oblique view of a polished slab (Text-fig. 16) shows the characteristic dark lime mudstone containing abundant sponge spicules, pyrite, and an articulated specimen of *Hedinaspis* parallel to the bedding surface.

Taphonomic characteristics of fossils and sedimentological analysis of entombing sediments suggest that *in situ* assemblages were probably adapted to deeper water slope habitats. The slope fauna consists of *Charchagia*, an early asaphid; the papyraspid *Hedinaspis*; the olenids *Westergaardites* and *Plicatolina*; and abundant agnostoids. *Bienvillia* and *Richardsonella s. l.* are found in both transported and *in situ* assemblages. Several of the genera are unknown from North America, but they are widespread in Asia (Taylor, 1976a).

Comparison of the known occurrences of trilobite genera in the Hot Creek section with those of other areas (Text-fig. 27) shows some well-marked relationships. The *in situ* *Hedinaspis-Charchagia* fauna is widely distributed in southeastern China, the Tien Shan region of northwestern China, and South Korea. In contrast, other Cambrian genera from the Hales, except for *Plicatolina*, all occur in allochthonous debris flow deposits. The only other known occurrence of the *Hedinaspis-Charchagia* fauna was described by Palmer (1968) from Upper Cambrian rocks in eastern Alaska. Significantly, Palmer's study showed that an *Hedinaspis* assemblage is present in the Hillard Limestone—a unit he interpreted to be a deeper water facies of the coeval Jones Ridge Limestone. The paleogeographic and environmental significance of the *Hedinaspis-Charchagia* fauna is discussed further below.

Stratigraphic ranges of trilobite genera recognized from the Whipple Cave Formation are shown in Text-figure 2. Those taxa represented by redeposited trilobite debris in the slope deposits of the Hales are indicated. All the Whipple Cave taxa are typical representatives of the shallow-shelf habitats of the North American Faunal Province. The fauna shows greater species richness and greater morphologic diversity than known slope faunas. Families well represented include the Dikelocephalidae, Lecanopygidae, Plethopeltidae, Parabolinoidea, and Ptychospididae, among others. Paleogeographic affinities of the Whipple Cave trilobites are especially strong with coeval shoal-water carbonate sites in central Texas (Winston and Nicholls, 1967; Longacre, 1970), Oklahoma (Stitt, 1971, 1976), and New York State (Taylor and Halley, 1974).

ZOOGEOGRAPHY

The taxa comprising the deeper water slope fauna are highly similar over a large area. Text-figures 28 and 29 compare representatives of the *Hedinaspis-Charchagia* fauna from Nevada and Asia. Systematic study has shown that generally the same species are found in both areas (Taylor, 1976a).

Locations of the North American Faunal Province and two faunal provinces in Asia are shown in Text-figure 30. Data on Asian faunas and environments are available from the works of Kobayashi (1967), Troedsson (1937), Norin (1937), and a recent critical appraisal by Lu Yen-Hao and his associates at the Nanking Institute of Geology and Paleontology (Lu and others, 1974).

HEDINASPIS Local Range Zone Hot Creek Range Nevada		Chiangnan Faunal Province						North American Faunal Province				
		NW China	SE China				So. Korea	Alaska	E. Nevada	Texas	Oklahoma	Appalachians
			Kweichow Prov.	Kwangsi Prov.	Kwangtung Prov.	Anhui Prov.						
CHARCHAQIA	I	●	●	—	●	●	●	—	●	—	—	—
HEDINASPIS	I	●	●	●	●	●	●	●	●	—	—	—
WESTERGAARDITES	I	●	●	—	—	●	●	●	—	—	—	—
BIENVILLIA	I, T	—	—	—	—	—	—	—	●	—	—	●
BRISCOLA?	T	—	—	—	—	—	—	—	●	●	●	●
DRUMASPIS?	T	—	—	—	—	—	—	—	●	●	●	—
EUREKIA	T	—	—	—	—	—	—	—	?	●	●	3
IDIOMESUS	T	—	—	—	—	—	—	—	—	●	●	●
LEIOCORYPHE	T	—	—	—	—	—	—	—	—	●	●	●
PLICATOLINA	I	—	—	—	—	—	—	—	—	—	—	●
RICHARDSONELLA	I, T	—	—	—	—	—	—	—	●	●	—	●
SARATOGIA	T	—	—	—	—	—	—	—	—	●	●	●
TATONASPIS?	T	—	—	—	—	—	—	—	●	—	—	●
TRIARTHROPSIS	T	—	—	—	—	—	—	—	—	●	●	●

I = In situ occurrence in Hales Limestone

— = Not known to occur

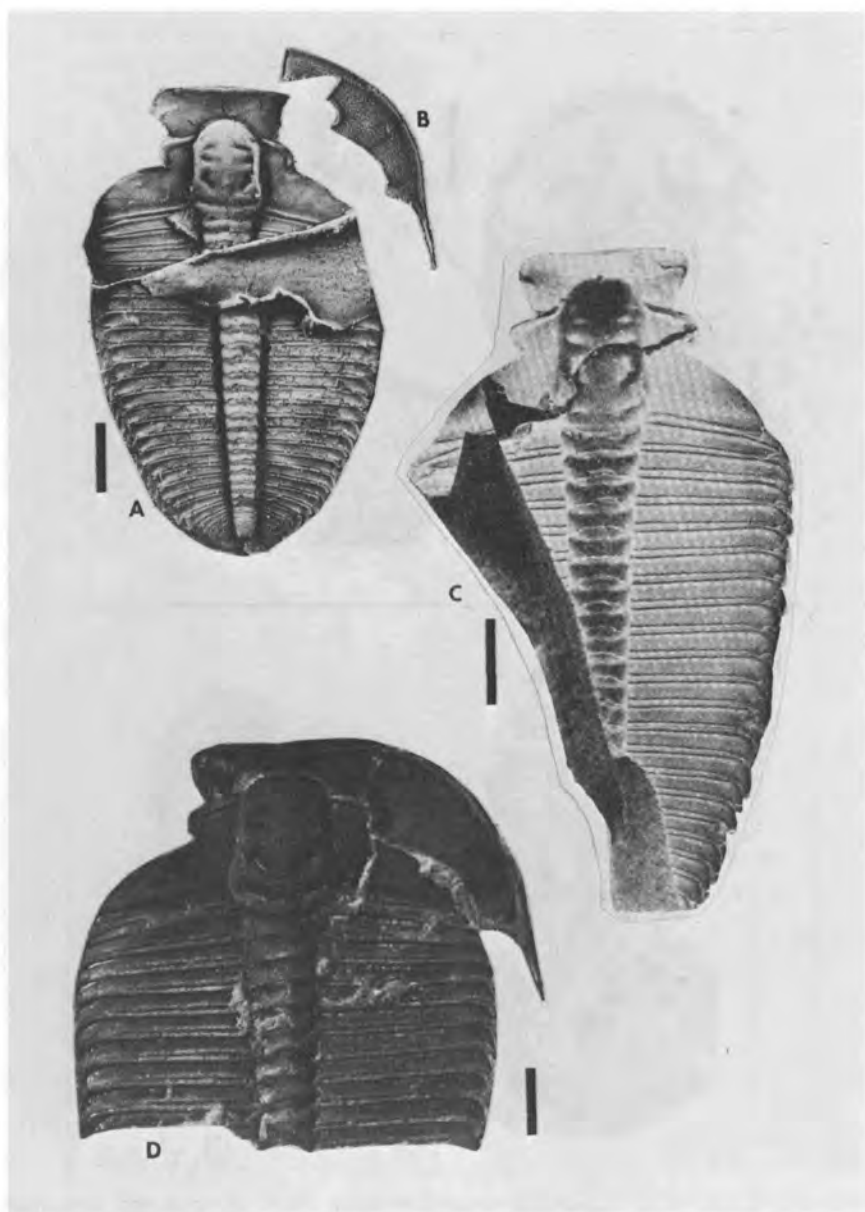
T = Transported occurrence in Hales Limestone

? = Occurrence uncertain or identification uncertain.

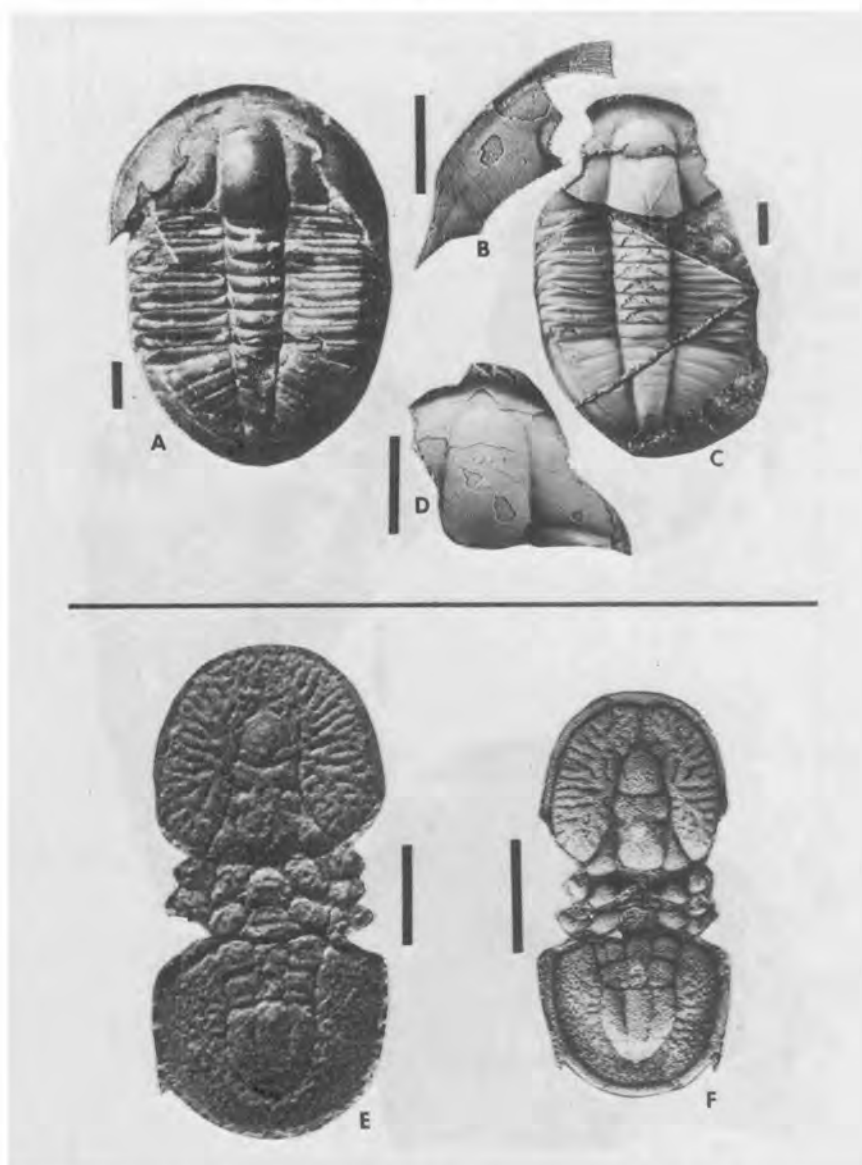
● = Known to occur

TEXT-FIGURE 27.—Late Cambrian polymeroid trilobites from the Hales Limestone compared with occurrences in Asia and other sites in North America. See Taylor (1976a) for more detailed discussion of trilobite distributions.

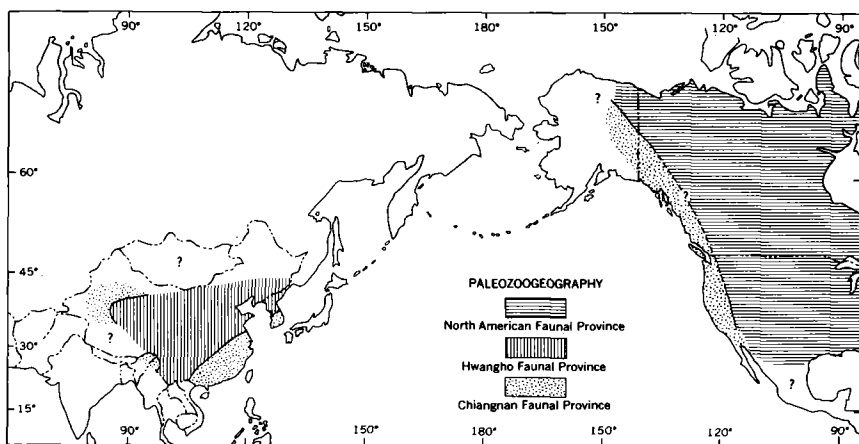
During the Cambrian, the North American shelf was associated with warm, relatively shallow water depositional environments. Similarly, a carbonate platform was present in southeastern China. Both areas of shallow-water carbonate deposition supported a highly diverse, but predominantly endemic, trilobite fauna (Palmer, 1973). The endemic Chinese faunas have been referred to the Hwangho Faunal Province (Kobayashi, 1967). The Hwangho Province in turn, is surrounded on two and perhaps three sides by the Chiangnan Province (Kobayashi, 1967) which contains the *Hedinaspis-Charchaqua* fauna. It is important to note that wherever faunas of the Chiangnan Province are known, they are associated with thin-bedded, dark, often-pyritic limestone and/or shale. These occurrences contrast markedly with the clean shelf carbonates of the southeastern Chinese platform and shoal-water carbonates of North American shelf sites.



TEXT-FIGURE 28.—*Hedinaspis regalis* (Troedsson, 1937). A and B, from the Hales Limestone of the Hot Creek Range, Nevada (from Taylor, 1976a); C, from the Hsiyangshan Formation in Chekiang Province, southeastern People's Republic of China (from Lu and others, 1974, pl. 2, fig. 3); D, from the Torsuqtagh Formation in Sinkiang Province, northwestern People's Republic of China (from Troedsson, 1937, pl. 8, fig. 7). All bar scales equal 5 mm.



TEXT-FIGURE 29.—A-D, *Charchagia novini* Troedsson, 1937. A, from the Torsuqtagh Formation in Sinkiang Province, northwestern People's Republic of China (from Troedsson, 1937, pl. 6, fig. 11); B-D, from the Hales Limestone, Hot Creek section (from Taylor, 1976a). E, *Lotagnostus punctatus* Lu from the Hsiyangshan Formation in Chekiang Province, southeastern People's Republic of China (from Lu and others, 1974, pl. 1, fig. 1); F, closely related *Lotagnostus trisectus* (Salter, 1864) from the Hales Limestone, Hot Creek section (USGS locality 7130-CO). All bar scales equal 2.5 mm.

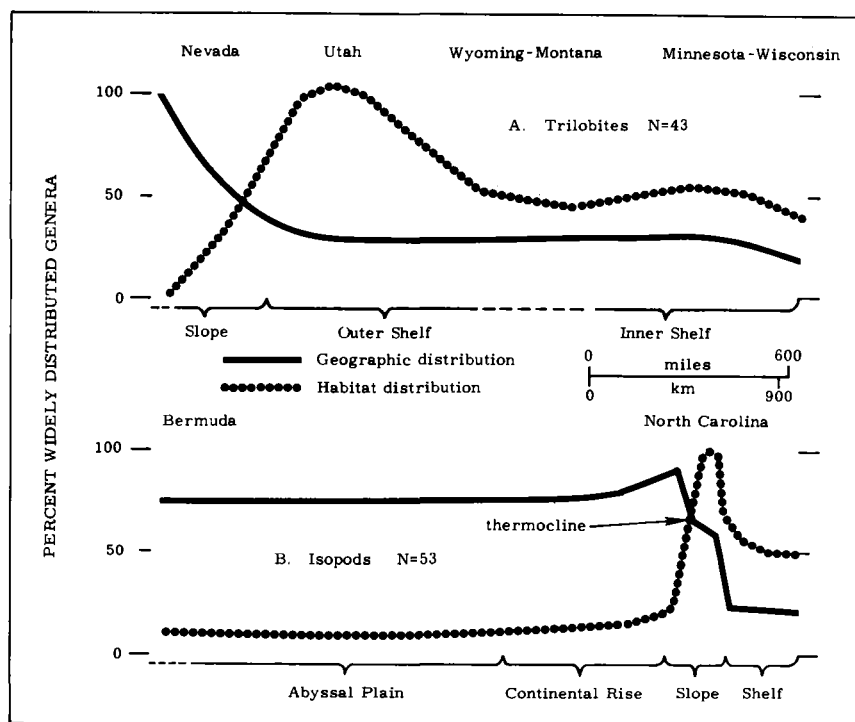


TEXT-FIGURE 30.—Late Cambrian (late Franconian-Trempealeuan) paleozoogeography of parts of North America and southern Asia. From Cook and Taylor (1975, Fig. 3).

By combining the sedimentological and paleontological analyses of the Hales and Whipple Cave formations with data on Asia from the work of Kobayashi and Lu, a model can be developed to explain the environmental significance of the Hwangho, Chiangnan, and North American Faunal Provinces. The depositional model (Text-fig. 25) suggests that a transition from shoal-water to slope environments occurs between the Egan and Hot Creek sections. We can ask the question: Does this transition represent an early Paleozoic continental margin or the edge of an infrashelf basin? Comparison of trilobite biofacies patterns with some ecological characteristics of faunas living on modern continental margins provides some insight into the question.

In an earlier paper, Taylor (1976b) suggested that Holocene marine isopod crustaceans may serve as zoogeographical analogs to trilobite distribution patterns. Text-figure 31 shows graphically the distribution of some characteristics of trilobite faunas across a shelf-to-slope profile in the western United States, and analogous characteristics of isopod faunas along a transect across the Atlantic Continental Shelf and down to the abyssal plains north of Bermuda. Orientation of the North Carolina-Bermuda transect has been reversed in the text-figure to facilitate visual comparison with the east-to-west trilobite profile in the upper graph.

The analysis is based on a two-fold classification of trilobite and isopod genera occurring along the respective transects. The *solid line* is based on the geographic distribution of taxa; high values indicate greater proportions of cosmopolitan taxa, and low values indicate that endemic genera predominate. The *dotted line* represents the proportions of taxa that are unrestricted in habitat distribution. High values denote faunas that are relatively eurytopic, whereas low values denote faunas that are relatively stenotopic. In both trilobite and isopod analyses, faunas associated with slope and deeper environments are typically stenotopic but geographically widespread; whereas, shelf faunas are relatively more eurytopic but geographically more restricted in distribution.



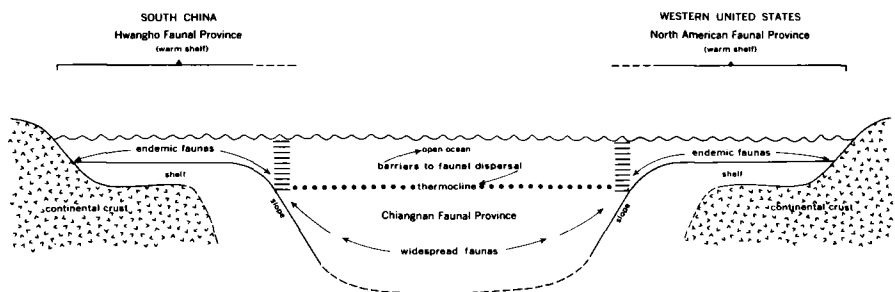
TEXT-FIGURE 31.—Distributional characteristics of Late Cambrian (late Franconian-Trempealeauan) trilobites compared with those of Holocene marine isopod crustaceans. In both analyses, greatest biofacies changes occur within the slope habitat. See text and Taylor (1976b) for further discussion. Graphs are generalized from Taylor (1976b, Text-figs. 11 and 12).

The point where the two curves cross is environmentally significant. In the case of the isopod faunas off the northeastern coast of the United States, the cross-over is associated with the base of the permanent thermocline, which at the latitude of this transect is approximately 33° N. The permanent thermocline is associated with a transitional zone between the warm northerly-flowing Gulf Stream and cold southerly-flowing Western Boundary Undercurrent as they impinge on the Atlantic Continental Slope.

CONCLUSIONS

During the Late Cambrian and earliest Ordovician of Nevada shoal-water carbonate banks existed to the east and adjacent deeper water slope environments to the west. The characteristics of the slope were the result of an interplay of hemipelagic sedimentation and submarine mass movements generated in both deeper water and shoal-water settings (Text-fig. 25).

The similarity of trilobite and isopod distribution curves suggests that a thermocline probably existed between the Egan and Hot Creek Range sections during the Late Cambrian (Text-fig. 25). Further, the presence of geograph-



TEXT-FIGURE 32.—Inferred environmental relationships of the Hwangho, Chiangnan, and North American trilobite faunal provinces. Not drawn to scale. From Cook and Taylor (1975, Fig. 4).

ically widespread trilobites in the slope habitat, but not in shallow-water habitats, and the apparent absence of coeval shallow-water rocks west of the Hot Creek Range, suggest that the Hales Limestone was deposited on an ocean-facing continental margin during early Paleozoic time. This interpretation is consistent with conclusions of Stewart and Poole (1974, p. 42) that at least some Upper Cambrian rocks (Harmony Formation) oceanward from the Hales outcrops may represent continental rise deposits.

There are several other implications of this analysis. The Hwangho, Chiangnan, and North American Faunal Provinces are not all analogous to one another. The North American and Hwangho provinces are shallow warm-shelf phenomena. Endemism within both the Hwangho and North American provinces suggests they were geographically separated during the early Paleozoic. In contrast, the Chiangnan Province contains an oceanic fauna associated with the colder and more stable environments of the deep sea adjacent to warmer shallow shelves in both southeastern Asia and western North America (Text-fig. 32).

The strong biofacies changes between warm shallow-shelf and adjacent slope deposits suggest that caution should be exercised in using trilobite faunal data for paleogeographic reconstructions of continental lithospheric plates. Often when such reconstructions have been attempted (for example, Whittington and Hughes, 1972, 1974; Jell, 1974), several assumptions were made: 1) trilobite faunal provinces were restricted to the shallow shelf seas surrounding single continental plates, which were in turn surrounded by oceanic basins that served as barriers to trilobite dispersal; and 2) the degree of faunal similarity or dissimilarity between two or more regions is a function of their past geographic proximity. Clearly, these assumptions are not justified if strong biofacies changes on ancient continental margins are not recognized and taken into consideration (compare Jell, 1974, p. 324). Conversely, the ecological characteristics of the *Hedinaspis-Charchagia* fauna suggest that its occurrence may indicate a site adjacent to a Late Cambrian oceanic basin, or at least a site subjected to oceanic water circulation patterns. The occurrences of the fauna in the eastern Tien Shan Mountains on the north flank of the Tarim Stable Block (Terman, 1973), southeastern China, South Korea, eastern Alaska, and central Nevada suggest that these areas were all influenced by the same oceanic currents during Late Cambrian time.

ACKNOWLEDGMENTS

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REFERENCES

- Bathurst, R. G. C., 1971, Carbonate sediments and their diagenesis: Developments in Sedimentology 12, Elsevier Publ. Co., New York, 620 p.
- Burchfiel, B. C., and Davis, G. A., 1972, Structural framework and evolution of the southern part of the Cordilleran orogen, western United States: *Amer. J. Sci.*, v. 272, p. 97-118.
- Churkin, Michael, Jr., 1974, Paleozoic marginal ocean basin-volcanic arc systems in the Cordilleran foldbelt: *Soc. Econ. Paleont. Miner. Spec. Publ.* 19, p. 174-92.
- Cook, H. E., 1972, Miette platform evolution and relation to overlying bank ("reef") localization, Upper Devonian, Alberta: *Can. Petrol. Geol. Bull.*, v. 20(3), p. 375A-411.
- , McDaniel, P. N., Mountjoy, E. W., and Pray, L. C., 1972, Allochthonous carbonate debris flows at Devonian bank ("reef") margins, Alberta, Canada: *Can. Petrol. Geol. Bull.*, v. 20, p. 439-97.
- Cook, H. E., and Taylor, M. E., 1975, Early Paleozoic continental margin sedimentation, trilobite biofacies, and the thermocline, western United States: *Geology*, v. 3(10), p. 559-62.
- Dietz, R. S., and Holden, J. C., 1966, Miogeoclines (miogeosynclines) in space and time: *J. Geol.*, v. 74, p. 566-83.
- Ebanks, J. W., Jr., 1967, Recent carbonate sedimentation and diagenesis Ambergris Cay, British Honduras: unpub. Ph.D. thesis, Rice Univ., 189 p.
- Garrison, R. E., and Fischer, A. G., 1969, Deep-water limestones and radiolarites of the Alpine Jurassic. in Friedman, G. M. (ed.), *Depositional environments in carbonate rocks*, a symposium: *Soc. Econ. Paleont. Miner. Spec. Publ.* 14, p. 20-56.
- Hintze, L. F., 1952, Lower Ordovician trilobites from western Utah and eastern Nevada: *Utah Geol. Miner. Sur. Bull.* 48, 249 p.
- Jell, P. A., 1974, Faunal provinces and possible planetary reconstruction of the Middle Cambrian: *J. Geol.*, v. 82, p. 319-50.
- Kellogg, H. E., 1963, Paleozoic stratigraphy of the southern Egan Range, Nevada: *Geol. Soc. Amer. Bull.*, v. 74, p. 685-708.
- Kobayashi, T., 1967, The Cambrian of eastern Asia and other parts of the continent: The Cambro-Ordovician formations and faunas of South Korea, pt. 10, sec. C.: *J. Fac. Sci. Tokyo Univ.*, 2 Geol., v. 16(3), p. 381-534.
- Lewis, K. B., 1971, Slumping on a continental slope inclined at 1°-4°: *Sediment.*, v. 16, p. 97-110.
- Lochman-Balk, C., and Wilson, J. L., 1958, Cambrian biostratigraphy in North America: *J. Paleont.*, v. 32(2), p. 312-50.
- Longacre, S. A., 1970, Trilobites of the Upper Cambrian Ptychaspis Biomere Wilberns Formation, central Texas: *Paleont. Soc. Mem.* 4 (*J. Paleont.*, v. 44(1), suppl.), 70 p.
- Lu Yen-Hao, Chu Chao-Ling, Chien Yi-Yuan, Lin Huan-Ling, Chow Tse-Yi, and Yuan Ke-Xing, 1974, Bio-environmental control hypothesis and its application to Cambrian biostratigraphy and palaeozoogeography [in Chinese]: *Nanking Inst. Geol. Palaeont. Mem. Acad. Sinica*, v. 5(2), p. 27-110.
- Mutti, Emiliano, and Ricci-Lucchi, Franco, 1972, Le torbidity dell'Appennino settentrionale: Introduzione all'analisi di facies: *Soc. Geol. Ital. Mem.* 11, p. 161-99.
- Norin, E., 1937, Geology of western Quruq Tagh eastern T'ien-Shan: *Reports Sci. Expedition to the North-western Provinces of China under leadership of Dr. Sven Hedin*, v. 3(1), p. 1-194.
- Palmer, A. R., 1960, Some aspects of the early Upper Cambrian stratigraphy of White Pine County, Nevada, and vicinity: *Guidebook to the geology of east central Nevada: Intermountain Assoc. Petrol. Geol.*, 11th Ann. Field Conf., p. 53-58.
- , 1965a, Biomere—a new kind of biostratigraphic unit: *J. Paleont.*, v. 39(1), p. 149-53.
- , 1965b, Trilobites of the Late Cambrian Pterocephaliid Biomere in the Great Basin, United States: *U. S. Geol. Surv. Prof. Paper* 493, 106 p.

- , 1968, Cambrian trilobites of east central Alaska: U. S. Geol. Surv. Prof. Paper 559-B, 115 p.
- , 1971, The Cambrian of the Great Basin and adjacent areas, Western United States: *in*, Holland, C. H. (ed.), Lower Paleozoic rocks of the world: Vol. 1, Cambrian of the New World, Wiley-Interscience, New York, p. 1-78.
- , 1973, Cambrian Trilobites, *in* Hallam, A. (ed.), Atlas of Palaeobiography: Elsevier, New York, p. 3-11.
- Reinhardt, Juergen, 1974, Stratigraphy, sedimentology and Cambro-Ordovician paleogeography of the Frederick Valley, Maryland: Maryland Geol. Surv., Rep. Invest. n. 23, 73 p.
- Roberts, R. J., Hotz, P. E., Gilluly, James, and Ferguson, H. G., 1958, Paleozoic rocks of north central Nevada: Am. Assoc. Petrol. Geol. Bull., v. 42, p. 2813-57.
- Roehl, P. O., 1967, Carbonate facies, Williston Basin and Bahamas: Am. Assoc. Petrol. Geol. Bull., v. 51(10), p. 1979-2032.
- Rona, P. A., 1970, Submarine canyon origin on upper continental slope off Cape Hatteras: J. Geol., v. 78, p. 141-52.
- Ross, R. J., Jr., 1951, Stratigraphy of the Garden City Formation in northeastern Utah, and its trilobite faunas: Peabody Mus. Nat. Hist. Bull., v. 6, 161 p.
- Shepard, F. P., 1973, Submarine Geology: 3rd ed., Harper and Row Publ., New York, 517 p.
- Shinn, E. A., 1968, Practical significance of birdseye structures in carbonate rocks: J. Sediment. Petrol., v. 38(1), p. 215-23.
- , Lloyd, R. M., and Ginsburg, R. N., 1969, Anatomy of a modern carbonate tidal-flat, Andros Island, Bahamas: J. Sediment. Petrol., v. 39, p. 1202-28.
- Stanley, D. J., and Silverberg, N., 1969, Recent slumping on the continental slope off Sable Island bank, southeast Canada: Earth Planetary Sci. Lett., v. 6, p. 123-33.
- Stanley, D. J., and Unrug, R., 1972, Submarine channel deposits, fluxoturbidites and other indicators of slope and base-of-slope environments in modern and ancient basins: *in* Rigby, J. K., and Hamblin, W. K. (eds.), Recognition of ancient sedimentary environments: Soc. Econ. Paleont. Miner. Spec. Publ. 16, p. 287-340.
- Stewart, J. H., 1972, Initial deposits in the Cordilleran Geosyncline: Evidence of a Late Precambrian (< 850 m.y.) continental separation: Geol. Soc. Amer. Bull., v. 83, p. 1345-60.
- , and Poole, F. G., 1974, Lower Paleozoic and uppermost Precambrian Cordilleran Miogeocline, Great Basin, western United States: Soc. Econ. Paleont. Miner. Spec. Publ., v. 22, p. 28-57.
- Stitt, J. H., 1971, Late Cambrian and Earliest Ordovician trilobites, Timbered Hills and Lower Arbuckle Groups, western Arbuckle Mountains, Murray County, Oklahoma: Oklahoma Geol. Surv. Bull., v. 110, 83 p.
- , 1976, Late Cambrian and earliest Ordovician trilobites, Wichita Mountains area, Oklahoma: Oklahoma Geol. Surv. Bull., in press.
- Taylor, M. E., 1971, Biostratigraphy of the Upper Cambrian (upper Franconian-Trempealeuan stages) in the central Great Basin, Nevada and Utah: unpub. Ph.D. dissertation, Univ. California (Berkeley), 428 p.
- , 1972, Late Cambrian trilobite biofacies in the western United States: Geol. Soc. Amer. Abst. Prog., v. 5(7), p. 836-37.
- , 1976a, Indigenous and redeposited trilobites from Late Cambrian basal environments of central Nevada: J. Paleont., v. 50, n. 4, in press.
- , 1976b, Upper Cambrian of western North America: Trilobite biofacies, environmental significance, and biostratigraphic implications, *in* Kauffman, E. G., and Hazel, J. E. (eds.), Concepts and methods of biostratigraphy: Dowden, Hutchinson, and Ross, Stroudsburg, Pennsylvania, in press.
- , and Halley, R. B., 1974, Systematics, environment, and biogeography of some Late Cambrian and Early Ordovician trilobites from eastern New York State: U. S. Geol. Surv. Prof. Paper 834, 38 p.
- Terman, M. J. (principal compiler), 1973 [1974], Tectonic map of China and Mongolia: Geol. Soc. Amer., 2 sheets.
- Thompson, A. F., and Thomasson, M. R., 1969, Shallow to deep water facies development in the Dimple Limestone (Lower Pennsylvanian), Marathon region, Texas, *in* Friedman, G. M. (ed.), Depositional environments in carbonate rocks, a symposium: Soc. Econ. Paleont. Miner. Spec. Publ. 14, p. 57-78.

- Troedsson, G. T., 1937, On the Cambro-Ordovician faunas of western Quruq Tagh, eastern T'ien-Shan. *Palaeont. Sinica*, New Series B, No. 2, Whole Series no. 106, 74 p.
- Uchupi, E., and Emery, K. O., 1963, The continental slope between San Francisco, California and Cedros Island, Mexico: *Deep Sea Res.*, v. 10, p. 397-447.
- Walker, R. G., and Mutti, Emiliano, 1973, Part IV—Turbidite facies and facies associations, in *Turbidites and deep-water sedimentation*: Soc. Econ. Paleontol. Miner., Pacific Sec., Anaheim, California, Short Course Lecture Notes, p. 119-57.
- Whittington, H. B., and Hughes, C. P., 1972, Ordovician geography and faunal provinces deduced from trilobite distribution: *Roy. Soc. London, Phil. Trans.*, B, v. 263(850), p. 235-78.
- , and Hughes, C. P., 1974, Geography and faunal provinces in the Tremadoc Epoch, in Ross, C. A. (ed.), *Paleogeographic provinces and provinciality*: Soc. Econ. Paleont. Miner. Sp. Publ. 21, p. 203-18.
- Wilson, J. L., 1957, Geography of olenid trilobite distribution and its influence on Cambro-Ordovician correlation: *Amer. J. Sci.*, v. 255, p. 321-40.
- , 1969, Microfacies and sedimentary structures in "deeper water" lime mudstones: in Friedman, G. M. (ed.), *Depositional environments in carbonate rocks*: Soc. Econ. Paleont. Miner. Spec. Publ. 14, p. 4-19.
- Winston, Don, and Nicholls, Harry, 1967, Late Cambrian and Early Ordovician faunas from the Wilberns Formation of Central Texas: *J. Paleont.*, v. 41(1), p. 66-96.
- Worzel, J. L., 1968, Survey of continental margins, in Donovan, D. T. (ed.), *Geology of shelf seas*. Inter-University Geol. Cong., 14th Proc., Oliver and Boyd, Edinburgh and London, p. 117-54.

Biostratigraphy of the Cambrian and Lowest Ordovician, Bighorn Mountains and Associated Uplifts in Wyoming and Montana

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ABSTRACT.—The biostratigraphic succession within the Sauk Sequence, as exposed in the Bighorn Mountains and associated uplifts in Wyoming and Montana, is dominated by trilobites. Uppermost Cambrian and lowest Ordovician strata also contain abundant conodont faunas. Brachiopods are generally minor faunal elements within the succession but lend themselves to an independent zonation. The sedimentary record was initiated by gradual encroachment of the sea and deposition of sediment containing a pre-*Bolaspidella* Zone faunal complex. An abrupt transgression of the sea introduced the *Bolaspidella* Zone. Another abrupt transgression nearly coincided with the Middle-Late Cambrian boundary, and trilobite and brachiopod faunas of the *Cedaria* and *Crepicephalus* zones became well established. The Dresbachian and Franconian are separated by an unconformity, and therefore, the Pteroccephaliid Biomere is incomplete. Seas receded and left behind only a patchy record of the lowest *Aphelaspis* Zone, but returned with a rich *Elvinia* Zone fauna. The remainder of the stratigraphic succession indicates continuous transgression. The Ptychaspid Biomere is complete and is made up of a lower *Taenicephalus-Idaboia* Zone and an upper *Saukia* Zone. Paraconodonts first appear with *Taenicephalus*. The first true conodonts initially appear high in the range of *Saukiella junia*, are more common in the *Saukiella serotina* Subzone, and enable a dual zonation of these and succeeding strata based on both trilobites and conodonts. The *Corbinia apopsis* Subzone (upper Cambrian) and *Mississquoia* and *Symphysurina* zones (lowest Ordovician) are based on trilobites, whereas the *Cordylodus proavus* Zone (A fauna) and younger zones (B and C faunas) are based on advanced cordylodids and other conodont taxa.

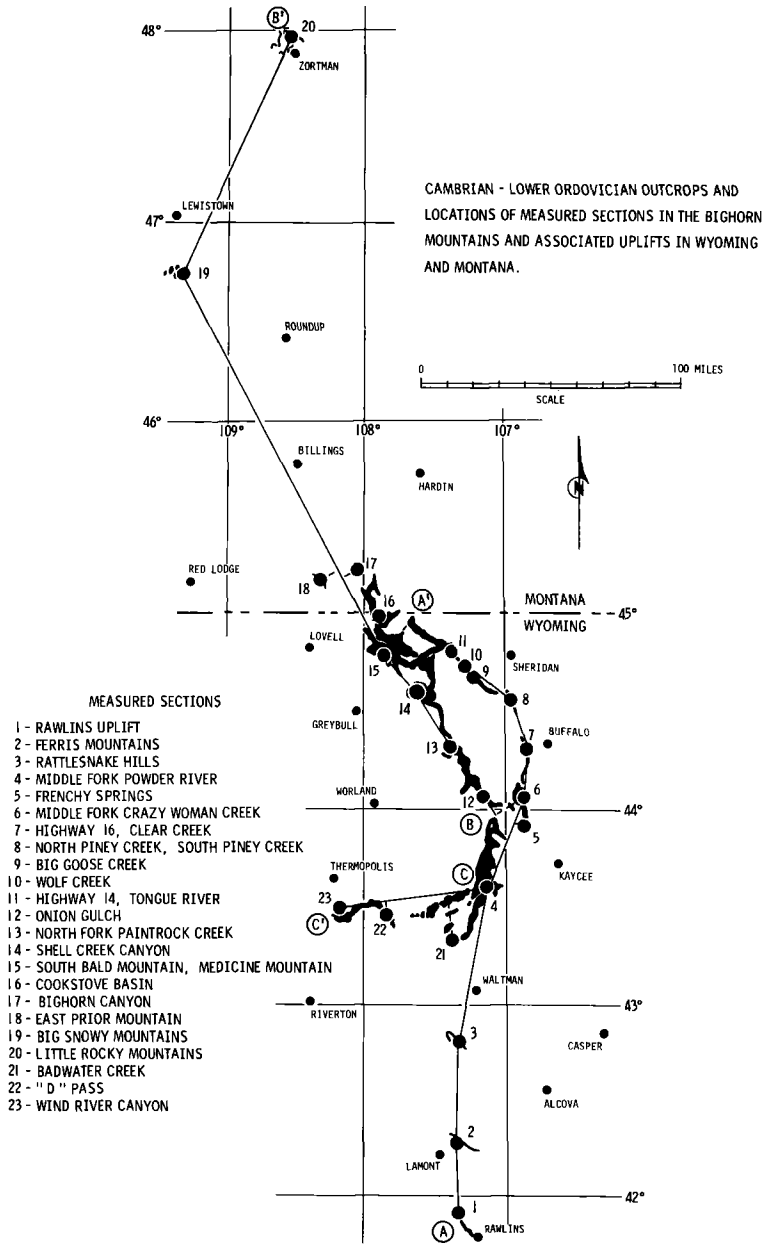
The post-Sauk unconformity progressively truncates Cambrian and Lower Ordovician strata, and rocks underlying the erosional surface range in age from Middle Cambrian in the south to Early Ordovician in the north.

INTRODUCTION

New information concerning Cambrian and Lower Ordovician biostratigraphy in Wyoming and Montana is derived from 23 measured sections in uplifts along a 430-mile traverse from the Rawlins Uplift in the south, through the Ferris Mountains, Rattlesnake Hills, Bighorn Mountains, Prior Mountains, Big Snowy Mountains, and Little Rocky Mountains in the north. Additional sections were measured in the Bridger Mountains and Wind River Canyon (Text-fig. 1).

Five hundred ninety-eight collections of trilobites and articulate brachiopods were obtained. An additional 480 samples were taken and etched for inarticulate brachiopods and conodonts. The fossils obtained document a biostratigraphic succession characterized by numerous epiboles separated by sparingly fossiliferous to barren intervals. Faunal assemblages are here grouped into pre-*Bolaspidella* and *Bolaspidella* zones of the Middle Cambrian; *Cedaria-Crepicephalus*, *Aphelaspis*, *Elvinia*, *Taenicephalus-Idaboia* and *Saukia* zones of the Upper Cambrian; and conodont faunas A, B, and C of Ethington and Clark (1971) of the Lower Ordovician (a few feet of strata at the base of Zone A belong to the uppermost Cambrian trilobite subzone of *Corbinia apopsis*).

Biostratigraphy and lithostratigraphy are coequal in helping to decipher geological history. Essential to such a study is the determination of time



TEXT-FIGURE 1.—Map of study area with location of cross sections shown in Text-figures 3 and 4.

planes in which biozone boundaries and abrupt vertical lithic changes play key roles. The verity of isochronous surfaces is reinforced by parallelism between lithic and faunal surfaces. Strata of the study area are comprised of a series of lithofacies laid down in a mostly advancing sea. The rate of transgression was not uniform, and episodes of still-stand and abrupt transgression affected the record. These interruptions define isochronous surfaces in the lithostratigraphic record. Although such surfaces are local in areal extent as compared with faunally determined isochrons, they represent, in my opinion, precise time planes.

PREVIOUS WORK

The starting point for this report is the pioneer geological mapping of the Bighorn by N. H. Darton (1906a, b, c). Published work since that time dealing directly with the Cambrian and Lower Ordovician of the Bighorns is limited to guidebooks (Carlson, 1949b; Shaw, 1954; Cygan and Koucky, 1963; Koucky and Cygan, 1963) and other published sources (Fisher, 1969; Hose, 1955; Mapel, 1959; Meyerhoff and Lochman, 1937; Tourtelot, 1946; Woodward, 1957). In addition, the following theses concern the uplifts studied and are prime sources of information for locations of sections that were measured: Beekly (1948), Carlson (1949a), Carson (1956), Case (1957), Durkee (1953), Goodwin (1961, 1964), Gossett (1957), Heroy (1941), Larson (1941), Maher (1959), Marshall (1940), Nichols (1965), Richardson (1950), Rogers (1958), Stevenson (1956), Stewart (1957), White (1940), Wingert (1958), Wright (1962), and Zakis (1950). Also, information gathered from regional studies by Lochman-Balk (1956, 1957, 1970, 1971), and Lochman-Balk and Wilson (1958, 1967) have been useful.

BIOSTRATIGRAPHY

Trilobites, conodonts, brachiopods each lend themselves to an independent zonation of Cambrian and Lower Ordovician strata (Text-fig. 2).

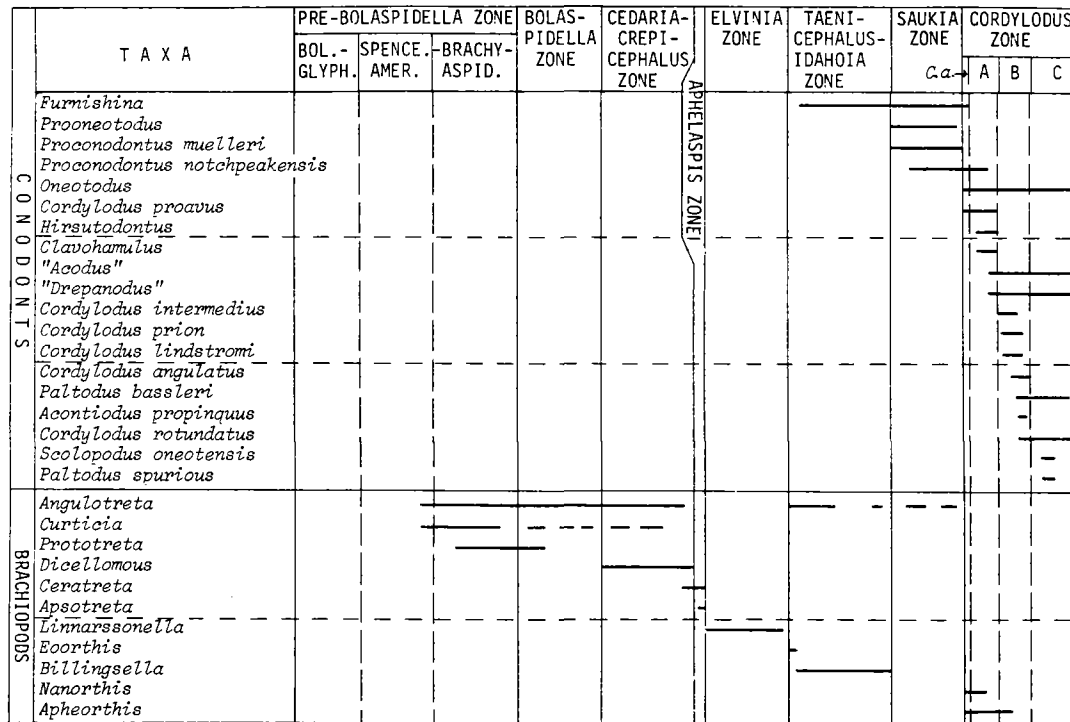
Trilobites constitute the most abundant and diverse faunas and are used to zone the Cambrian. In the lowest Ordovician, conodonts seem to me to provide the basis for a more pragmatic zonation.

Brachiopod faunas, for the most part, do not allow the detailed zonations that are possible with trilobites and conodonts, but under certain circumstances, brachiopods may be retrievable when trilobites are not.

Trilobite Biostratigraphy

The older faunal assemblages are grouped into a pre-*Bolaspidella* Zone consisting of a lower fauna dominated by *Bolaspis* and *Glyphaspis*, a middle fauna characterized by *Americare* and *Spencella*, and an upper fauna dominated by Marjumiidae with an epibole of *Brachyaspidion* in the middle. *Bolaspidella* is absent. However, the occurrence of *Brachyaspidion* may indicate correlation with the *Bathyriscus fimbriatus* Subzone of the *Bolaspidella* Zone in western Utah (Robison, 1964; Hintze and Robison, 1975).

The *Bolaspidella* Zone of this study corresponds to the *Bolaspidella contracta* and *Lejopyge calva* subzones of the *Bolaspidella* Zone of Robison (1964). An epibole of the short-ranging *Rawlinsella* (less than 10 feet of strata) in association with rare specimens of *Bolaspidella* occur at the base of the zone. Both *Bolaspidella* and Marjumiidae occur higher in the zone. *Eldoradia* appears a few feet below the top of the Middle Cambrian in the



TEXT-FIGURE 2.—Observed ranges of characteristic trilobite, conodont and brachipod taxa in the Bighorn Mountains and associated uplifts.

Bighorn Mountains and probably correlates with the *Lejopyge calva* Subzone in the Great Basin (Robison, 1964; Palmer, 1971; Hintze and Robison, 1975).

The base of the Upper Cambrian is marked by the appearance of relatively rare specimens of *Cedaria* and *Cedarina*. The *Cedaria-Crepicephalus* Zone is dominated by *Arapahoia* in the lower part and *Tricrepicephalus* in the upper part.

The *Aphelaspis* Zone is exposed in only a few sections and is limited to a few feet of strata. The fauna is composed almost exclusively of *Aphelaspis*.

An unconformity between the Dresbachian and Franconian is well-expressed in the area of study. Only the lowest part of the *Aphelaspis* Zone is present and the succeeding trilobite fauna is up in the *Elvinia* Zone. Representative trilobites of the *Dunderbergia* and lowest *Elvinia* Zone were not found.

Within the *Elvinia* Zone *Housia* and *Elvinia* are most abundant, but *Pterocephalia* and *Cliffia* are fairly common. An epibole of *Comanchia* associated with scattered specimens of *Irvingella major* terminates the zone.

The base of the *Taenicephalus-Idahoia* Zone is marked by an epibole of *Parabolinoides*. *Eoorthis* occurs in the lowest foot or two of the range of *Parabolinoides*. *Parabolinoides* then disappears and *Taenicephalus* dominates the fauna. Barren strata intervene between the highest occurrence of the latter genus and an upper fauna characterized by *Ptychaspis*, *Ellipsocephaloides* and *Idahoia*. The upper boundary of this zone is ill defined because of a scarcity of fossils.

The *Saukia* Zone in the area of study begins with the occurrence of *Saukiella junia*. Above this, *Saukiella serotina* is accompanied by *Leiocoryphe platycephala* and *Euptychaspis kirki*. *Corbina apopsis* and *Homagnostus reductus* were the youngest Cambrian trilobites collected.

Apoplanias rejectus initiates the Lower Ordovician and is followed by *Highbgatella*. This latter genus also occurs with a basal *Symphysurina* Zone fauna at one locality. *Symphysurina* occurs in abundance throughout its range. Float from high in the section in the Big Snowy Mountains contains *Bellefontia*, but the precise stratigraphic position of its origin is unknown.

Conodont Biostratigraphy

Conodonts were not found in Middle Cambrian and Dresbachian (Upper Cambrian) strata. Paraconodonts are present but rare in Franconian beds. The first true conodonts are associated with *Saukiella junia* and continue upward in relative abundance to the top of Lower Ordovician exposures.

Representatives of the *Proconodontus* and *Cordylodus proavus* zones of Miller (1975) are present in my collections. However, species diagnostic of his subzones are too rare for use in this study.

Conodont zonation of the Lower Ordovician is in a state of flux. The zonation proposed by Ethington and Clark (1971) works reasonably well. Their A fauna, if restricted to the *Cordylodus proavus* Zone of Miller (1975, p. 21), is limited to 70 to 75 feet of strata and is a usable unit. Strata with a B fauna may be much thinner than the approximately 60 feet shown in Text-figure 4. In my collections are two species of the C fauna, *Paltodus bassleri*, and *Acontiodus propinquus*, in what I consider to be a B fauna. If the base of the C fauna is determined by the first occurrence of these species, then the B fauna is found in only about 15 to 20 feet of strata. The C fauna is recognized only from the unusually thick Lower Ordovician carbonate section in the Big Snowy

Mountains. The A, B, and C faunas are grouped into the *Cordylodus* Zone in this paper.

Furnishina first appears in the *Taenicephalus-Idahoia* Zone and continues as a rare element to the top of the Cambrian. *Proconodontus muelleri* and *Prooneotodus* first appear with *Saukiella junia* and are relatively common through the remainder of the Cambrian. Shortly above the first appearance of *P. muelleri*, *Proconodontus notchpeakensis* occurs and is the most common species in the *Saukiella serotina* Subzone.

Cordylodus proavus is abundant throughout its range and is easily recognized. These factors make it a convenient guide fossil for the uppermost Cambrian (*Corbinia apopsis* Subzone) and lowest Lower Ordovician (*Mississquoia* and lower *Symphysurina* zones). *Oneotodus* first appears with *C. proavus* but extends up through the B fauna into the C fauna. Less common elements of the A fauna (*Cordylodus proavus* Zone) are *Hirsutodontus* and *Clavohamulus*. The former genus extends into the lower part of the B fauna. "*Acodus*" and "*Drepanodus*" first appear high in the A fauna and continue upward to the top of the section.

Cordylodus intermedius, *C. prion*, *C. lindstromi*, and *C. angulatus* are common in the B fauna. *Paltodus bassleri* is common in what is regarded here as the upper part of the B fauna where it is associated with *Acontiodus propinquus* and *Cordylodus rotundatus*.

Paltodus spurius and *Scolopodus oneotensis*, together with the long ranging *Cordylodus angulatus*, *C. rotundatus* and *P. bassleri*, make up the C fauna in the Big Snowy Range.

Brachiopod Biostratigraphy

Curticia and *Angulotreta* are long ranging, and as genera are not usable for detailed zonation. However, species of *Angulotreta* have been effectively used by Grant (1965) for zonation in Wyoming and Montana to the west of my area of study. Both genera appear at about the same horizon with the *Marjumiidae*. *Curticia* occurs sporadically up into the lower part of the range of *Tricrepecephalus*, and *Angulotreta* ranges to the top of the Cambrian. *Prototreta* is restricted to the upper part of the pre-*Bolaspidella* Zone and lower part of the *Bolaspidella* Zone.

Dicellomous is an excellent guide to the *Cedaria-Crepicephalus* Zone, being abundant and easily recognized. Overlapping the uppermost range of *Dicellomous* and extending into the *Aphelaspis* Zone is an undescribed species of *Ceratreta*. This genus has heretofore been reported only from the lower part of the *Taenicephalus* Zone in association with *Eoorthis* and *Parabolinoides*.

Apsotreta is known from only the Wind River Canyon section. Christina Lochman-Balk (personal communication) has reported finding *Aphelaspis* from the same part of the section.

The range of *Linnarssonella* is coincident with the range of *Elvinia* in the area of study and was not found with *Irvingella major*.

Scattered specimens of *Eoorthis* were found low in the range of *Parabolinoides*. *Billingsella* occurs high in the range of the latter genus and continues up through the *Taenicephalus-Idahoia* Zone. *Apheorthis* and *Nanorthis* span the Cambrian-Ordovician boundary, and are associated with conodonts through about the lower third of Zone A. Both genera frequently make up coquinas. James F. Miller (personal communication) has noted brachiopod coquinas associated with this boundary in Utah.

ROCK TYPES

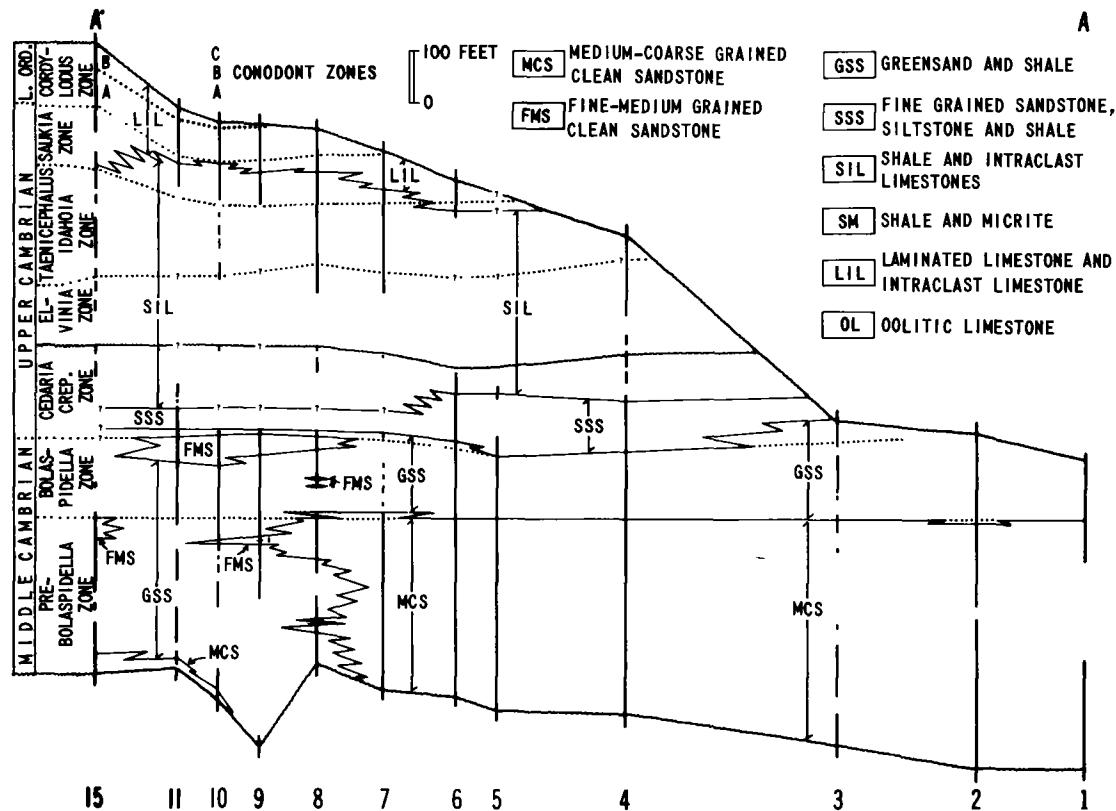
Cambrian and Lower Ordovician strata in the area of study are represented by eight major rock types or lithofacies (Text-figs. 3, 4). Each shows both non-burrowed and burrowed phases. Burrows are common, and the scarcity of non-burrowed layers contributes to the sparse faunal control in parts of the section. Formation names are not used or proposed in this paper. Some names previously given to rock units in the study area are inapplicable, and to achieve a uniformity in presentation, and because the thrust of this paper is biostratigraphic, all major rock types are referred to descriptively.

Seas transgressed from the northwest and the resulting sedimentary facies tend to be arranged in NE-SW trending belts. The eight facies show a different succession from the shoreline basinward depending on whether the water depth remained generally shallow or deepened. The complete shallow-water succession is medium- to coarse-grained sandstone—fine- to medium-grained sandstone—greensand and shale—sandstone, siltstone and shale—shale and intraclast limestone—laminated limestone and intraclast limestone (with much echinoderm debris)—oolitic limestone. In this succession the unit with fine- to medium-grained sandstone and the unit with sandstone, siltstone and shale may be limited in extent and, in effect, merge with the greensand and shale unit. The sequence formed in deepening water is different: medium- to coarse-grained sandstone—fine- to medium-grained sandstone—greensand and shale—shale and micrite. All of the foregoing sedimentary facies show interrelated or gradational contacts with adjacent units with the exception of the laminated limestone and intraclast limestone—oolitic limestone boundary, which is sharp. Beds of shale and micrite may also occur in the greensand and shale unit.

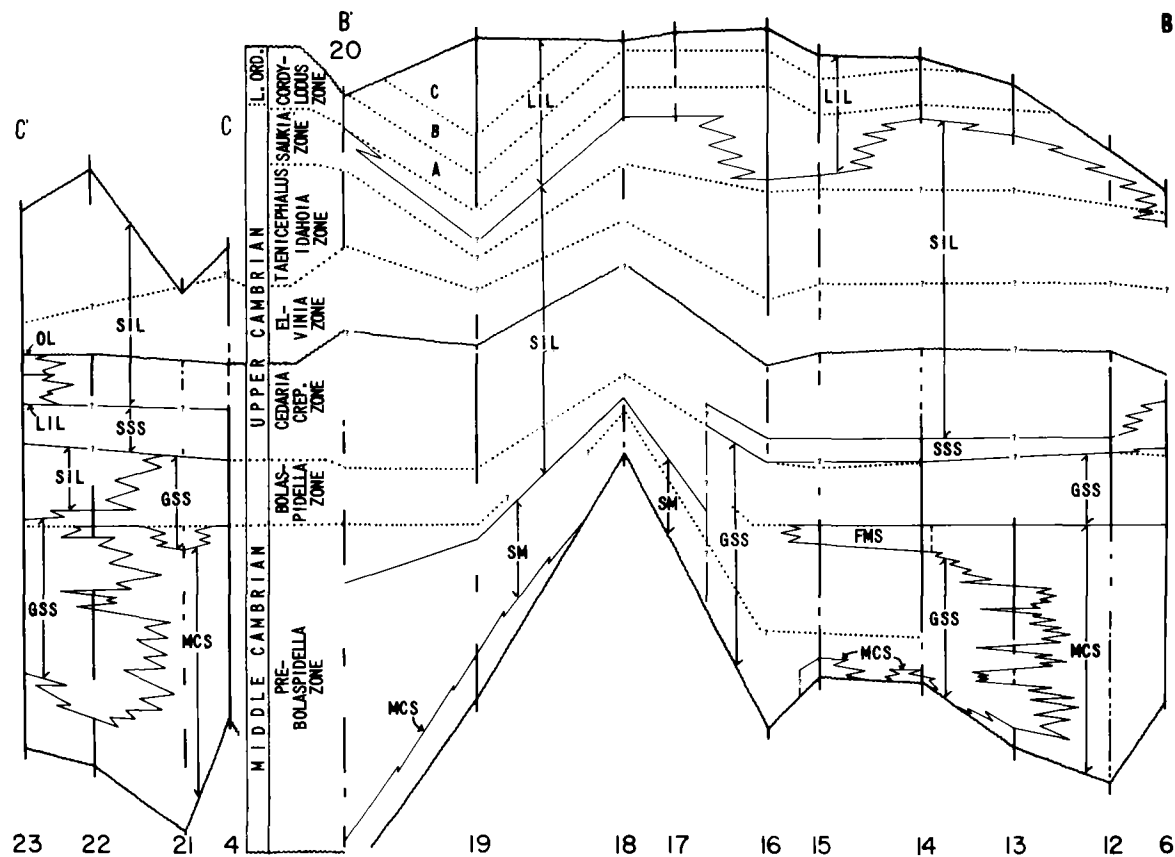
GEOLOGICAL HISTORY

Middle Cambrian seas reached the area of the Big Snowy and Little Rocky Mountains at the time the *Bolaspis-Glyphaspis* fauna was extant. Continued advance brought the seas to the area of the Bighorn Mountains, and the advance was accompanied by the appearance of *Americare* and *Spencella*. In the Little Rocky, Big Snowy, and Pryor mountains the dominant lithology is the shale and micrite facies. A basal sandstone is not everywhere present and, depending on the locality, the shale and micrite facies or greensand and shale facies may rest on the Precambrian. During the existence of this latter fauna and continuing just later than the appearance of *Brachyaspion*, a balance was maintained between the rising sea and the sediment supply so that the boundary between the medium- to coarse-grained sandstone facies and the greensand and shale facies shifted little across the depositional strike (See Text-fig. 3, columns 7, 8, 9, and Text-fig. 4, columns 12, 13, 14). This balance then changed and a tongue or sheet of fine- to medium-grained sandstone spread northwestward (Text-fig. 4, columns 14, 15) in response to a slowing of sea level rise.

The appearance of *Rawlinsella* and *Bolaspidella* generally coincided with the termination of clean-sandstone deposition and the development of a thin layer (less than 10 feet thick) of ferruginous sandstone and calcarenites. The ferruginous material, hematite and limonite, is believed to have developed in response to a widespread stagnation of the shallow sea and the concurrent development of anaerobic conditions. *Rawlinsella* disappeared coincident with an abrupt readvance of the sea and a sudden southeastward shift of the



TEXT-FIGURE 3.—Cross section A-A' along the east side of the Bighorn Mountains and south to the Rawlins uplift, showing faunal zones and vertical distribution of lithofacies in Cambrian and Lower Ordovician strata. See Text-figure 1 for localities.



TEXT-FIGURE 4.—Cross section B-B' along the west side of the Bighorn Mountains and north to the Little Rocky Mountains, and C-C' from the southern Bighorns west to Wind River Canyon. Other information same as for Text-figure 3. See Text-figure 1 for localities.

lithotope belts. The greensand and shale facies were covered by the clean-sand facies (Text-fig. 3, columns 1-8, Text-fig. 4, columns 6, 12-15, 21-22), and the shale and intraclast-limestone facies appeared in the area of the westernmost sections (Text-fig. 4, columns 22, 23) and northern sections (columns 19, 20). In the area of the southern sections (Text-fig. 3, columns 1 and 2) a high iron content was maintained throughout the greensand and shale lithotopes, which suggests continuing of anaerobic, stagnant, shallow waters.

A lens of fine- to medium-grained sandstone near the top of the green-sand and shale facies in the eastern Bighorn Mountains (Text-fig. 3, columns 8-11) is interpreted as a basinward extension of a buried medium- to coarse-grained sandstone facies to the east, and suggests a repetition of events that led to the earlier development of a sandstone tongue just before the appearance of *Bolaspidella*. Once more, ferruginous sandstone and calcarenite were developed as a stagnant anaerobic environment spread over the sandstone tongue at the end of the Middle Cambrian and the beginning of *Cedaria-Crepicephalus* Zone time.

The fine-sandstone, siltstone, and shale facies indicates a new advance of the sea and concurrent shift in lithotope belts. This facies is most typically developed as a glauconite-free unit in the Middle Fork Powder River section (Text-fig. 3, column 4) where it contains abundant *Arapahoia*. Elsewhere variable amounts of glauconite are present, and in the northern part of the Bighorns the unit is a glauconitic siltstone and shale with *Cedaria* locally common. Continued advance of the sea is indicated by spread of the shale and intraclast-limestone facies over the area of study. This lithofacies grades from shale and limestone at the base to limestone at the top. The *Cedaria* fauna, dominated by *Arapahoia*, occurs in shale and limestone; whereas, the *Crepicephalus* fauna, characterized by *Tricrepicephalus*, is found in a dominantly micrite and calcarenite facies. In the Wind River Canyon section to the west (Text-fig. 4, column 23), two new lithofacies have a *Crepicephalus* fauna. The lower one is a laminated-limestone and intraclast-limestone facies, and the upper is an oolitic-limestone facies with much fossiliferous calcarenite and quartz sand at the top.

Aphelaspis is present in the uppermost few feet of the carbonate section in only a few localities. Shale locally overlies this carbonate, and *Aphelaspis* is known from the shale at one horizon in the Wind River Canyon section (Lochman-Balk, personal communication). A near craton-wide Dresbachian-Franconian unconformity was developed when the sea retreated, and shale deposition continued when the ocean returned with an *Elvinia* Zone fauna. Lower *Elvinia* Zone strata are almost exclusively shale, but conglomerate beds of intraclast limestone and lenses of micritic and calcarenitic limestone all increase upward through the *Elvinia* and *Taenicephalus-Idahoia* zones. Domal stromatolites are found in this part of the section.

Saukia Zone strata show the transition from the shale and intraclast-limestone facies to the laminated-limestone and intraclast-limestone facies. The contact is gradational and intercalated, and placement is arbitrary. The laminated limestone is fine grained, silty, and was probably deposited in sheltered lagoonal environments between banks of intraclast limestone and echinodermal calcarenite debris.

At the base of the Ordovician all strata are of the laminated-limestone and intraclast-limestone facies. These facies continue upward to the post-Sauk

unconformity. Rocks ranging in age from Middle Cambrian in the south to Early Ordovician in the north underlie the unconformity. Overlying rocks range in age from Middle Ordovician to Mississippian.

ACKNOWLEDGMENTS

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REFERENCES

- Beekly, E. K., 1948, *Geology of the Wolf Creek area, Bighorn Mountains, Wyoming*: unpub. M.S. thesis, Univ. of Iowa.
- Carlson, C. E., 1949a, *Areal geology and stratigraphy of the Red Fork-Powder River area, Johnson County, Wyoming*: unpub. M.S. thesis, Univ. of Wyoming.
- , 1949b, *Geologic map and structure sections of the Red Fork-Powder River area*: Wyo. Geol. Assoc. Guidebook, 4th Ann. Field Conf., Powder River Basin, insert.
- Carson, J. R., 1956, *Stratigraphy and structure of the east flank of the Bighorn Mountains, west-southwest of Buffalo, Wyoming*: unpub. M.S. thesis, Univ. of Iowa.
- Case, L. E., 1957, *General geology of the Horn Fault region, Bighorn Mountains, Wyoming*: unpub. M.S. thesis, Univ. of Iowa.
- Cygan, N. E., and Koucky, F. L., 1963, *The Cambrian and Ordovician rocks of the east flank of the Bighorn Mountains, Wyoming*: Northern Powder River Basin Guidebook, Wyo. Geol. Assoc.—Billings Geol. Soc., 1st Joint Field Conf., p. 26-37.
- Darton, N. H., 1906a, *Geology of the Bighorn Mountains*: U. S. Geol. Surv. Prof. Paper 51, 121 p.
- , 1906b, *Bald Mountain-Dayton Folio*: U. S. Geol. Surv., Atlas, Folio 141, 16 p.
- , 1906c, *Cloud Peak-Fort McKinney Folio*: U. S. Geol. Surv., Atlas, Folio 142, 16 p.
- Durkee, E. F., 1953, *Cambrian stratigraphy and paleontology of the east flank of the Bighorn Mountains, Johnson and Sheridan Counties, Wyoming*: unpub. M.S. thesis, Univ. of Wyoming.
- Ethington, R. L., and Clark, D. L., 1971, *Lower Ordovician conodonts in North America*: in Sweet, W. C., and Bergstrom, S. M. (eds.), *Symposium on conodont biostratigraphy*: Geol. Soc. Amer., Mem. 127, p. 63-82.
- Fisher, J. H., 1959, *Basal Cambrian strata in the Northern Bighorn Mountains, Wyoming*: Geol. Soc. Amer. Bull., v. 30, p. 1603 (abstr.).
- Goodwin, P. W., 1961, *Fauna and stratigraphy of the Cambrian and Lower Ordovician of the Bighorn Mountains, Wyoming*: unpub. M.S. thesis, Univ. of Iowa.
- , 1964, *Ordovician formations of Wyoming*: unpub. Ph.D. thesis, Univ. of Iowa.
- Gossett, C. J., 1957, *Cambrian stratigraphy in the Bighorn Mountains, Wyoming*: unpub. M.S. thesis, Univ. of Illinois.
- Grant, R. E., 1965, *Faunas and stratigraphy of the Snowy Range Formation (Upper Cambrian) in southwestern Montana and Northwestern Wyoming*: Geol. Soc. Amer., Mem. 96, 171 p.
- Heroy, W. B., Jr., 1941, *The geology of the Shell Canyon area, Bighorn Mountains, Wyoming*: unpub. Ph.D. thesis, Princeton University.
- Hintze, L. F., and Robison, R. A., 1975, *Middle Cambrian stratigraphy of the House, Wah Wah and adjacent ranges in western Utah*: Geol. Soc. Amer. Bull., v. 86, p. 881-91.
- Hose, R. K., 1954, *Geology of the Crazy Woman Creek area, Johnson County, Wyoming*: U. S. Geol. Surv. Bull., v. 1027-B, p. 33-118.
- Koucky, F. L., and Cygan, N. E., 1963, *Paleozoic rocks exposed along U.S. Highway 14 on the east flank of the Bighorn Mountains, Wyoming*: Northern Powder River Basin Guidebook, Wyo. Geol. Assoc.—Billings Geol. Soc., 1st Joint Field Conf., p. 17-25.

- Larson, G. O., 1941, Geology of the southwest portion of Sheridan Quadrangle, Wyoming: unpub. M.S. thesis, Univ. of Iowa.
- Lochman-Balk, C., 1956, The Cambrian of the Rocky Mountains and southwest deserts of the United States and Mexico: 20th Int. Geol. Cong., Mexico, part II, p. 509-29.
- , 1967, Stratigraphy of the Upper Cambrian-Lower Ordovician Subsurface Sequence in the Williston Basin. Amer. Assoc. Petrol. Geol. Bull., v. 56, p. 883-917.
- , 1970, Upper Cambrian faunal patterns on the craton. Geol. Soc. Amer. Bull., v. 81, p. 3197-224.
- , 1971, Cambrian of the craton of the United States. *in* Holland, C. H. (ed.), Lower Paleozoic rocks of the world: Vol. 1 Cambrian of the New World, Wiley-Interscience, New York, p. 79-167.
- , and Wilson, J. L., 1958, Cambrian biostratigraphy in North America: J. Paleont., v. 32, p. 312-50.
- Maher, L. J., 1959, The geology of the east flank of the Bighorn Mountains near Story, Wyoming: unpub. M.S. thesis, Univ. of Iowa.
- Mapel, W. J., 1959, Geology and coal resources of the Buffalo-Lake Desmet area, Johnson and Sheridan counties, Wyoming: U. S. Geol. Surv. Bull. 1078.
- Marshall, C. H., 1940, Geology of the Hazelton area, Bighorn Mountains, Wyoming: unpub. M.S. thesis, Univ. of Iowa.
- Meyerhoff, H. A., and Lochman, C., 1935, Deadwood faunas in South Dakota and eastern Wyoming: Geol. Soc. Amer., Proc., v. 1935, p. 386-87 (abstr.)
- Miller, J. F., 1975, Central and western Utah: Cambrian paleontology and depositional environments, third day. *in* Robison, R. A. (compiler), Unpublished information packet, Geol. Soc. Amer., Field Trip Nine, p. 16-30.
- Nichols, C. E., 1965, Geology of a segment of Deep Creek Fault zone. Southern Bighorn Mountains, Wyoming: unpub. M.S. thesis, Univ. of Iowa.
- Palmer, A. R., 1971, The Cambrian of the Great Basin and adjacent areas, western United States. *in* Holland, C. H. (ed.), Lower Paleozoic rocks of the world: Vol. 1, Cambrian of the New World, Wiley-Interscience, New York, p. 1-78.
- Robison, R. A., 1964, Late Middle Cambrian faunas from western Utah. J. Paleont., v. 38, p. 510-66.
- Richardson, A. L., 1950, Geology of the Mayoworth region, Johnson County, Wyoming: unpub. M.S. thesis, Univ. of Wyoming.
- Rogers, W. P., 1958, General geology of the Medicine Mountain area, Bighorn Mountains, Wyoming: unpub. M.S. thesis, Univ. of Iowa.
- Shaw, A. B., 1954, The Cambrian and Ordovician of the Pryor Mountains, Montana and northern Bighorn Mountains, Wyoming: Billings Geol. Soc. Guidebook, 5th Ann. Field Conf., p. 32-37.
- Stevenson, D. L., 1956, General geology east flank of the Bighorn Mountains, south-southwest of Buffalo, Wyoming: unpub. M.S. thesis, Univ. of Iowa.
- Stewart, J. C., 1957, Stratigraphy, physiography and structural geology of the Dryhead-Garvin Basin, south central Montana: unpub. Ph.D. thesis, Princeton University.
- White, M. G., 1940, Geology of the upper basin of North Fork Powder River, Bighorn Mountains, Wyoming: unpub. M.S. thesis, Univ. of Iowa.
- Wingert, J. R., 1958, Geology of the Bald Mountain area, Bighorn Mountains, Wyoming: unpub. M.S. thesis, Univ. of Iowa.
- Woodward, T. C., 1957, Geology of Deadman Butte area, Natrona County, Wyoming: Amer. Assoc. Petrol. Geol. Bull., v. 41, p. 212-62.
- Zakis, W. N., 1950, Geology of the east flank of the Bighorn Mountains, near Dayton, Sheridan County, Wyoming: unpub. M.S. thesis, Univ. of Wyoming.