PALEOENVIRONMENTAL STUDY OF THE HELDERBERG GROUP OF WEST VIRGINIA AND VIRGINIA

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This is to certify that the

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PALEOENVIRONMENTAL STUDY OF THE HELDERBERG
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ABSTRACT

PALEOENVIRONMENTAL STUDY OF THE HELDERBERG GROUP OF WEST VIRGINIA AND VIRGINIA

By

Jack Watson Travis

The variations of stratigraphic, petrographic, and paleontologic attributes of the Helderberg Group, Lower Devonian, of West Virginia and Virginia have been systematically analyzed for meaningful environmental indicators so that logical inferences concerning conditions of deposition of Helderberg sediments can be made.

Data have been derived from a detailed field study of 22 Helderberg outcrops, from a petrographic study of 425 randomly and purposely collected rock samples, and from fossil population studies along 260 sampling lines in 14 outcrops.

In outcrops north of Monterey, Virginia the Coeymans Limestone can be subdivided into lower, middle, and upper limestone members. The middle limestone member is a thin-bedded, finely crystalline crinoidal limestone with chert nodules and shows a general thinning from north to south.

possibly existed in the Virginias during deposition of New Scotland sediments and the communities trended northeast-southwest with the species diversity gradient increasing from northwest to southeast.

There is a direct relationship between the number of strophomenids in a sample and the amount of fine-grained sediments, in that those sampling sites with a high proportion of strophomenids generally contain a larger percentage of fine-grained sediments.

Since the Helderberg Group appears to represent a transgressive phase of deposition and the various stratigraphic units are rock-stratigraphic units, a stratigraphic unit overlying another unit in a Helderberg outcrop grades laterally into a subjacent or superjacent unit. This indicates that the sediments of the various rock-stratigraphic units were deposited simultaneously under differing environmental conditions in different parts of the depositional basin.

The occurrence of mud cracks in some micritic beds of the upper Keyser Limestone suggests that deposition occurred in a supratidal, mud-flat environment. These sedimentary structures also can serve as references in reconstructing the environmental gradient.

Stratigraphic and petrographic evidence suggest that the Coeymans Limestone and the crinoidal limestone and sandstone facies of the New Scotland Formation were deposited in a high energy beach environment. However, Overall the Helderberg Group represents a transgressive phase of deposition during early Devonian time in West Virginia and Virginia and the formations comprising the Helderberg Group are rock-stratigraphic units rather than time-stratigraphic units.

Based on the type of grain support and the proportion of grains, matrix, and cement the following rock types can be recognized in the Helderberg Groups: micrite, biomicritic wackestone, biomicritic packstone, biosparitic packstone, biosparitic grainstone, pelsparitic grainstone, and intrasparitic grainstone. Most of the sparry calcite occurring in the packstone and grainstone is a primary pore filling cement. However, microsparry calcite represents recrystallized grains of microcrystalline calcite. Chert, which is common in the New Scotland Formation, appears to be a replacement phenomenon.

A chi-square test for independence identifies 33 interspecific fossil associations which involve 10 of the 34 fossil species identified in the field. These associations can be grouped into a primary recurrent group and a related secondary recurrent group. All species, with the exception of _S_. _strictum_, which is associated with another species, have a positive association with limestone and all species have a negative association with chert.

The spatial distribution of the computed indices of species diversity suggests that three fossil communities sediments of the limestone and chert facies of the New Scotland Formation and the Shriver Chert-Licking Creek Limestone interval were deposited in an open marine environment probably below wave base.

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By

Jack Watson Travis

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CHAPTER I

INTRODUCTION

Rocks in the Appalachian region have been studied extensively and are generally considered to typify most of the Paleozoic systems recognized in North America. Much of the research conducted on this sequence of rocks has been concerned with their stratigraphic, structural, and paleontological aspects resulting in their being subdivided into numerous stratigraphic units. More recently the emphasis in some Appalachian studies has been concerned with gathering information and interpreting data relative to paleoenvironments of some of these strata.[1]

The Lower Devonian Helderberg Group is a stratigraphic unit in the Appalachians which is amenable to the latter type of study. It is a lithologically diverse rock unit consisting of limestone, chert, sandstone, and shale. Many Helderberg outcrops have been measured, described, and subdivided by previous investigators. In the course

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[1] Some of the recent paleoenvironmental studies in the Appalachians are Pelletier, 1958; Donaldson, 1960; Folk, 1960; Alling and Briggs, 1961; Yeakel, 1962; Weber and others, 1965; Matter, 1967; Johnson and Friedman, 1969; Laporte, 1969; and Bretsky, 1970.

of such studies several facies have been recognized. Stratigraphic relationships and equivalencies have been generally established between various outcrops and type sections. Few previous investigations have dealt with the petrographic and paleoecologic aspects of these rocks even though the occurrence of different lithologies suggest that more than one type of environment prevailed at any given time during deposition of Helderberg sediments.

The purpose of this investigation is to systematically analyze variations of stratigraphic, petrographic, and paleontologic attributes of the Helderberg Group for meaningful environmental indicators and to make logical inferences from these analyses concerning environmental conditions during deposition of these sediments in the central Appalachians.

Composition, texture, sedimentary structures, and fossil content are all possible indicators of a given sedimentary environment. But certain diagenetic processes can produce compositions or textures which are characteristic of entirely different environmental conditions. Also the observable fossil content probably is not a true representation of the total suite of organisms that were indigenous to the site of deposition due to postmortem transport of skeletal material, non-preservation, or obliteration of head parts by diagenetic processes.

Since the original lithologic and paleontologic character of a local sedimentary deposit is a product of its depositional environment, it can be said that areal variations of the lithology and paleontology of a stratigraphic unit in a given time interval represent different local depositional environments within a basin of sedimentation. Lateral shifts in facies with time point to corresponding changes in the depositional environments of a given area.

It is, therefore, important to look for indicators of the original environments and evaluate their temporal and spatial distributions before depositional conditions can be inferred for the Helderberg Group.

Location of Study Area

Outcrops of Lower Devonian rocks occur mainly in the Ridge and Valley physiographic province between the Blue Ridge Mountains and their continuations to the east and the Allegheny Front on the west. Helderberg outcrops are practically continuous from the Hudson River in New York to the southwest corner of Virginia. The best exposures are restricted to road cuts, railroad cuts, quarries, and occasional stream beds.

This study is restricted to Helderberg outcrops of parts of West Virginia and Virginia. In this area the Helderberg Group displays several facies and a number of available outcrops contain various portions of these facies so their areal and temporal distributions can be studied. The northern extent of the study is along a line running from New Creek, Mineral County, West Virginia through Romney, Hampshire County, West Virginia. The southern-most Helderberg exposure investigated is in the vicinity of Bluefield, Virginia. The distribution of Helderberg rocks and outcrops which were studied are shown in Figure 1.

General Stratigraphy

The Devonian System has been divided into the Ulsterian, Erian, Senecan, Chautauquan and Bradfordian Series by Cooper and others (1942). They further subdivided the Ulsterian Series into the Helderberg, Deerpark, and Onesquethaw Stages. The Helderberg Stage was to include the Helderberg Group and its correlatives.

A generalized columnar section of the Devonian System is presented in Figure 2 to show the relative stratigraphic position of the Helderberg Group in West Virginia and Virginia.

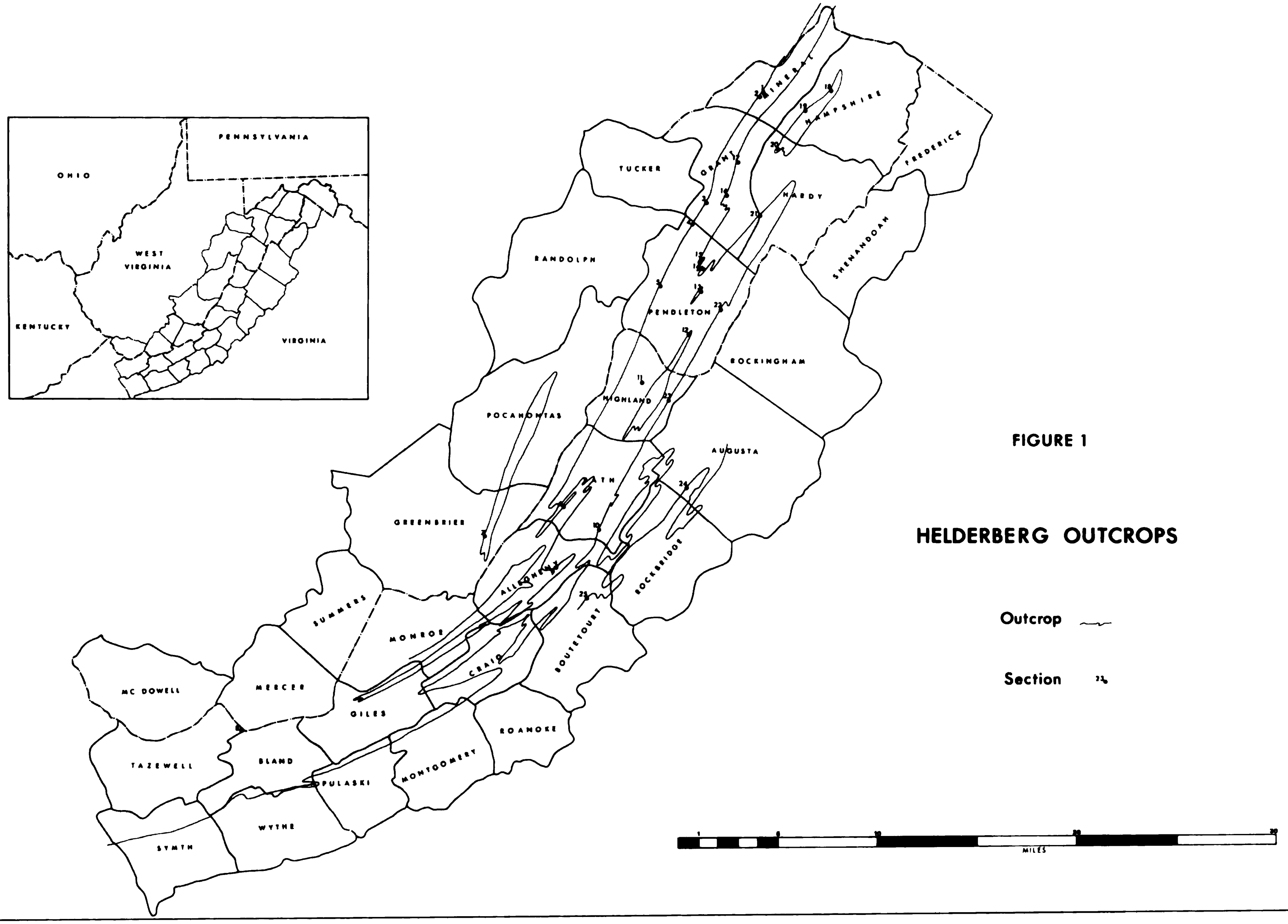

FIGURE 1

HELDERBERG OUTCROPS

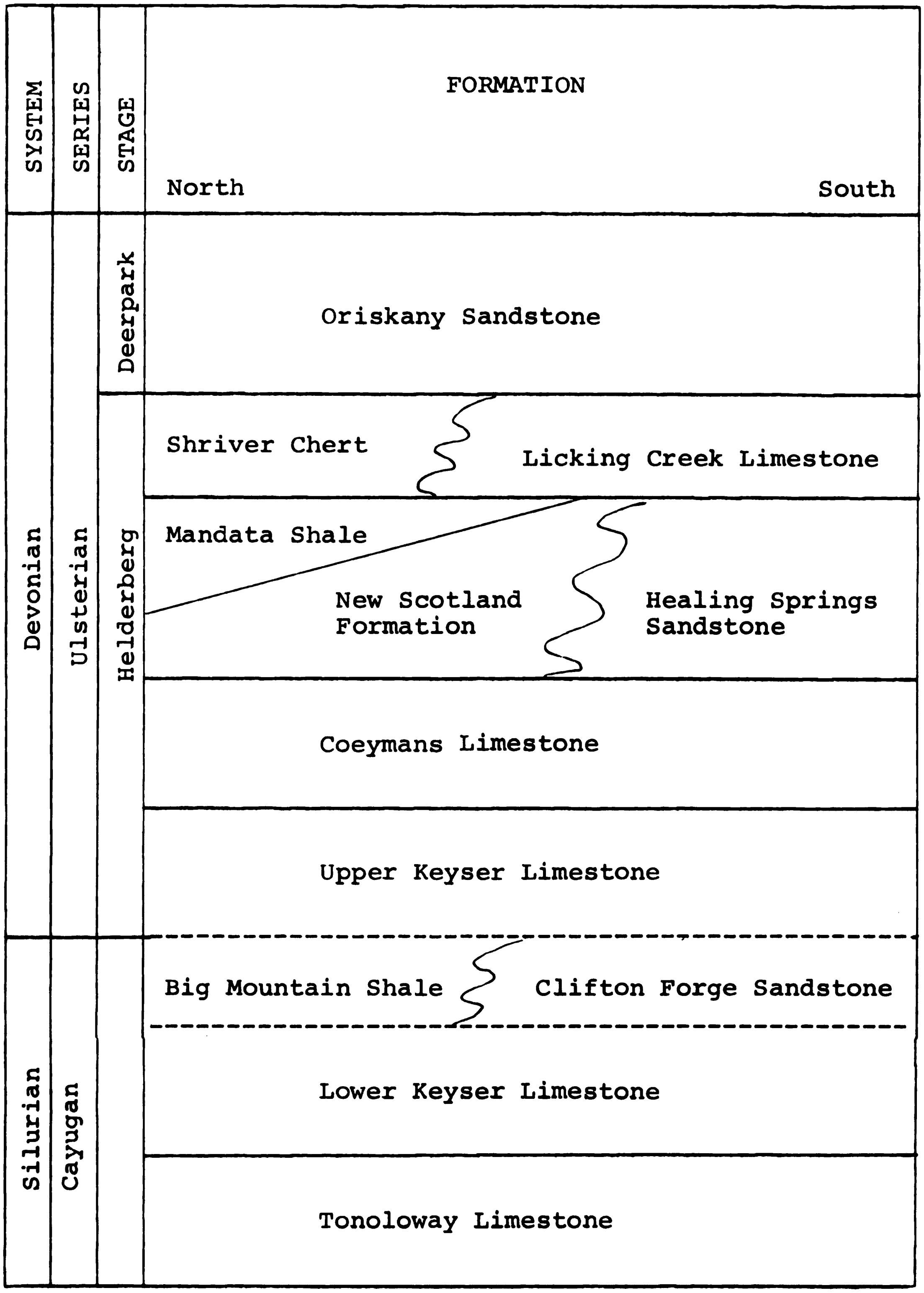

Figure 2.--Generalized columnar section of the Helderberg Group.

CHAPTER II

STRATIGRAPHY

This section of the report is primarily concerned with evaluating previous stratigraphic studies of the Helderberg units and re-evaluating the vertical and lateral relationships of lithologic units of the Coeymans Limestone and New Scotland Formation in the study area.

Previous Investigations

Many stratigraphic studies have been conducted on Helderberg rocks since Conrad (1839) designated an interval of rocks in New York as the Helderberg limestones and sandstones. Today these presumably include the interval from the base of the New Scotland Formation through the Schoharie Grit and possibly the Onondaga Limestone (Berdan, 1964).

Berdan (1967) has summarized the geological reasoning and conclusions of various stratigraphers concerning the Helderberg Group and the position of the Silurian-Devonian boundary in North America, from Conrad's work through that of Rickard (1962). Figure 3 summarizes these positions.

Conrad 1839	Hall 1859			Clarke 1889	Clarke and Schuchert		Williams 1900	Weller 1900	Weller 1903	Cooper and Others 1942			Rickard 1962	
Helderberg Limestones and Sandstones	DEVONIAN	Upper Helderberg		Lower Helderberg	Helderberg Group	Kingston Limestone			Kingston Limestone	Helderberg Stage	Helderberg Group	Port Ewen Limestone	Helderberg Group	Port Ewen Limestone
												Alsen Limestone		Alsen Limestone
						Becraft Limestone		Becraft Limestone	Becraft Limestone			Becraft Limestone		Becraft Limestone
						New Scotland Formation		New Scotland Formation	New Scotland Formation			New Scotland Formation		New Scotland Formation
						Coeymans Limestone		Coeymans Limestone	Coeymans Limestone			Kalkberg Limestone		Kalkberg Limestone
												Coeymans Limestone		Coeymans Limestone
														Manlius Limestone
							Oriskany Sandstone	Manlius Limestone						Rondout Limestone
AGE ?	SILURIAN	Upper Pentamerus Limestone	Lower Helderberg			Manlius Limestone	Helderberg Group		Manlius Limestone					Rondout Limestone
		Crinoidal Limestone												Cobleskill
		Delthyris Shaly Ls.												
		Pentamerus Limestone												
		Thin mass of limestone												
		Tentaculites Limestone												
		Onondaga Salt Group												
		Coralline or Niagara Limestone												

Figure 3.--Historical summary of the Silurian-Devonian boundary.

Some of these investigations have been concerned with redefining the Helderberg interval and determining the age of the Helderberg formations. Clarke and Schuchert (1899) subdivided the Helderbergian interval as designated by Hall (1859) into the Coeymans Limestone, New Scotland Formation, Becraft Limestone, and Kingstone Limestone (Alsen and Port Ewen limestones of modern usage). Later, Chadwick (1908) suggested the terms Kalkberg Limestone and Port Jervis Limestone for beds between the Coeymans Limestone and New Scotland Formation and above the Port Ewen Limestone respectively. Some investigators (Hall, 1859 and Williams, 1900) have considered the Helderberg as Silurian, others have considered the Helderberg as Devonian (Clarke, 1889; Clarke and Schuchert, 1899; Weller, 1900 and 1903; Schuchert, 1900 and 1903; Ulrich, 1911; Stose and Swartz, 1912; Schuchert and others, 1913; Swartz, 1929 and 1939; Butts, 1940; Cooper and others, 1942; Woodward, 1943; Rickard, 1962; Bowen, 1967; Boucot and Johnson, 1967).

Other stratigraphic studies have been concerned primarily with recognizing lateral equivalents of the Helderberg Group of New York in other regions. Schuchert (1903) correlated an interval of rocks in Maryland and West Virginia with New York Helderberg formations based on stratigraphic position and similarity of faunal content. Swartz (1929) correlated Helderberg outcrops throughout Virginia and West Virginia and was able to demonstrate facies changes occurring within the Helderberg Group, especially a sandstone facies in the southwestern outcrops. Later Swartz (1939) correlated Helderberg outcrops throughout Pennsylvania and was again able to show some facies changes; for example, Stormville (Elbow Ridge) Sandstone-Coeymans Limestone, Falling Springs Sandstone-New Scotland Formation, Mandata Shale-New Scotland Formation, and Licking Creek Linestone-Shriver Chert. Recently Epstein and others (1967) have re-evaluated correlations of the Helderberg Group from New York through New Jersey to eastern Pennsylvania.

Prior to 1962 most investigators have considered the Helderberg formations to represent time-stratigraphic units (see Figure 4a). For example, Cooper and others (1942) elevated the Helderberg Group to a stage rank (Helderberg Stage) with the type section in the Helderberg Mountains of New York. From detailed stratigraphic studies of Rondout Formation, Manlius Limestone, and Helderberg formation outcrops in New York, Rickard (1962) has been able to show that these formations are rock-stratigraphic units rather than time-stratigraphic units because they transgress time lines and interfinger laterally with one another (see Figure 4b).

Stratigraphy of the Helderberg Group in Virginia and West Virginia

The following formations comprise the Helderberg Group in the study area: (1) Keyser Limestone (at least

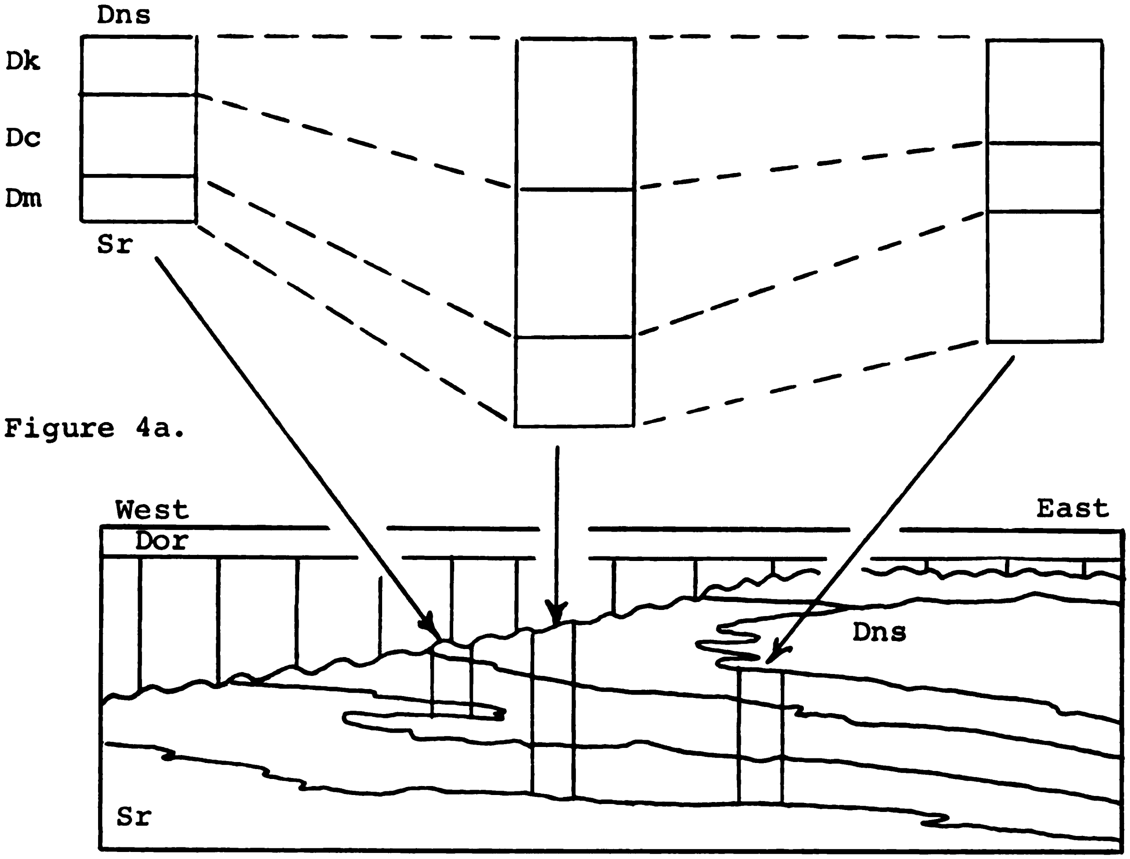

Figure 4a.

Figure 4b.

Figure 4.--Stratigraphic interpretation of Helderberg Group. Figure 4a represents a time-stratigraphic interpretation for the Helderberg Group prior to 1962. Figure 4b shows a rock-stratigraphic interpretation for the Helderberg Group since 1962. (After Rickard, 1962 and Laporte, 1969).

the upper part, based on the results of a paleontological investigation by Bowen, 1967); (2) Coeymans Limestone; (3) New Scotland Formation--Healing Springs Sandstone; and (4) Shriver Chert-Licking Creek Limestone (Port Ewen Chert and Port Jervis Limestone as employed by the West Virginia Geological Survey). However, this study is primarily concerned with the Coeymans Limestone and the New Scotland Formation.

Coeymans Limestone

Generally speaking, the Coeymans Limestone is a massive, coarsely crystalline, crinoidal limestone characterized by *Gypidula coeymanensis*. Schuchert (1903) correlated the presently recognized Coeymans Limestone of Maryland with that of New York primarily on similarities of lithology and the presence of *G. coeymanensis*.

Recently, Bowen (1967) presented some arguments for changing the name of the Coeymans Limestone of Maryland and adjacent areas to New Creek Limestone. His reasons for proposing a new formational name are (1) the unit can not be traced entirely to the type area because of many complex facies changes and unconformities, and (2) the fossils must be re-examined because they have not been studied in 50 years.

This investigator does not believe that a name change is justifiable because the name, Coeymans Limestone, is well established in the geological literature for a given formation in the central Appalachians as well as in the vicinity of the type area.

In a vertical sequence the Coeymans stratigraphically overlies the Keyser Limestone. In most outcrops studied the Keyser-Coeymans contact is lithologically distinct but in some outcrops (Trinity Road, Thrasher Springs School, Bull Pasture Mountain, Gala, Island Ford, and Bluefield sections) a gradational contact is present. In most outcrops the Keyser beds adjacent to the contact are thin-bedded, fine-grained, silty or dolomitic limestones. Fragments of the underlying Keyser beds were observed in the basal beds of the Coeymans Limestone at New Creek I and New Creek II sections.

In outcrops north of Monterey, Virginia the Coeymans Limestone can be subdivided into three members: (1) a lower limestone member which is a massive-bedded, coarsely crystalline, crinoidal limestone containing G. coeymanensis; (2) a middle limestone member which is a thin-bedded, finely crystalline, crinoidal limestone with chert nodules and lenses containing G. coeymanensis in the basal beds only; and (3) an upper limestone member which is a massive-bedded, coarsely crystalline, crinoidal limestone containing G. coeymanensis.

Overall there is an increase in size of pelmatozoan stem debris from north to south and from west to east. The average diameter of the stems in the northwestern outcrops is 1/4 inch; whereas, in the southeastern outcrops it is

3/4 inch. Also, the average diameter of the stems is larger in the lower limestone member than the upper member.

Poor to well developed cross-bedding occurs in the lower and upper limestone members but it is better developed in the lower member. The cross-bedding is best developed in accumulations of stem fragments where the stems have a larger diameter. These accumulations of stem fragments are lens shaped and are surrounded by finer grained crystalline limestone. One lens of pelmatozoan debris is generally situated adjacent to two other lenses and above the finer grained crystalline limestone occupying the area between the lower lenses. The arrangement of the lenses develops somewhat of a diagonal pattern to the bedding (see Figure 5). The cross-bedding displays two general trends, southeast and northwest. However, there does not appear to be any preferred orientation of the long axis of the pelmatozoan stems. Generally articulated shells of G. coeymanensis are associated with the crinoidal lenses and disarticulated shells of the species occur in the interareas between lenses. The cross-bedding, lens-shaped accumulations of pelmatozoan stems and distribution of articulated and disarticulated shells of G. coeymanensis are best developed in the Thrasher Spring School section.

The middle limestone member is a thin-bedded, fine grained limestone. Lenses of black chert parallel to the bedding occur randomly throughout this unit. G. coeymanensis

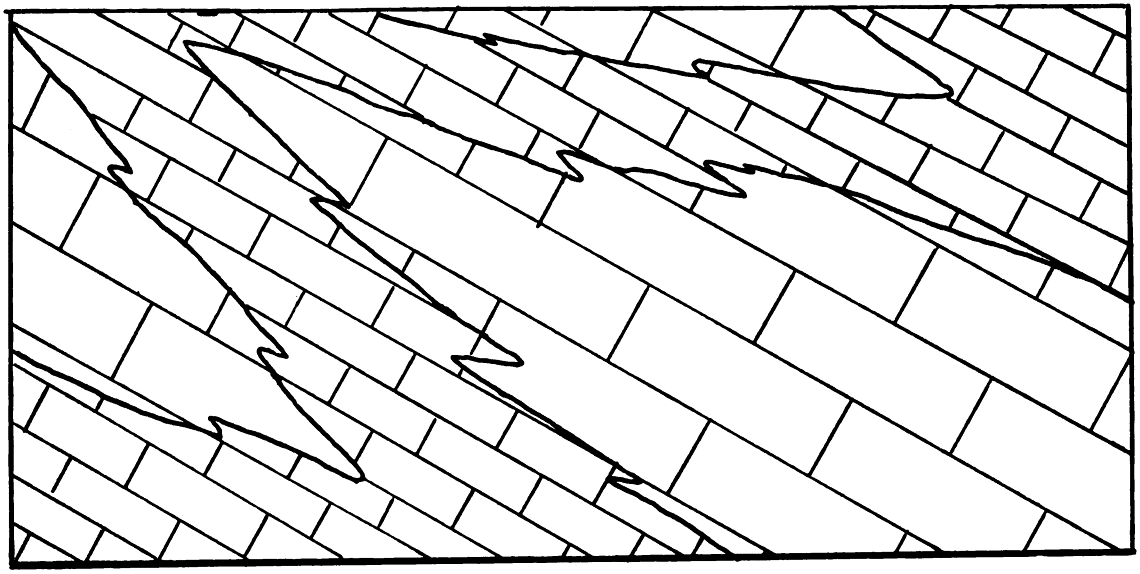

Figure 5.--Arrangement of crinoidal lenses in Coeymans Limestone. The thicker limestone symbol represents the coarser pelmatozoan debris. Scale: 1 inch represents 2 feet.

was observed only in the basal beds of the member. This member shows a general thinning from north to south, even though two adjacent outcrops might show local thickening or thinning. The member is not present in the Island Ford or Gala sections. It is not possible to determine if the member is present in the faulted Millboro Springs section.

New Scotland Formation

Based on fossil content and stratigraphic position Swartz (1929 and 1939), Butts (1940), and Woodward (1943) have suggested that four facies or members[2] comprise the New Scotland Formation in the study area. Regionally there are four facies (1) crinoidal sandstone (Healing Springs Sandstone) which occurs in the southern most outcrops of the New Scotland interval in Virginia and West Virginia, (2) crinoidal limestone which occurs between the crinoidal Coeymans Limestone and Licking Creek Limestone in the vicinity of Fordwick, Augusta County, Virginia, (3) limestone and chert beds, and (4) calcareous shale (Mandata Shale). The third and fourth facies occur in the northern most outcrops of the study area with the calcareous shale facies overlying the limestone and chert facies.

In this study each of these lithologic units is interpreted as a facies of the New Scotland Formation. Three of the units may be demonstrated at the Millboro Springs section. This section displays beds typical of the crinoidal sandstone, crinoidal limestone, and limestone and chert facies interbedded. The contact between one lithologic type and another is gradational. Also, crinoidal limestone beds interbedded with limestone and chert beds at the Bull Pasture Mountain section possibly indicate that the crinoidal limestone facies comprises

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[2] Swartz considered each entity as a facies of the New Scotland Formation; whereas, Woodward only recognized the crinoidal limestone and sandstone beds as facies of the New Scotland. Butts considered each entity as a member.

part of the New Scotland Formation. In the northermost outcrops of the study area the limestone and chert beds generally become more argillaceous toward the top of the interval and then grade upward into a calcareous shale. These observations suggest that the calcareous shale unit is also a facies of the New Scotland Formation.

The limestone and chert facies, crinoidal limestone facies, and crinoidal sandstone facies of the New Scotland Formation in their respective locations are stratigraphically above the Coeyman Limestone. The Coeymans-New Scotland contact is gradational and all outcrops studied in this investigation.

The spiriferid brachiopod, *Macropleura macropleura*, has been considered as the "index fossil" for the New Scotland Formation. Schuchert (1903) correlated the presently recognized New Scotland Formation of Maryland with the type section of New York, primarily on stratigraphic position and the presence of *M. macropleura*. *M. macropleura* is fairly abundant in the limestone and chert facies outcrops but is rare in outcrops of the crinoidal limestone facies. During this study no occurrence of *M. macropleura* was observed in any of the crinoidal sandstone or calcareous shale facies outcrops in the study area. Swartz (1929 and 1939) indicates that fragments of *M. macropleura* occur in the crinoidal sandstone facies in the vicinity of Healing Springs, Virginia and in the calcareous shale facies in central Pennsylvania.

Crinoidal Sandstone Facies

The crinoidal sandstone facies of the New Scotland Formation has been designated as the Healing Springs Sandstone by Swartz (1929) with the type section in the vicinity of Healing Springs, Virginia. The facies occurs in the southern most outcrops (Bluefield, Gala, Island Ford, Howards Creek, and Healing Springs sections) of the study area.

This facies is predominantly a cross-bedded, calcareous sandstone. The sandstone beds in the lower portion of the Healing Springs Sandstone (as displayed in the Gala and Island Ford sections) are generally lens-shaped and interbedded with thin beds of shale which are generally thicker between lenses of sandstone. The sandstone beds in the upper portion of the interval are also cross-bedded but the bedding is massive and several conglomeratic beds are present. With the exception of imprints of crinoid stems on the bedding planes and an occasional calyx of _Edriocrinus pocilliformis_, fossils are rare in the Healing Springs Sandstone.

Crinoidal Limestone Facies

The crinoidal limestone facies of the New Scotland Formation which occurs in the vicinity of Fordwick, Virginia is very difficult to distinguish from the underlying Coeymans Limestone. The contact was arbitrarily placed at the base of the crinoidal limestone bed containing the lowest observed specimen of _M. macropleura_. With the exception of an abundance of pelmatozoan fragments, fossils are rare in this interval. Though disarticulated ossicles of pelmatozoan stems are scattered throughout the interval the mass of the unit consists primarily of fine, sand-sized prismatic crystals of calcite which probably are disarticulated plates and ossicle prisms of pelmatozoans.

Limestone and Chert Facies

The limestone and chert facies is characteristic of the northern-most outcrops of the study area. A vertical sequence from bottom to top in any of the limestone and chert facies outcrops is generally as follows: (1) coarse to very fine-grained, fossiliferous limestone and chert lenses without *M. macropleura*; (2) thick- to medium-bedded, very fine-grained, fossiliferous limestone containing *M. macropleura* and irregular-bottomed chert lenses; (3) medium- to thin-bedded, very fine-grained, fossiliferous, argillaceous limestone containing *M. macropleura* and irregular-bottomed chert lenses interbedded with thin shale beds; (4) thin-bedded, fossiliferous, argillaceous limestone containing *M. macropleura* and irregular-bottomed chert lenses interbedded with thin shale beds; and (5) thin-bedded, fossiliferous, argillaceous limestone with *M. macropleura* restricted to the basal layers if present and irregular-bottomed chert lenses interbedded with thin shale beds.

The thickness of the limestone and chert facies varies from 21.5 feet at the Thrasher Spring School section to 32.5 feet at Petersburg Gap section. The observed thickness of the facies at Thrasher Spring School section is somewhat low as surrounding outcrops display thicknesses of 25 feet or greater for the interval in question. There is no evidence of faulting in the facies at Thrasher Spring School section to account for the thinning of the facies.

A gradational contact occurs in all limestone and chert facies outcrops in the study area between the facies and the underlying Coeymans Limestone. The contact interval shows a textural gradation from coarse grained limestone beds at the bottom to very fine grained limestone beds at the top. Lenses of white chert occur parallel to the bedding. Neither G. coeymanensis nor M. macropleura was observed in the gradational zone at any of the outcrops studied.

Occasional lenses of crinoidal limestone showing textural similarities with that of the underlying Coeymans Limestone occur in the basal portions of the limestone and chert facies. These are best developed in the Bull Pasture Mountain section. In this section one crinoidal limestone bed also occurs above the lowest limestone bed containing M. macropleura.

Within the limestone and chert facies at Smoke Hole Cavern section nineteen asymmetrical sedimentary cycles are well developed and plainly visible in the exposed portions of the section. Each cycle consists of the following lithologic units from bottom to top: (1) very fine-grained argillaceous limestone with a low fossil density; (3) very fine-grained cherty limestone with a very low fossil density; and (4) irregular-bottomed white chert lens or layer.

Calcareous Shale Facies

Swartz (1939) designated a unit of siliceous shale beds occurring between the New Scotland Formation and the Shriver Chert in the vicinity of Mandata, Northumberland County, Pennsylvania as the Mandata Shale. He considered the lower portion of the unit to be a facies of New Scotland age, based on the occurrence of M. macropleura, and the upper portion to be post-Becraft in age. He was also able to trace the Mandata Shale throughout most of the Helderberg outcrops of Pennsylvania and into the vicinity of Cumberland, Maryland.

Woodward (1943) recognized shaly beds lying between the New Scotland limestone and chert beds and the Shriver (Port Ewen) Chert but had reservations for applying the term Mandata Shale to these beds. He considered the shaly beds as an upper member of the New Scotland Formation.

In most outcrops of the study area a calcareous shale unit occurs between the limestone and chert facies of the New Scotland Formation and Shriver Chert (Port Ewen Chert). This shale unit is considered as a facies of the New Scotland Formation and probably correlates with the Mandata Shale which occupies the same stratigraphic position in central Pennsylvania.

The shale is thickest in the northern outcrops (18 and 33 feet thick at New Creek I and Rocks sections respectively) of the study area and thins southward (1.5 feet at Monterey). The contacts between the shale and the underlying limestone and chert beds of the New Scotland Formation and the overlying beds of the Shriver Chert are generally gradational. The lower and upper contacts of the shale unit were arbitrarily placed at the uppermost white chert horizon and the lowermost black chert horizon respectively.

Throughout the study area the shale is olive green on fresh surface. Also, the shale is calcareous and breaks with a fissile to hackly parting. In some of the northern outcrops phosphatic nodules occur one to two feet above the base of the shale but in southern outcrops lenses of coquinal limestone consisting primarily of fragments of *Anoplotheca concava* occur in the shale unit.

Construction of Stratigraphic Cross-Sections

The stratigraphic horizon which appears to represent the most plausible time plane for this study occurs at the midinterval of the middle limestone member of the Coeymans Limestone. Five stratigraphic cross-sections were drawn using this stratigraphic horizon as the datum plane so vertical and lateral relationships of Coeymans and New Scotland lithologic units can be evaluated (see Figures 6, 7, 8, 9, and 10). Three cross-sections were drawn essentially parallel to the trend of the depositional

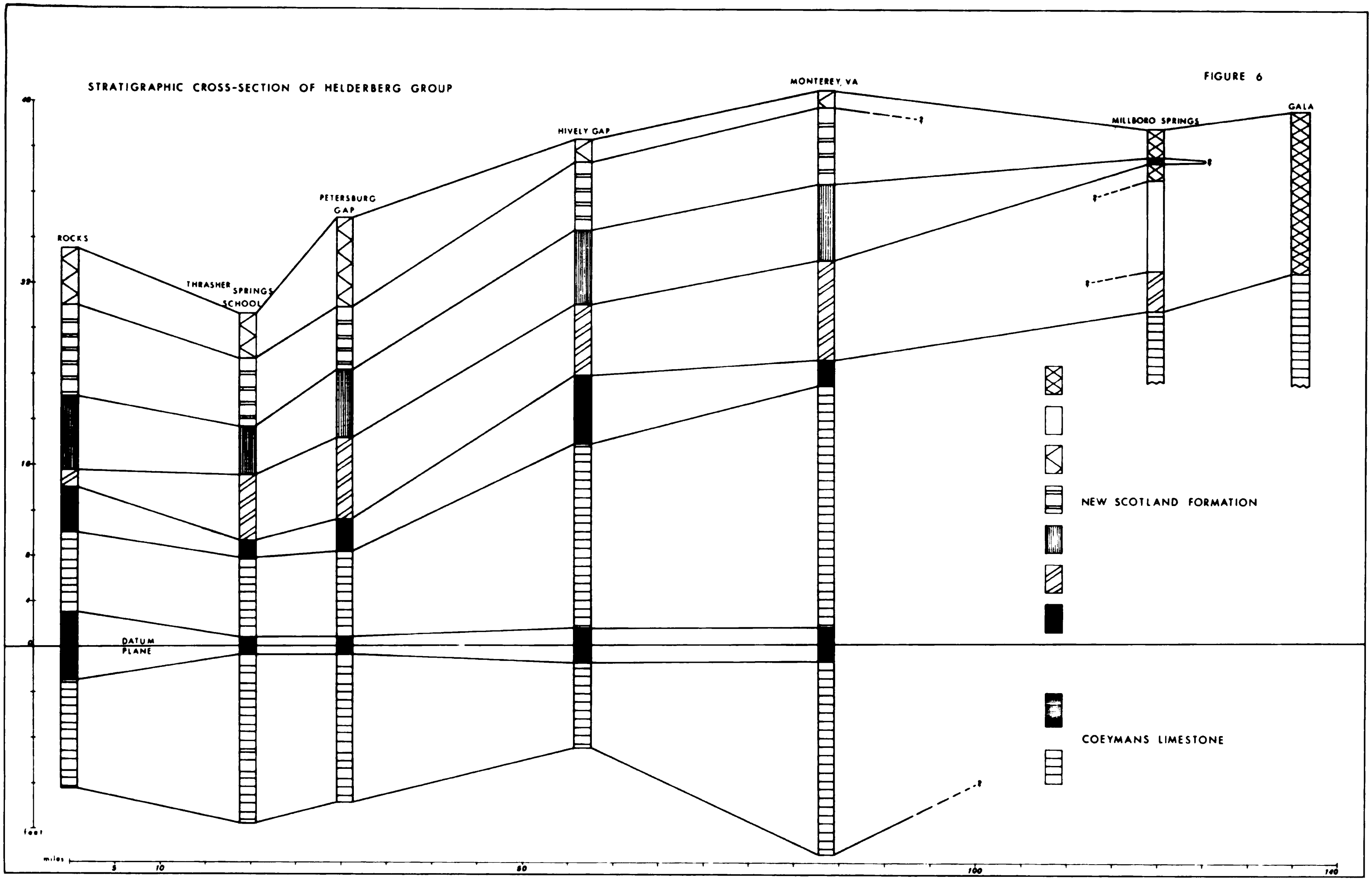


FIGURE 6

STRATIGRAPHIC CROSS-SECTION OF HELDERBERG GROUP

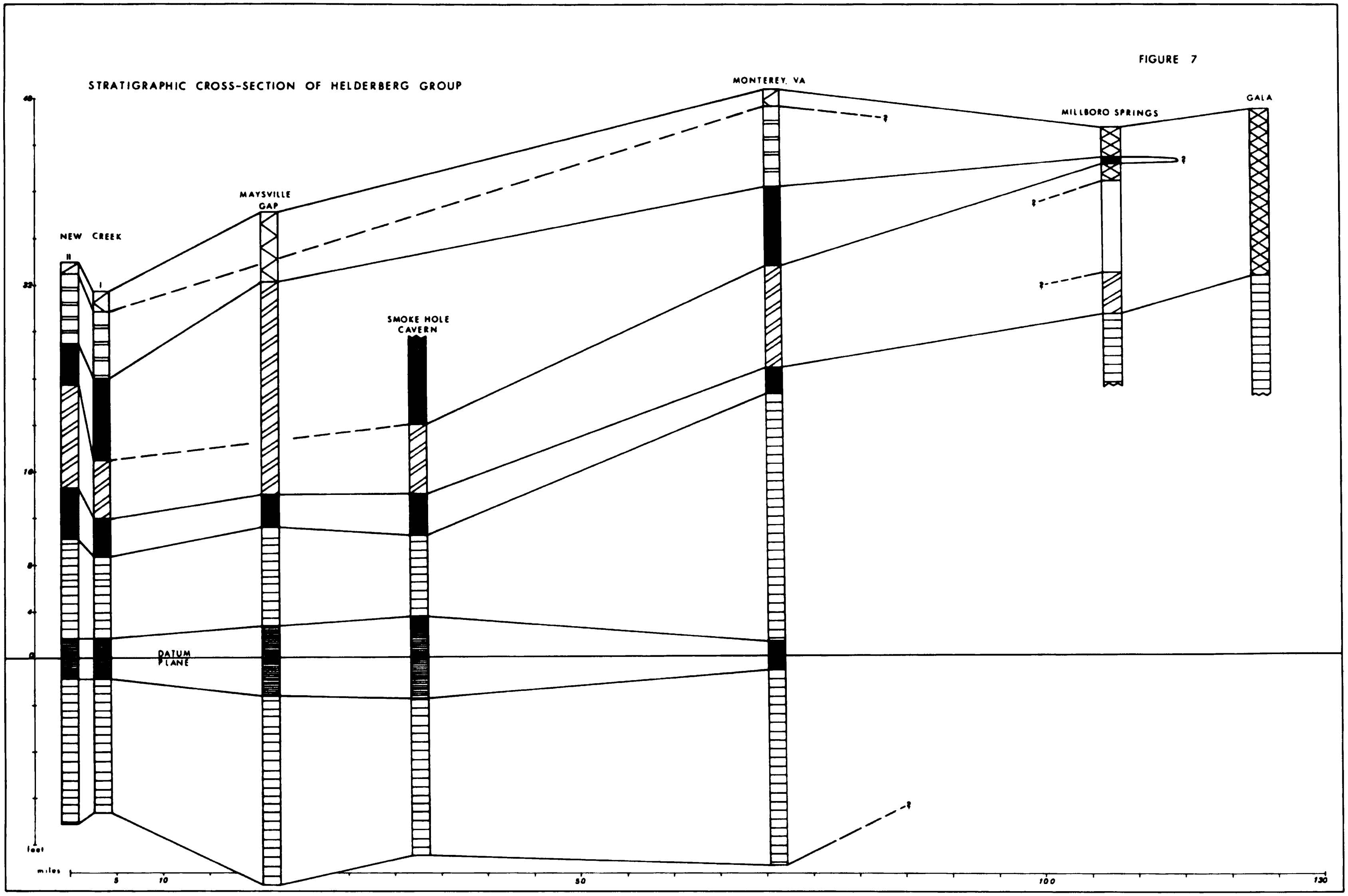


FIGURE 7

STRATIGRAPHIC CROSS-SECTION OF HELDERBERG GROUP

FIGURE 8

STRATIGRAPHIC CROSS-SECTION OF HELDERBERG GROUP

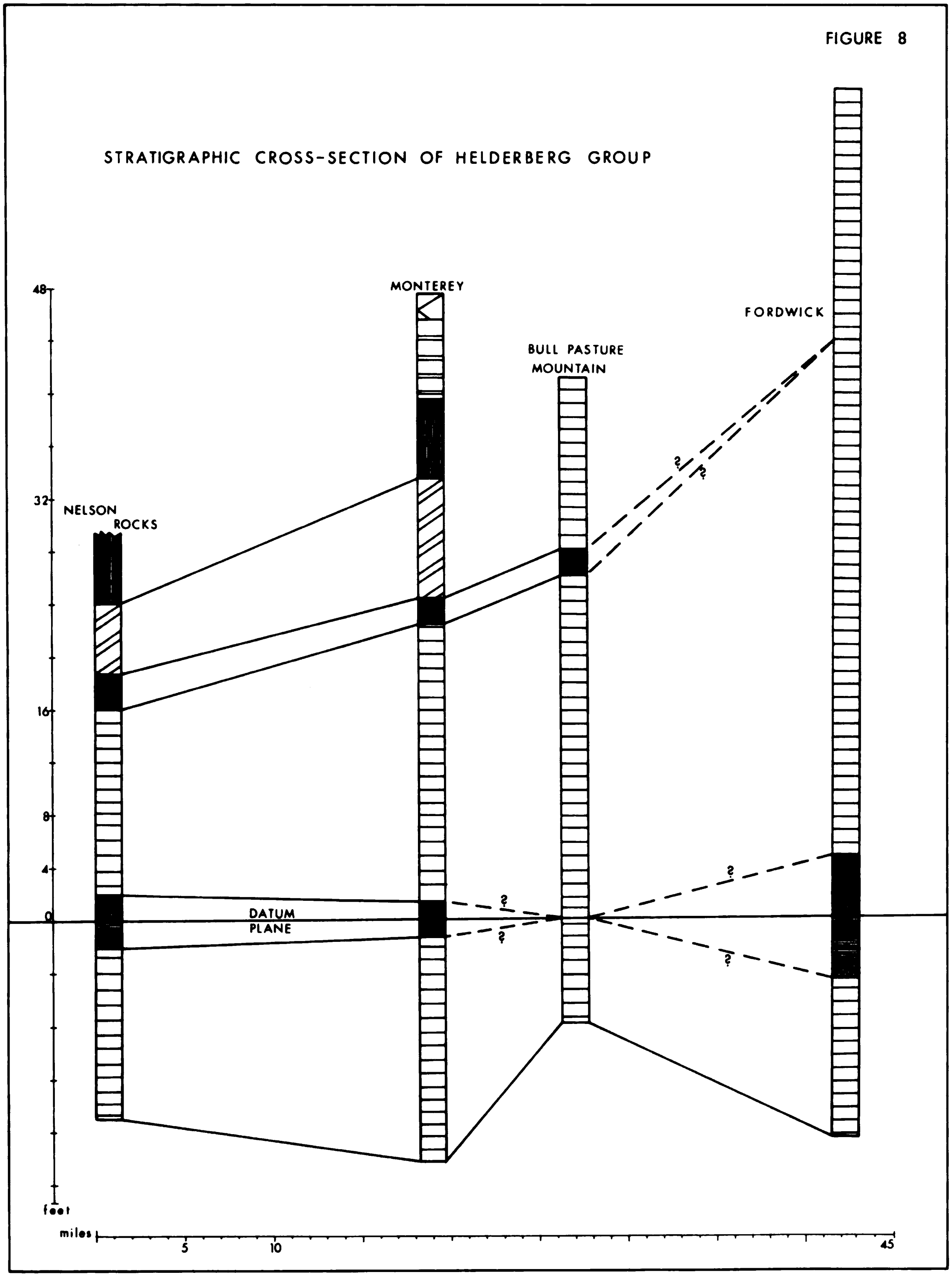


FIGURE 9

STRATIGRAPHIC CROSS-SECTION OF HELDERBERG GROUP

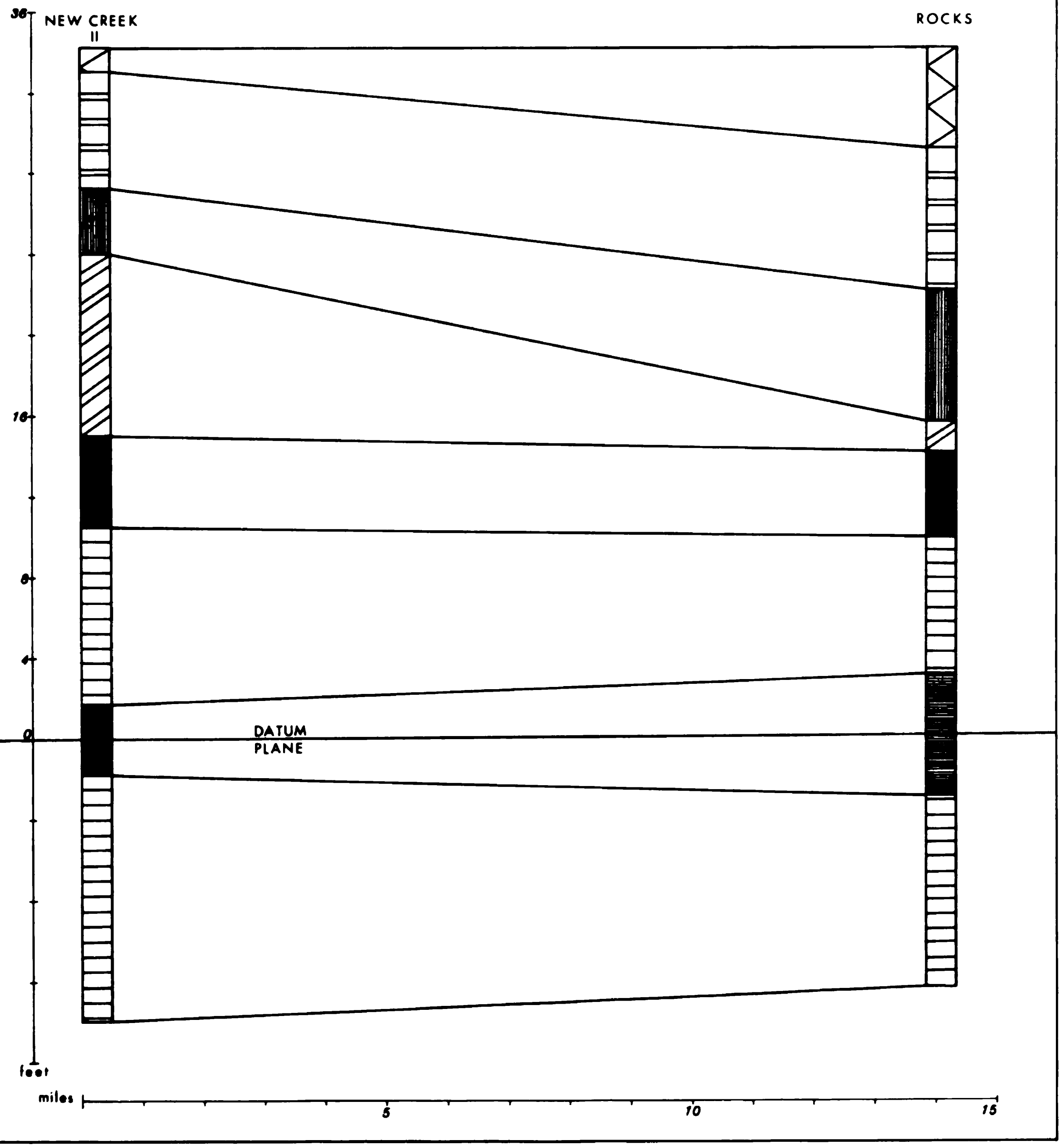
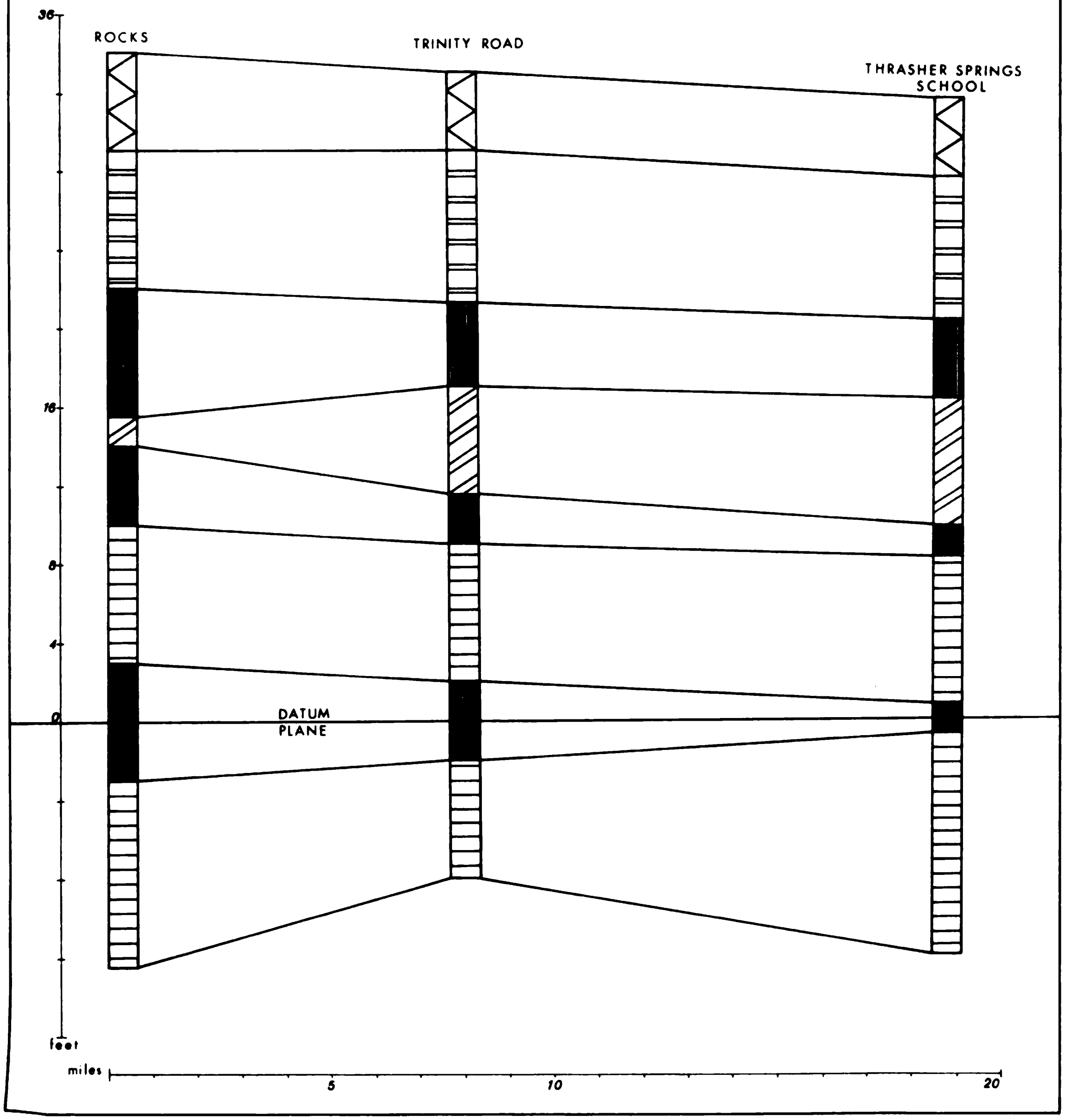


FIGURE 10

STRATIGRAPHIC CROSS-SECTION OF HELDERBERG GROUP



basin as recognized by Woodward (1943) and the others were drawn more or less perpendicular to the trend of the basin. (See Figure 1 for the location of the five cross sections).

Interpretation of Stratigraphic Cross-Sections

The validity of any conclusions regarding the vertical and lateral relationships of Coeymans and New Scotland lithologic units recognized in the study area is dependent upon two assumptions. The first one is that the datum plane used in the construction of the stratigraphic cross-sections actually represent a time plane. Secondly, we assume that any changes in the geometry of the basin floor were not tectonically controlled during deposition of sediments overlying that time plane.

The choice of a datum plane within the middle limestone member of the Coeymans Limestone is based on (1) the repetition of coarsely crystalline, cross-bedded, crinoidal limestone beds in the Coeymans interval; (2) the regional variation of thickness of the middle member; and (3) the vertical distribution of *G. coeymanensis* within the Coeymans Limestone.

The repetition of the coarsely crystalline, cross-bedded, crinoidal limestone beds of the Coeymans could have resulted from a minor regressive phase of deposition superimposed on the overall transgressive conditions of deposition. Then the finer grained, thin-bedded limestone beds of the middle member would represent a deeper water facies of the transgressive and regressive phases of deposition.

The general thinning of the middle limestone member from north to south could have resulted from erosion or nondeposition in the southeastern portion of the study area, or from transgressive and regressive phases of deposition of Coeymans sediments superimposed on an overall transgressive mode of deposition of Helderberg sediments. If the thinning resulted from erosion or nondeposition one would expect to find some evidence of this, such as fragments of the underlying beds encased in the overlying beds or discordant relationships of the beds. However, no evidence to support this hypothesis appears in any of the outcrops where the three members occur. The contacts between the middle limestone member and the lower or upper limestone members are gradational and lack fragments of the underlying beds. Also, the beds within the middle limestone member are essentially parallel.

Previous investigators (Swartz, 1929; Butts, 1940; and Woodward, 1943) have considered *G. coeymanensis* as an "index fossil" of the Coeymans Limestone. As mentioned previously, *G. coeymanensis* is more or less restricted to the coarsely crystalline, crinoidal lower and upper limestone members of the formation in the study area. This distribution suggests that *G. coeymanensis* is a facies fossil which preferred a coarse pelmatozoan debris substratum when it was alive. Also, since *G. coeymanensis* is more or less restricted to the lower and upper members this again suggests transgressive and regressive phases of deposition for Coeymans sediments.

As regional thinning of the middle limestone member, repetition of coarsely crystalline limestone units, and distribution of _G. coeymanensis_ are suggestive of transgressive and regressive phases of deposition for Coeymans sediments, sediments of the lower and upper halves of the middle limestone member probably represent synchronous deposition with sediments of the respective lower transgressive and upper regressive limestone members.

Izraelsky (1949) has demonstrated that inherent time planes occur in transgressive-regressive cycles (see Figure 11). Barring tectonic complications, the time lines coincide with lines passing through points corresponding to maximum depths of deposition for each unit of the transgressive-regressive cycle (Izraelsky, 1949). Thus, if the lower, middle, and upper members of the Coeymans Limestone represent a transgressive-regressive cycle, then the sediments of the middle member probably were deposited in somewhat deeper water.

Based on the above lines of evidence and the absence of any evidence for tectonic complications occurring within the Coeymans Limestone interval in the study area the likelihood that the boundary between the lower and upper halves of the middle limestone member at each outcrop represents a time plane is high. Therefore, the

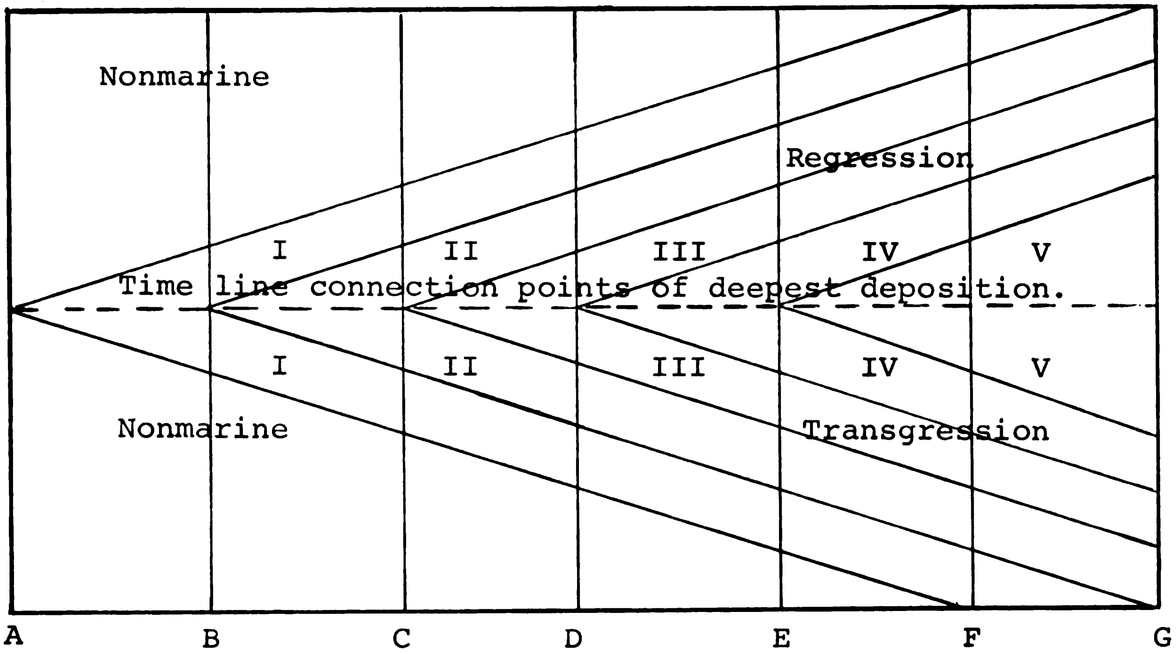


Figure 11.--Hypothetical transgressive-regressive cycle. A,B,C,D,E,F, and G represents hypothetical stratigraphic sections. Zones I, II, III, IV, and V represent brachish water, beach, shallow neritic, deep neritic, and bathyal environments respectively. (After Izraelsky, 1949).

assumption that the datum plane corresponds to a time plane probably is a valid one.

There are no other obvious stratigraphic horizons in each outcrop of the Coeymans or New Scotland formations which can be used as subordinate datum planes which correspond to time planes. Therefore, it is also necessary to assume that tectonic deformations did not alter the geometry of the basin floor significantly during deposition of the sediments comprising these formations so the lateral and vertical relationships of the various lithologic units involved can be evaluated.

Admittedly, the occurrences of a crinoidal bearing quartzose sandstone facies and a calcareous shale facies in an otherwise non-detrital interval suggest that some tectonic activity occurred during deposition of Helderberg sediments in the study area. Dennison (1961) believes that the source area for the detrital material of Cayugan, Helderbergian, and Deerparkian sandstones resulted from tectonic activity during post-Clinton and pre-Oriskany times in the vicinity of Smyth and Washington counties, Virginia. According to Swartz (1939) the source area for the detrital material comprising the Madata Shale probably ranged from eastern Pennsylvania to Massanutten Mountain, Virginia.

However, it is questionable if the tectonic activity which possibly accounted for the detrital fraction of the Helderberg Group affected the geometry of the basin floor because there are no other tectonic structural attributes in any of the Helderberg outcrops of the study area. Field relationships suggest that there was continuous deposition of Coeymans and New Scotland sediments in the study area. This is based on the predominance of gradational contacts between different lithologic units, the general parallelism of the major bedding, and the general lack of conglomeratic beds in any of the non-detrital units. Therefore, the assumption that tectonic activity did not significantly affect the geometry of the basin floor during deposition of Coeymans and New Scotland sediments appears to be valid.

Since the two assumptions involved in the stratigraphic analysis of the Coeymans and New Scotland formations do not conflict with the observations, subordinate time lines drawn parallel to the datum plane can be superimposed on the stratigraphic cross-sections above and below the datum plane to show the vertical and lateral relationships of the various lithologic units.

Previously, it was concluded that the upper crinoidal limestone member of the Coeymans Limestone represented regressive deposition. However, based on the fine-grained texture and poor sorting of fossiliferous beds in the overlying New Scotland limestone and chert facies, the sediments comprising the facies are believed to have been deposited in somewhat deeper water than those of the upper limestone member of the Coeymans. This suggests that the sediments of the limestone and chert facies were deposited during transgressive conditions. Therefore, the upper limestone member probably represents both regressive and transgressive phases of deposition.

If subordinate time planes (lines) are drawn on the stratigraphic cross-sections parallel to and above the datum plane it is apparent in most cross-sections that a stratigraphic unit overlying another unit in a vertical section grades laterally into an underlying or overlying unit in another location. This indicates that sediments of the different stratigraphic units were deposited simultaneously in different portions of the depositional basin. For example, while sediments comprising the upper limestone member of the Coeymans Limestone were being deposited at a given time in the vicinity of Monterey, Virginia, other sediments making up some of the stratigraphic units recognized in the New Scotland limestone and chert facies were being deposited contemporaneously in different portions of the basin (see Figures 6, 7, and 8).

As mentioned previously, beds of the limestone and chert facies, crinoidal limestone facies, and crinoidal sandstone facies are intercalated at Millboro Springs section. This is strong evidence that these three facies of the New Scotland Formation are lateral equivalents. Since a complete section of the Coeymans Limestone is lacking at this outcrop because of faulting, the vertical position of the columnar section on the stratigraphic cross-section is questionable. The columnar section for this outcrop was arbitrarily positioned so the Coeymans-New Scotland contact corresponded with an extended line passing through the same points in the columnar sections for the Hively Gap and Monterey sections. If subordinate time planes (lines) are drawn so they extend from the limestone and chert facies to the sandstone facies, they further suggest that sediments of the sandstone facies are time equivalent to those of the different stratigraphic units comprising the limestone and chert facies (see Figure 6). Similar lateral relationships are apparent between the crinoidal limestone facies and the sandstone facies or the limestone and chert facies (see Figures 7 and 8, respectively).

CHAPTER III

PETROGRAPHY AND PETROLOGY

According to Krynine (1948) sedimentary rocks possess three basic properties: composition, texture, and structure. These properties may reflect depositional conditions. However, the character of a given rock unit may have resulted from (1) original constituents, textures, and structures; (2) predominance of diagenetic features; or (3) mixture of original features and diagenetic features. Therefore, it is necessary to distinguish between primary and secondary characters if the petrographic aspects of a given rock unit are to be used, in part, to delineate the depositional environment.

If any two adjacent formations of the Helderberg Group observed in an outcrop of the study area actually represent lateral facies of each other, as concluded in the previous section; then, the textural or lithologic differences between these two formations probably reflect spatial variations of depositional conditions during a given time interval.

A petrographic investigation of the Helderberg Group was undertaken to (1) determine relative proportions of constituent particles; (2) classify rock types present and outline their vertical and horizontal distribution; (3) relate particle form and arrangement to possible mode of origin; (4) note relationships between diagenetic alteration and specific particle type; and (5) establish sequence of diagenetic changes. Data for these variables are necessary for making inferences concerning the depositional environments of Helderberg sediments.

Method of Study

Twenty-two partial and complete Helderberg outcrops were measured and described in Virginia and West Virginia during the summer of 1966. A total of 425 rock samples were randomly and purposely collected from these outcrops for further petrographic studies.

Each sample was cut into three pieces perpendicular to the bedding and polished. The samples were categorized into groups representing different textures, colors (hues), and stratigraphic units. At least one sample from each category was selected for thin section studies. A total of 80 thin sections were made. Also, plexiglass peels were made on each sample following the procedures outlined by Frank (1965) for additional textural and compositional analyses.

Relative proportions of constituent particles of each thin-section were determined from 300 point counts following the method outlined by Chayes (1949 and 1956). Then, point counts were made on plexiglass peels corresponding to the samples from which the thin sections were made. There was a maximum of 4 percent difference in the relative proportions for any of the constituent particles between the two counts for a given sample. Since there was good agreement between counts on thin sections and plexiglass peels, the relative proportions of the constituent particles of the remaining samples were determined by point-counting plexiglass peels of these samples.

Petrographic Aspects of the Helderberg Group

From a mineralogical and textural standpoint the Helderberg Group is composed of the following basic lithologies; limestone, sandstone, shale and chert. Limestone is the dominant lithology of all the stratigraphic units of the group except in the Shriver Chert, Mandata Shale, and the Healing Springs Sandstone. Sandstone is predominantly restricted to the Healing Springs Sandstone. Shale occurs as the dominant lithology of the Mandata Shale and thin beds of calcareous shale occur in the limestone and chert facies of the New Scotland Formation and in the Shriver Chert-Licking Creek Limestone interval. Chert occurs as lenses or nodules in the Coeymans Limestone, New Scotland Formation, Shriver Chert, and Licking Creek Limestones.

Mineralogical Composition

Analysis of polished sections and thin sections reveal that one or more of the following are the dominant mineral components of all Helderberg rock types: calcite, quartz, illite(?), and chert. Dolomite, collophane, tourmaline, feldspar, zircon, and organic material are generally present in some samples as accessory components.

The characteristics of some of these components probably are indicative of the depositional and post-depositional history of the rock units. The following section is concerned with the petrographic aspects of the Helderberg mineral components.

Calcite

Calcite is the dominant mineral component of the carbonate rock units and the second most abundant mineral of the sandstone unit. Several different varieties of calcite can be recognized in most samples of the Helderberg rock types. These different calcite varieties are bio-skeletal calcite, microcrystalline calcite, microsparry calcite, and sparry calcite.

Bioskeletal Calcite.--This variety of calcite includes all bioskeletal material, either entire, or fragments of calcareous hard parts. Generally it was possible to identify the type of material in thin section by shape, internal morphology or by a combination of both of these criteria, even though some fossil material had been fragmented, abraded or diagenetically altered to a considerable extent. However, some calcite crystals which were classified as sparry calcite in this study may actually represent bioskeletal calcite, such as disarticulated calcite prisms of gastropod or pelecypod shells or plates of crinoid calyces. Also some sparry calcite possibly represents bioskeletal calcite which has undergone recrystallization to such an extent that any evidence of bioskeletal material is lacking.

Bioskeletal calcite is a major constituent of most of the Helderberg carbonate units and also commonly occurs in samples from the crinoidal sandstone unit.

<u>Microcrystalline Calcite</u>.--According to Folk (1959 and 1962) microcrystalline calcite includes all carbonate grains smaller than four microns and lacks clarity when viewed in thin section. In this study, however, microcrystalline calcite includes those calcite particles smaller than ten microns because all grains smaller than this lacked clarity.

As seen in thin section the grains appear to be subtranslucent and display a faint brownish cast. Under higher magnification (above 250X) individual microcrystalline calcite crystals are generally subtranslucent and the crystals appear to be anhedral to subhedral, interlocking grains.

In hand specimens and polished sections microcrystalline calcite has a dull and opaque appearance. Generally the colors of this ultrafine-grained material varies from grayish-white to gray in Coeymans samples, from gray to bluish and brownish-gray in New Scotland samples, and from gray to grayish-black in Shriver-Licking Creek samples.

Microcrystalline calcite is one of the major constituents of the fine-grained limestones of the New Scotland limestone and chert facies and the middle member of the Coeymans Limestone. It is also present in lesser amounts in the lower and upper members of the Coeymans Limestone and the crinoidal limestone facies of the New Scotland Formation.

Sparry Calcite.--Sparry calcite includes most of the clear calcite crystals whose shortest dimension is greater than ten microns. Some of these crystals show polysynthetic twinning, especially the larger crystals. The crystals are usually subhedral to euhedral in shape and interlocking. The smaller crystals of sparry calcite were primarily distinguished from microcrystalline calcite by their clarity.

In hand specimens and polished sections sparry calcite appears clear with a vitreous luster. In most cases it appears as a simple pore-filling cement. The samples containing greater amounts of sparry calcite generally display a lighter color.

In thin section sparry calcite crystals were observed occurring as cementing material filling the pore spaces between allochem carbonate grains and as recrystallized microcrystalline calcite or calcite prisms of some fossils. Two types of sparry calcite cement were recognized in thin sections: (1) corona sparry calcite crystals as radiating overgrowths on allochem carbonate grains and (2) interstitial sparry calcite in the pores.

Crystals of the corona type are usually subhedral to euhedral, elongated crystals that radiate approximately normal to the surface of the allochem grains. The corona overgrowths include only one layer of crystals that surround the grains. The crystals ranged from ten microns to 0.1 mm in width and from ten microns to 0.2 mm in length. The crystals were generally in optical continuity with the allochem grains they were enclosing. All allochem carbonate grains were not surrounded, however, by corona sparry calcite crystals.

Interstitial sparry calcite crystals occur in void spaces between allochem carbonate grains or corona calcite crystals which are surrounding these carbonate grains. The interstitial sparry calcite crystals are generally larger than corona sparry calcite crystals and display good polysynthetic twinning.

Microsparry Calcite.--Microsparry calcite refers to crystals of clear calcite ranging in size from four microns to 0.6 mm and do not show any relationship to allochem carbonate grains or pore spaces. These crystals generally occurred as isolated patches or grains incased in microcrystalline calcite. The crystal shape was generally subhedral to euhedral.

This variety of calcite was most common in samples of the New Scotland limestone and chert facies. However, occasional microsparry calcite crystals occurred in some of the samples from the Coeymans middle limestone member.

Quartz

Quartz is a common constituent in the Helderberg Group but it is most common in the New Scotland sandstone facies. Both detrital and secondary varieties of quartz were noted in thin sections.

Generally the quartz grains observed in carbonate samples were angular to subangular silt-sized particles; however, in sandstone samples the grains were subangular to rounded sand-sized particles.

Secondary quartz occurred as overgrowths on detrital quartz grains. Secondary quartz overgrowths were distinguished from the detrital grains in most cases by the presence of a "dust" ring between the detrital grain and the overgrowth. However, if a "dust" ring was absent the secondary quartz could generally be distinguished from the detrital grain by difference in clarity in plain light. The detrital grains often had a turbid appearance due to inclusions: whereas, the secondary quartz generally lacked inclusions.

Secondary overgrowths were observed on many of the detrital quartz grains in samples from the New Scotland sandstone facies. In some thin sections of the sandstone samples occasional detrital quartz grains were surrounded by two or more cycles of secondary quartz overgrowths, as indicated by two or more "dust" rings. There were no secondary quartz overgrowths observed on any of the detrital quartz grains in the carbonate samples.

Illite(?)

Argillaceous material is finely disseminated throughout much of the New Scotland limestone and chert facies. McCue and others (1939) indicate that the argillaceous material in the New Scotland limestone beds is probably illite. Illite(?) is the dominant mineral of the New Scotland shale facies. The remainder of the Helderberg units generally do not contain much argillaceous material.

Chert

Chert is a microcrystalline variety of quartz and was readily recognized in thin section by its pin-point extinction. Chert occurred as disseminated particles and nodular or lens-shaped masses. The disseminated chert particles occurred encased in microcrystalline calcite. Nodular or lens-shaped chert aggregates vary in size. Some of the chert masses were developed solely within a bioskeletal fragment; whereas, others were much larger and no evidence of clastic carbonate grains was apparent. Of those bioskeletal fragments which had been partially replaced by chert the punctate brachiopod shells were generally the least affected.

Chert is most common in the limestone and chert facies of the New Scotland Formation but it is also a significant component in the middle limestone member of the Coeymans Limestone. Chert was not observed in any samples or outcrops of coarse grained limestone units.

Dolomite

Dolomite generally occurs as isolated rhombohedral crystals in Helderberg carbonate samples. The crystals were most common as replacement crystals in bioskeletal material other than punctate brachiopod shell fragments; however, they also were occasionally embodied in microcrystalline calcite. The total amount of dolomite in any Helderberg sample ranged from zero to about 4 percent.

Collophane

Nodules of collophane occur in some Helderberg units, particularly in the upper portion of the New Scotland limestone and chert facies and in the lower part of the Mandata Shale. These nodules are generally elliptical with their longest axes being parallel to the bedding, but some nodules display irregular forms.

In polished sections and thin sections occasional grains of oolitic collophane were observed in some samples as well as the nodular masses. The size of these colitic collophane grains was similar to that of other associated allochem carbonate grains. Occasional shell fragments or detrital quartz grains were encased in the massive collophane nodules.

In thin section the collophane displayed a dark amber color in plain light but with crossed nicols the collophane showed no or very weak birefringence colors. No evidence of concentric layering was observed in any of the collophane portions of the thin sections except in the oolitic grains of collophane.

Tourmaline

Detrital grains of tourmaline were observed in most thin sections of the New Scotland sandstone facies; however, none was observed in any of the Helderberg carbonate samples. The grains are generally well rounded but some of the grains were subangular. In plain light the grains are pleochroic in shades of green and brown. The amount of tourmaline present in the sandstone slides was always less than 2 percent.

Feldspar

A very small amount of detrital feldspar grains were noted in thin sections of samples from the New Scotland sandstone facies but none was observed in any of the carbonate slides. Microcline was the most abundant variety of feldspar noted, followed by orthoclase, albite, and oligioclase. The grains were subangular to rounded and usually highly altered to give a cloudy appearance.

The amount of feldspar content in any of the sandstone samples was less than 1 percent.

Zircon

Detrital grains of zircon were present in all sandstone thin sections but none was noted in any of the carbonate samples. These grains, however, constitute less than 1 percent of any of the sandstone samples. The grains are generally rounded but some subangular shaped grains were observed.

Organic Material

Streaks, patches, and specks of opaque material, presumably carbonaceous material, occurred in some Helderberg samples. In reflected light the material has a dull, "sooty" appearance. This material was most common in those samples where the collophane content was highest, particularly in samples from the upper units of the New Scotland limestone and chert facies and from the lower beds of the Mandata Shale.

Textural Components

The following section is concerned with the petrographic aspects of the Helderberg textural components.

Carbonate Textural Elements

Grain, matrix (microcrystalline calcite), and cement (sparry calcite) are the primary textural elements of all Helderberg carbonate rocks. Different carbonate textures are characterized by varying proportions of these elements.

Grains.--Grains are discrete particles capable of forming a rock framework. Four basic grain types were recognized in Helderberg carbonate samples. They are (1) terriginous; (2) bioskeletal; (3) intraclasts; and (4) pellets.

Terriginous grains include all grains which were derived outside the basin of deposition. The most common type of terriginous grains observed in the carbonate samples were quartz and illite(?). The quartz grains were generally angular, silt-sized fragments. In most samples the clay content was low enough to be masked by microcrystalline calcite in thin section. Terriginous grains, particularly quartz, were observed in most carbonate samples but they generally did not occur in abundance.

Bioskeletal grains are the remains of hard parts secreted by organisms. They may occur as broken, abraded fragments or as whole shells. It was generally possible to identify the various kinds of skeletal material from their internal structure and overall morphology as outlined by Johnson (1951). Pelmatozoa, brachiopod, bryozoa, coral, trilobite, ostracod, sponge, gastropod, and pelecypod bioskeletal grains were recognized in Helderberg carbonate samples. Pelmatozoan debris and fragments of bryozoa and brachiopods were the most abundant skeletal grains in the

Coeymans samples. Brachiopod and bryozoa fragments commonly occurred in New Scotland carbonate samples.

Intraclasts are allochem carbonate grains which range in size from fine sand to pebbles or boulders. Previous investigators have called these pebble or boulder sized intraclasts "edgewise conglomerates" or "flat pebble conglomerates." Intraclasts were observed at the base of the Coeymans Limestone at New Creek I and New Creek II sections. The majority of the intraclasts were rounded but some were subrounded to subangular. The intraclasts consisted of some bioskeletal fragments encased in microcrystalline calcite. Lithologically, the intraclasts were similar to the carbonate beds of the underlying Keyser Limestone.

Pellets are rounded to avoid homogeneous aggregates of microcrystalline calcite, without any internal structure. They range between 0.03 and 0.2 mm in size. They are distinguished from intraclasts by the lack of internal structure, small size, and general uniformity of shape. Pellets were observed in only two samples which were collected from the lower member of the Coeymans Limestone at the Pendleton-Grant county line section. These allochem carbonate grains were not recognizable before the samples were slabbed and polished. Therefore, it is possible that some beds containing pellets were not recognized in the field.

Matrix.--Matrix refers to a natural material in which allochem carbonate or terrigenous grains were embedded. The matrix material is generally several powers smaller than the grains. In carbonate rocks microcrystalline calcite is the common matrix material if the rock contains any matrix material.

Microcrystalline calcite is the common matrix material of all Helderberg carbonate samples. The amount of matrix material varies, however, from one sample to another. Matrix material is more common in samples from the New Scotland limestone and chert facies than the other carbonate units.

Cement.--Cement refers to clear, crystalline material which occurs in the interstices between grains and matrix material. In carbonate rocks sparry calcite is a common cementing material if the rock contains any cement.

Sparry calcite is the common cementing material of all Helderberg carbonate samples. Cement is more common in samples from the Coeymans Limestone and from the New Scotland crinoidal limestone facies than the other carbonate units.

Carbonate Rock Types

From the standpoint of textural elements the Helderberg carbonates can be classified according to a limestone classification proposed by Folk (1959 and 1962). This classification is descriptive and places primary emphasis on the relative proportions of grains, matrix (microcrystalline calcite), and cement (sparry calcite). The classification system, however, does not necessarily consider whether the grains are in mutual contact with one another or not.

The fabric of carbonate rocks is another important indicator of depositional conditions. Dunham (1962) has advanced a descriptive carbonate classification that is primarily concerned with the grain fabric of such rocks. Carbonate rocks of the Helderberg Group can also be classified according to these criteria. This scheme does not, however, provide a means of differentiating carbonate rock types which contain both matrix material and cement.

Since both classifications are applicable to the carbonates of the Helderberg Group and both are descriptive approaches from which genetic interpretations can be drawn, a combination of the two is probably adequate for classifying the carbonate rocks in this study. Based on the type of grain support and the proportion of grains, matrix, and cement the following carbonate rock types have been recognized in the Helderberg Group: (1) micrite; (2) biomicritic wackestone; (3) biomicritic packstone; (4) biosparitic packstone; (5) biosparitic grainstone; (6) pelsparitic grainstone; and (7) intrasparitic grainstone. The terms wackestone, packstone, and grainstone were first proposed by Dunham (1962). The terms micrite, biomicritic, biosparitic, pelsparitic, and intrasparitic were first introduced by Folk (1959).

Micrite.--Micrite is defined as a carbonate rock that is comprised of crystals of microcrystalline calcite and contains less than 10 percent allochem carbonate grains.

Micrite is the dominant carbonate rock type of the Shriver Chert-Licking Creek Limestone and the upper beds of the Keyser Limestone. It also makes up a portion of the limestone and chert facies of the New Scotland Formation. In the New Scotland it generally occurs beneath the chert lenses or layers which corresponds to the third unit of the previously mentioned asymmetrical sedimentary cycles.

In polished sections, peels, and thin sections both laminated and bioturbated micrites were recognized (see Plate 1, Figures A and B). Disseminated chert commonly occurred in greater abundance in the disturbed portions of bioturbated micrite samples. Occasional grains of microsparry calcite were randomly scattered in the microcrystalline calcite.

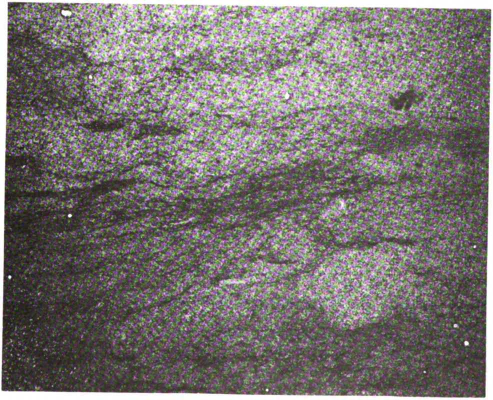
Biomicritic Wackestone.--Biomicritic wackestone is a type of limestone that contains more than 10 percent allochem carbonate grains and they are supported by microcrystalline calcite. Bioskeletal grains are the dominant type of allochems in this category.

This is the dominant carbonate rock type in the New Scotland limestone and chert facies, corresponding to the

Plate 1

Figure A.--Laminated micrite. Print of thin section shows suggestion of bedding in otherwise uniform texture (6X). Up is toward top of bed. Shriver Chert.

Figure B.--Bioturbated micrite. Print of thin section shows evidence of disrupted bedding, probably due to burrowing organisms (6X). Up is toward top of bed. New Scotland Formation.



first and second sedimentational units of the asymmetrical cycle. This rock type is also common in the Shriver Chert-Licking Creek Limestone interval.

Shells and shell fragments of brachiopods are the most common type of bioskeletal grains in samples from both stratigraphic units; however, fragments of bryozoa, crinoids, trilobites, and ostracods are common in some samples. Bioskeletal grains of corals, sponges, gastropods, and pelecypods occasionally occur in some of the samples, especially in the New Scotland samples. In some samples most of the disarticulated shells display a preferred convex upward orientation; whereas, in other samples the shells have a spiral orientation which suggests that the sediments were possibly disturbed after deposition by burrowing organisms (see Plate 2, Figures A and B). In both situations the bioskeletal material was usually completely encased in microcrystalline calcite.

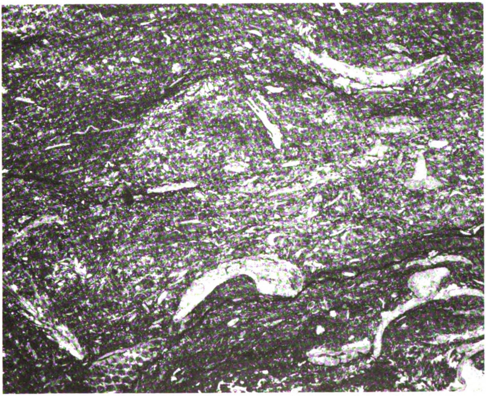
Biomicritic Packstone.--Biomicritic packstone refers to a type of limestone in which the allochem carbonate grains are grain supported and more than 50 percent of the interstitial material is microcrystalline calcite. Bioskeletal fragments are the dominant allochems in this category (see Plate 3, Figure A, page 60).

This rock type comprises a portion of the Shriver Chert-Licking Creek interval and the New Scotland limestone and chert facies.

Plate 2

Figure A.--Biomicritic wackestone. Print of thin section with brachiopod shell debris being the dominant bioskeletal material and embedded in a lime mud matrix (6X). Note preferred orientation of shell material. Up is toward top of bed. New Scotland Formation.

Figure B.--Bioturbated biomicritic wackestone. Print of thin section (6X) with brachiopod bioskeletal material displaying a random orientation and embedded in a lime mud matrix. Up is toward top of bed. New Scotland Formation.



The framework grains are predominantly bioskeletal material and are of the same types that characterize the biomicritic wackestones. Sparry calcite occurs in the interstices between some shell fragments to produce a geopetal structure. Usually the sparry calcite adjacent to the shells is of the corona variety.

Biosparitic Packstone.--Biosparitic packstone is defined as a type of limestone in which the allochem carbonate grains (predominantly bioskeletal grains) are grain supported and less than 50 percent of the interstitial material is microcrystalline calcite.

This type of limestone is the dominant type comprising the Coeymans Limestone and the crinoidal limestone facies of the New Scotland Formation. Individual beds of this type of limestone also occur near the boundary between the Oriskany Sandstone and the Shriver Chert in some outcrops (Petersburg Gap section) of the study area.

Fragments of pelmatozoan stems and bryozoa are the dominant bioskeletal material in samples belonging to this rock type. Occasional fragments of brachiopod shells occur in the samples. Except at the points of grain contact most grains were surrounded with crystals of the corona variety of sparry calcite and the remainder of the pore space was filled with the interstitial variety. However, microcrystalline calcite was patchily distributed in some of the interstitial areas of all samples, ranging from 3 to about 13 percent.

Biosparitic Grainstone.--The term biosparitic grainstone refers to a type of limestone in which the allochem carbonate grains (predominantly bioskeletal grains) are grain supported and no microcrystalline calcite occurs in the interstices between the grains (see Plate 3, Figure B).

This carbonate rock type is restricted to the Coeymans Limestone and even then it is not too common. The bioskeletal grains have undergone some recrystallization and the pore spaces between the grains are completely filled with the interstitial variety of sparry calcite.

Pelsparitic Grainstone.--Pelsparitic grainstone is a type of limestone in which the allochem carbonate grains (pellets) are grain supported and no microcrystalline calcite occurs in the interstices between the grains.

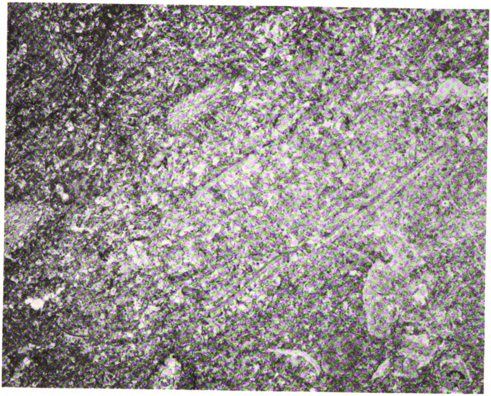
Only two samples are representative of this type of limestone. These samples were collected from the Coeymans Limestone at an outcrop near the Pendleton-Grant counties line. The textural attributes of this rock type were not recognized until the samples had been cut and polished; therefore, there may have been more beds of this type of limestone which were not recognized in the field.

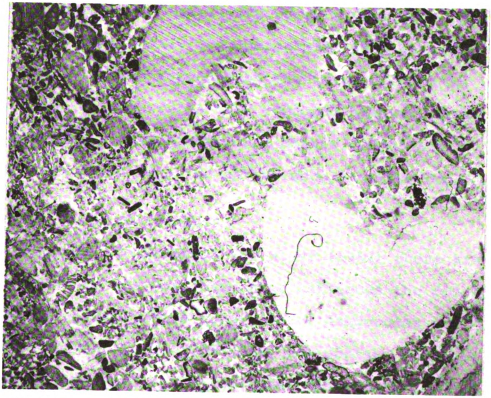
One sample consisted of layers of microcrystalline calcite interbedded with the pellets. The pellets appear to consist of microcrystalline calcite similar to that comprising the micrite layers (see Plate 4, Figure A, page 63). The second sample consisted of well sorted, fine

Plate 3

Figure A.--Biomicritic packstone. Print of thin section (6X) consisting primarily of pelmatozoan stem debris and lesser proportions of bryozoan fragments. Note that the bioskeletal material is grain supported. Some microcrystalline calcite occurs in the interstices between the bioskeletal grains. Coeymans Limestone.

Figure B.--Biosparitic grainstone. Print of this section (6X) consisting principally of pelmatozoan stem debris and lesser amounts of bryozoan fragments. Note that the bioskeletal grains are grain-supported. Coeymans Limestone.





sand sized pellets which are cemented with sparry calcite cement (see Plate 4, Figure B). Even though the pellets are in contact with adjacent pellets there is no evidence of grain penetration. Also, none of the pellets display any internal structures. The pellets are generally surrounded with a layer of corona variety of sparry calcite.

Intrasparitic Grainstone.--Intrasparitic grainstone refers to a type of limestone in which the allochem carbonate grains (intraclasts) are grain supported and no microcrystalline calcite occurs between the grains.

This type of limestone was recognized in the basal portion of the Coeymans Limestone at two outcrops (New Creek I and New Creek II sections).

The intraclasts consist of micrite which is very similar to that of the underlying Upper Keyser beds in this area. Dimensionally the intraclasts were generally a half inch thick and ranged from one to two inches in length. Most of the grains were rounded, however, some were subangular. Some bioskeletal debris (coral and bryozoa) were mixed with the intraclasts in these beds.

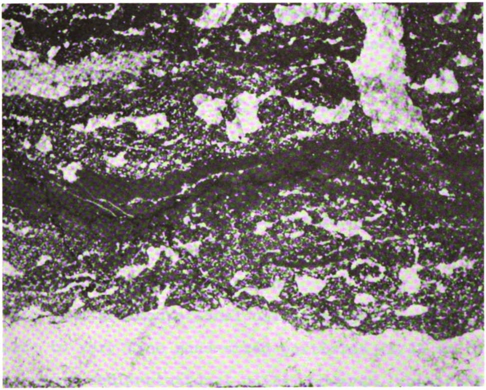
Terrigenous Textural Elements

According to Krumbein and Sloss (1963) there are six properties of the particles that influence the final character of a terrigenous rock. These properties are (1) size, (2) shape, (3) roundness, (4) surface texture, (5) orientation, and (6) mineralogical composition. All

Plate 4

Figure A.--Pelsparitic grainstone and layers of micrite. Print of thin section (6X) consisting of layers of grain supported pellets interbedded with thin layers of micrite. Note the similarity of appearance between the pellets and the microcrystalline calcite which comprises the micrite layers. Coeymans Limestone.

Figure B.--Pelsparitic grainstone. Print of thin section (6X) consisting of grain supported pellets which are cemented with sparry calcite cement. Coeymans Limestone.



of these textural properties, except grain orientation, were analyzed primarily in thin section because of the lithified character of the samples. The mineralogical components of the terrigenous rock units have been discussed in a previous section of this report.

Size.--The true grain size is underestimated when measured in thin section (Griffiths and Rosenfeld, 1950). In an attempt to keep this underestimation at a minimum the longest dimension of 40 grains per thin section of each sandstone sample were measured.

In some sedimentational units the grains ranged from silt- to very fine sand-sized particles (1/32 mm to 1/8 mm). Most sedimentational units, however, consisted of fine- to medium-sized grains (1/8 mm to 1/2 mm) with the average being medium sand-sized grains (1/4 mm). Occasionally the coarses sedimentational units would contain some individual grains having a diameter up to 4 mm. Within any given sedimentational unit the sorting was generally good.

Shape, Roundness, and Surface Texture.--In hand specimen most of the grains appear to be somewhat spherical. At times it is impossible to determine, however, in a thin section whether a well-rounded grain has a spherical or cylindrical shape.

In thin section the shape of the original terrigenous grains comprising the New Scotland sandstone facies varies from sub-rounded to rounded. Some grains show authigenic overgrowths which also show sub-rounded to rounded surfaces.

Some of the grains, as seen in the weathered portions of hand specimens, have pitted surfaces which give the grains a frosted appearance. In thin section this pitted surface appears to be a corroded surface of the quartz grains due to embayments of calcite cement.

Terrigenous Rock Types

From the standpoint of terrigenous grain size rocks of the New Scotland sandstone facies can be classified as siltstones, sandstones, and conglomeratic sandstones.

The sandstones, with few exceptions, can be classified as an orthoquartzite (Krynine, 1948). Quartz accounts for more than 95 percent of the terrigenous grains in the sand-sized sedimentational units. Some bioskeletal grains, such as pelmatozoan stem debris, is associated with the terrigenous grains. The grains are cemented with sparry calcite cement.

The pebbles occurring in the conglomeratic sandstone units are generally polymineralic in content. They are composed of interlocking crystals of quartz and feldspar.

The siltstones can be classified as feldspathic siltstone (Pettijohn, 1957) since feldspars constitute about 10 percent of the terrigenous fraction. Both the quartz and feldspar grains are subangular to sub-rounded. The terrigenous grains are cemented with sparry calcite cement.

Origin of Helderberg Rock Types

The compositional and textural aspects of a sedimentary rock are a product of its origin, the environmental conditions pertaining at the time of deposition and any post-depositional processes that affected the rock.

This section of the report is concerned with the origin of the various rock types of the Helderberg Group, a postulated relationship to plausible depositional environments and later diagenetic alterations. Inferences concerning the origin of Helderberg rock types, especially the carbonates, are somewhat speculative but plausible conclusions can be made by comparing the various textures of these rocks to similar characteristics which have been observed and studied in areas of recent carbonate deposition.

Origin of Rock Components

The basic components of terrigenous and carbonate rocks are grains, matrix, and cement. Grains can be encased in matrix, cement, or a combination of both. The origin of the components is significant to the overall understanding of the rock.

Grains

As mentioned previously, grains can be either terrigenous or allochems. The term terrigenous, as used in this report, refers to grains of minerals and rock fragments which have been derived from outside the basin of deposition; whereas, allochem refers to carbonate grains which originated within the basin of deposition and were transported to a site of accumulation in a solid state.

Terrigenous Grains.--Quartz, illite(?), feldspar, tourmaline, and zircon grains plus granitic pebbles are the common terrigenous grains recognized in the Helderberg terrigenous rock types. Quartz and illite(?) occur in some of the carbonate rock types.

These types of terrigenous grains suggest that the original source area for the sediments of the sandstone facies was a granitic source area. The occurrence of some quartz grains which show at least two stages of rounding suggest, however, that some of the sediments were derived from preexisting sedimentary rocks.

Also the preponderance of well-rounded grains of the more stable minerals suggest that rather intensive chemical weathering conditions occurred in the source area and the sediments were deposited in a high energy environment.

Allochems.--Bioskeletal grains, intraclasts, and pellets are the common allochems recognized in the Helderberg carbonate rocks. Since the origin of bioskeletal material is beyond the scope of this study this will not be discussed; however, the environmental significance of bioskeletal material is considered in other sections of this report.

Intraclasts: Illing (1954) indicates that intraclasts (grapestones and encrusted lumps) are formed from the accumulation of chemically precipitated lime mud and silt by accretion and agglutination.

Folk (1959 and 1962) suggests a mechanical origin for most intraclasts which involves penecontemporaneous erosion of weakly consolidated calcareous sediments in some area of the basin of deposition and then abrasion and redeposition in some adjacent portion of the basin. Folk (1962) further suggests that exposed, mud-cracked, carbonate flats may provide much of the intraclast material.

The lack of any rolled layering which would result from accretionary and agglutinating processes and the high degree of lithologic similarity between the intraclasts observed in the base of the Coeymans Limestone and the micrite beds of the subjacent Keyser Limestone suggest a mechanical origin for the intraclasts.

Pellets: Four basic processes have been suggested for the origin of pellets. These processes are as follows: (1) fecal excretions of organisms (Thorp, 1939; Illing, 1954; Newell and Rigby, 1957; and Folk, 1959 and 1962); (2) auto-agglutination of formerly homogeneous calcareous mud (Folk, 1962); (3) flocculation of suspended particles of colloidal calcium carbonate (Hobbs, 1957); and (4) current-worn fragments of poorly consolidated sediments of microcrystalline calcite (Laporte, 1969).

The pellets observed in some Coeymans Limestone samples probably represent current-worn fragments of weakly consolidated micrite. This conclusion is based on the general absence of any shell fragments within any of the pellets and the lithologic similarity between pellets and subjacent micrite beds.

Matrix

Clay minerals are the dominant matrix material in Helderberg terrigenous rocks. Most clays probably have resulted from chemical breakdown of alumino- and ferromagnesium silicates in the source area.

Microcrystalline calcite is the dominant matrix material in allochem carbonate rocks. Several theories have been proposed for the origin of microcrystalline calcite and these may be listed as follows: (1) physicochemical precipitation from waters of abnormally high salinity and carbonate saturation (Black, 1953 and Cloud, 1962); (2) precipitation through bacterial metabolism and decay (Lalou, 1957; Oppenheimer, 1961; and Greenfield, 1963); (3) skeletal disintegration by removal of binding organic matter (Lowenstam, 1955, and Stockman and others, 1967); (4) skeletal disintegration resulting from activity of boring organisms (Ginsburg, 1957); and (5) breaking and abrasion of skeletal material in turbulent water (Cloud, 1959; Chave, 1964; Folk and Robles, 1964; Matthews, 1966; and Force, 1969). Even though several modes of origin have been proposed for the origin of microcrystalline calcite (lime mud) there are no methods of detecting the origin of a given crystal grain. However, the conditions in which microcrystalline calcite can be deposited is of environmental significance. Deposition of these clay-sized particles requires quiet water conditions.

Cement

Sparry calcite cement is the dominant cementing material in the terrigenous and carbonate rocks of the Helderberg Group. Sparry calcite cement can result from the following: (1) calcite precipitation from carbonate-rich solutions; (2) inversion of aragonite precipitated from sea water into the void spaces; or (3) recrystallization of microcrystalline calcite occurring between the framework grains.

Before any plausible inferences can be deduced regarding the depositional environments of carbonate rock types, particularly the packstones and grainstones, it is necessary to recognize the origin of the sparry calcite cement.

The following petrographic observations have been interpreted as being useful criteria in this study for recognizing primary sparry calcite cement that was precipitated from a carbonate-rich solution: (1) occurrence of corona variety of sparry calcite around the grains and interstitial variety filling in the remainder of the void space, and (2) presence of sharp boundaries between grains and cement.

If both conditions were observed in a given portion of a thin section or plexiglass peel it was assumed that the sparry calcite represented a primary pore filling. If recrystallization of microcrystalline calcite had occurred the boundary between the grain and the cement would probably not be sharp and clearly defined. In addition, the fact that crystals of the corona variety radiate normal to the surface of the allochem carbonate grain suggests that original grain growth was unobstructed in the pore space. Bathhurst (1958) and Cotter (1966) believe that this type of crystal growth indicates a primary origin for the sparry calcite cement.

If, however, sharp and well-defined boundaries occur between the grains and cement but the corona crystals are lacking this may indicate that aragonite was originally precipitated into the void spaces from sea water and later underwent inversion to form a sparry calcite cement.

Gevirtz and Friedman (1966) have presented conclusive evidence that aragonite cement can be precipitated in pore spaces from sea water. Berner (1966) has shown that aragonite readily inverts to calcite when it comes in contact with either brackish or fresh water.

Microsparry Calcite

Crystals of microsparry calcite are silt-sized particles that generally were randomly distributed in a groundmass of microcrystalline calcite. These particles may represent either recrystallized grains of microcrystalline calcite or finely comminuted bioskeletal material. Since the grains generally exhibit a random distribution in thin sections and peels, it is assumed that these particles are recrystallized grains of microcrystalline calcite.

Origin of Helderberg Cherts

Chert occurs as nodules, lenses, stringers, and beds or as disseminated silica in the middle limestone member of the Coeymans Limestone, in the limestone and chert facies of the New Scotland Formation, and in the Shriver Chert-Licking Creek Limestone interval.

In some cases the origin of a cherty mass, such as a silicified brachiopod shell, is readily apparent. However, other massive chert bodies, as well as disseminated chert, can have a primary or replacement origin.

Therefore, it is important to determine the origin of the chert occurring in the Helderberg units.

The bedded chert layers generally show an irregular-bottomed surface, an occasional faint trace of relict bedding, encased masses of limestone, and occasional ghosts of fossils. These observations suggest that the chert lenses, beds, and nodules represent a replacement origin.

In thin section shell fragments were observed in varying stages of being replaced by chert. Some shells which had been completely replaced with chert were also completely surrounded by chert to produce a nodular mass. In other thin sections there were no evidence of preexisting bioskeletal material in the chert nodules. This is a further indication that the chert masses are of a replacement origin.

Disseminated silica was noted in all samples collected from a horizon subjacent to a chert lens or bed. These samples are generally a bioturbated micrite. Those samples which displayed the greatest amount of bioturbation generally contained larger amounts of disseminated silica than samples which were less disturbed. This suggests that the more disturbed portions of the carbonate sediments possibly acted as avenues for movement of silica-rich solutions. On this basis the overlying massive chert layer may represent an accumulation of chert where the sediments were more disturbed by burrowing organisms. This could also explain the sparseness of fossils or fossil ghosts in the more massive chert layers.

In a given sample or sample locality the amount of microcrystalline calcite should theoretically decrease as the amount of chert increases. A rank correlation coefficient was calculated so the microcrystalline calcite-chert relationship could be evaluated. This type of statistic was used since the population distribution is unknown. The rank correlation coefficient value is -0.16 but is not significant at the 0.05 level of significance. However, if the amount of microsparry calcite is included with that of microcrystalline calcite the rank correlation coefficient value for the matrix (microcrystalline calcite plus microsparry calcite)- chert relationship is -0.97 which is significant at the 0.05 level of significance. This suggests that microsparry calcite is recrystallized microcrystalline calcite; and that at least disseminated and fossil replaced chert were more favorable at those sites where recrystallization had occurred.

Field and petrographic evidence suggests that most of the chert occurring in the Helderberg units is of a replacement origin. Therefore, the presence and characteristics of the chert can not be used to infer conditions at the time of deposition of Helderberg carbonate sediments.

Origin and Environmental Significance of the Helderberg Rock Types

The Helderberg Group displays several facies of both carbonate and terrigenous rocks implying a diversity of local environments at the time of origin. The following discussion is concerned with the origin or mode of deposition of the various terrigenous and carbonate Helderberg rock types and their environmental significance.

Terrigenous Rock Types

Variations in grain size (clay versus silt versus sand) and mineral composition suggest that sediments of the various terrigenous rock types were deposited under somewhat different depositional conditions.

Orthoquartzite.--The very high percentage of quartz grains comprising the orthoquartzitic beds, their high degree of roundness, and their good sorting suggest that rather slow rates of sediment influx occurred during deposition and the sediments were deposited in a high energy environment such as a beach.

The flat-bottomed, lens-shaped nature of the orthoquartzitic beds and the presence of some cross-stratification further indicate that the sediments represent migrating sand bar deposits.

Feldspathic Siltstone.--The smaller grain size, greater angularity, and lower percentage of quartz grains in the siltstones suggest that these sediments were deposited in an entirely different depositional environment than those of the orthoquartzitic beds. The smaller grain size of the siltstones indicate that deposition occurred in an area where water turbulence was not as intense as that associated with the sand-sized particles of the orthoquartzites. Siltstone beds are, however, laterally adjacent, superjacent, and subjacent to orthoquartzitic beds in the New Scotland sandstone facies (Healing Springs Sandstone) and this indicates that sediments of the two rock types were deposited simultaneously in the same general area. Therefore, the silt-sized sediments were probably deposited in an area that was somewhat protected from intense water turbulence, such as in basins on the lee side of the sand bars.

Shale.--Deposition of very small clay-sized particles comprising a shale requires calm water conditions. Therefore, the shale units of the Helderberg Group were deposited in either deeper water environments or more protected environments.

Carbonate Rock Types

Even though studies of recent carbonate sediments indicate that depositional conditions producing different types of carbonate deposits are complex, it is possible to make two generalities concerning the accumulation of carbonate particles. They are as follows: (1) deposition of microcrystalline calcite generally occurs in areas lacking persistent strong currents, and (2) deposition of allochems having higher degrees of grain contact require more agitated water conditions.

Assuming that diagenetic textures can be differentiated from primary depositional textures, it is possible to formulate logical depositional conditions for the various Helderberg carbonate rock types by referring to the two generalities, mentioned above, since the rock types are based on the relative amounts of microcrystalline calcite present and the number of grains having grain contacts.

Micrite and Wackestone.--Microcrystalline calcite is the dominant component of micrite and wackestone varieties of limestone. This implies that deposition probably occurred in areas lacking strong currents. Microcrystalline calcite can be deposited in the following conditions: (1) in protected lagoons (McKee, 1949); (2) in broad, shallow platforms on the lee side of barriers (Fairbridge, 1950); (3) on the slope of a geosyncline or basin below wave base (Tyrrell, 1969); (4) in basinal portion of geosyncline (Garrison and Fischer, 1969; Thomson and Thomasson, 1969; Wilson, 1969; and Tyrrell, 1969); (5) in fairly high energy environments where organic material, such as marine grasses or algal growths, act as baffles (Ginsburg and Lowenstam, 1959); and (6) in carbonate tidal flats (Laporte, 1967).

If micrites and wackestones display mud-cracked surfaces this suggests that deposition occurred in a supratidal, mud-flat environment (Laporte, 1967 and 1969). Based on the occurrences of mud-cracked surfaces and micritic beds the uppermost beds of the Keyser Limestone were deposited in a supratidal, mud-flat environment.

Micrite and wackestone beds of the New Scotland Formation and the Shriver Chert-Licking Creek Limestone interval were probably deposited below wave base. This conclusion is based on the stratigraphic relationship of the two units to the Coeymans and Keyser limestones and on the high faunal diversity (see section on paleosynecology) of the New Scotland which suggests an open marine environment.

Many of the micrite and wackestone beds do not show distinct bedding or laminations, but disrupted bedding. This could be a result of burrowing organisms or slumping. The absence of slump structures (Potter and Pettijohn, 1963) further indicate that the activity of burrowing organisms accounts for most of the disrupted bedding.

Packstone and Grainstone.--Packstones and grainstones are limestones that are characterized by self-supporting allochems with little or no microcrystalline calcite occurring in the interstices. This type of grain arrangement is generally a property of rocks deposited in agitated water. This type of depositional condition occurs on the margins of carbonate banks and platforms (Newell and others, 1951; Illing, 1954; Ginsburg, 1956; Newell and Rigby, 1957; and Newell and others, 1960).

Packstone and grainstone beds comprising the Coeymans Limestone and the crinoidal limestone facies of the New Scotland Formation were deposited in more strongly agitated water conditions than other Helderberg carbonate beds. They represent marginal or shelf deposits associated with an overall transgressive sea. These conclusions are based on the degree of sorting these rock types display and their stratigraphic relationships to the other Helderberg units.

Pelmatozoan stem debris is the dominant type of clastic carbonate grain in most Helderberg packstones and grainstones. It is not certain whether these rock types resulted simply from physical removal of smaller grains to form a lag deposit or the durrent-swept areas provided favorable sites for the development of crinoidal meadows. Since most of the packstone and grainstone beds are lens-shaped and cross-bedded, this probably indicates that the deposits are lag deposits.

Theoretically, packstone varieties of limestone should not occur because grain-support and muddiness require entirely different modes of deposition. The occurrence of microcrystalline calcite in the interstices of grain-supported carbonate rocks (packstones) could result as follows: (1) compaction of wackestone; (2) infiltering;

(3) mixing due to burrowing organisms; (4) incomplete winnowing; or (5) partial leaching (Dunham, 1962).

If a packstone resulted from compacting a wackestone, one should observe the development of styolites or microstyolites, evidence of grain penetration, or both. Microstyolitic surfaces were observed in some thin sections of packstones; but no evidence of grain penetration was observed.

If the occurrence of microcrystalline calcite in the interstices of a grain-supported carbonate rock was due to infiltering, the minute crystals should be concentrated in the bottom portion of the interstices. This type of evidence was not recognized in all Helderberg packstone samples.

If a packstone resulted through partial leaching of the microcrystalline calcite comprising a wackestone, one would expect to observe some evidence that the allochem were also affected. Evidence of this type observed was not in any of the Helderberg samples.

It is almost impossible to differentiate between a localized mass of microcrystalline calcite resulting from the mixing activity of burrowing organisms and one resulting from incomplete winnowing unless the material has a vertical orientation. Most of the matrix material in the interstices of Helderberg packstones is due to either burrowing organisms or incomplete winnowing. However, some occurrences may be due to compaction.

CHAPTER IV

PALEONTOLOGY

Woodward (1943) lists 32 Coeymans and 91 New Scotland fossil species which have been identified in outcrops of these formations in West Virginia. However, he did not indicate their relative abundance, species associations, or species-rock type associations. Also, Swartz (1929 and 1939), Butts (1940), and Woodward frequently mention the G. coeymanensis or the M. macropleurus faunal assemblages without indicating what other species comprise these assemblages.

In this study 18 fossil species from the Coeymans Limestone and 32 fossil species have been identified subjectively, plus numerous crinoid stems and undifferentiated bryozoa from both formations. Table 1 is a listing of those species identified in this study and their relative percentage of occurrence. Generic nomenclature of sponges, corals, brachiopods, crinoids, gastropods, and trilobites follows the Treatise on Invertebrate Paleontology for the respective phylum.

TABLE 1.--Helderberg Fossils.

	Formation	
Fossil	Coeymans	New Scotland
Porifera		
Hindia sphaeroidalis	0.00	0.09
Coelenterata		
Streptelasma strictum	0.41	4.06
Pleurodictyum lenticulare	0.00	0.09
Favosites conicus	3.83	0.44
Crinoidea		
Edriocrinus pocilliformis	0.00	**
Trilobita		
Phacops logani	0.14	0.18
Dalmanites pleureptys	0.00	0.18
Gastropods		
Platyceras trilobatum	0.14	0.18
Brachiopoda		
Dalmanella perelegans	0.00	0.18
Platyorthis planoconvexa	0.00	0.09
Rhipidomella assimillis	0.00	0.71
R. oblata	3.55	9.36
Gypidula coeymanensis	33.06	0.00
Camarotoechia litchfieldensis	0.27	0.18
Eatonia peculiaris	0.00	0.26
Eatonia singularis	0.00	0.26
Uncinulus abruptus	0.27	0.26
Anoplotheca concava	0.00	0.09
Atrypa "reticularis"	5.87	6.27
Atrypina imbricata	0.00	0.09
Delthyris perlamellosus	4.37	8.91
Macropleura macropleurus	0.00	18.18
Meristella lata	1.64	11.56
Nucleospira elegans	0.00	0.35
"Spirifer" concinnus	0.00	0.35
"S." cyclopterus	0.00	3.35
Trematospira equistriata	0.00	0.62
T. multistriata	0.00	0.97
Leptaena "rhomboidalis"	3.28	9.36
Schellwienella woolworthana	8.74	14.03
Stropheodonta planulata	0.27	5.21
Rensselaeria subglobosa	0.27	0.88
Rhynchospirina species	0.00	0.09
Crinoid stems	33.61	2.47
Undifferentiated Bryozoa	0.00	0.79

**Observed in some outcrops of Healing Springs Sandstone.

CHAPTER V

PALEOSYNECOLOGY

Paleosynecology is the study of living communities of the past, their relationships with their physical and chemical environment, and their interrelationships among themselves (Ager, 1963). This section of the report is concerned with the interspecific associations and environmental significance of 34 species of New Scotland invertebrate macrofossils observed at 14 outcrops in West Virginia and Virginia.

The knowledge of the ecology of fossil species provides a means of interpreting the physical and biological conditions of the geologic past. Ideally, if a group of fossils shows no evidence of abrasion or breakage and displays a certain growth orientation it is possible to infer a life assemblage for this group of fossils. However, fossil assemblages are rarely found where preservation and orientation of the fossils indicate a primary association (Craig, 1954).

Preliminary field observations showed that most New Scotland fossils had been transported to some degree.

Therefore, some other criterion is necessary to determine their interspecific associations.

When a fossil shell or fragment of a certain species occurs in close proximity with a fossil shell or fragment of another species at a given location in an outcrop it usually does not have much paleoecologic significance. But if this same association recurs at several locations within many outcrops throughout a large area this fossil relationship probably is significant. A basic assumption utilized in this portion of the study is that the probability of having two fossil species associated with each other is much higher if they originally lived together than if they did not. Some fossil associations may be due to factors influencing accumulation and preservation, samples representing two or more unrecognized environments, or chance. If a large number of random samples from lithological similar units are evaluated, it should be possible to statistically exclude some, if not all, of the extraneous associations. Johnson (1962a) used this approach in a study to determine the interspecific associations of Pennsylvania fossils. Also Valentine and Mallory (1965) found that fossil species associations based on many samples corresponded to recent living associations even though some transportation of shells had occurred.

Method of Determining Species Associations

Several statistical and empirical methods have been utilized to analyze interspecific association of natural ecological units (Forbes, 1907 and 1925; Jaccard, 1908; Cole, 1949; and Fager, 1957) and paleoecological units (Beerbower, 1957; Beerbower and McDowell, 1960, Johnson, 1962a; Ellison, 1963; and Valentine and Mallory, 1965).

The empirical method, such as the one proposed by Jaccard (1908), does not provide a means of excluding those associations which might be due to chance.

Beerbower (1957) used a correlation statistic to study the faunal association of the Centerfield coral zone in Pennsylvania. However, the frequency distribution of fossil abundances in unknown and is probably not normal. Moreover, two species may occur together frequently in marine communities and have no constant relationship between their numbers (Johnson, 1962a). Since the use of a correlation statistic is questionable, one was not used to determine interspecific associations for the New Scotland fossils.

A chi square test was used to test the independence of the distribution of two species from 260 samples. The results of the chi square test are interpreted to indicate that two species are or are not associated at a stated level of significance (Johnson, 1962a). The chi square test has been used previously by Beerbower and McDowell (1960), Johnson (1962a), and Valentine and Mallory (1965) to determine the interspecific associations of Devonian, Pennsylvania, and Pleistocene strata respectively.

Method of Sampling

All statistical methods of data analysis assume that the data are random and independent. The chi square test for independence is no exception.

To insure that the data were random and independent, two groups of random numbers were generated for each outcrop by the use of random number tables in the appendix of Introduction to Statistical Analysis (Dixon and Massey, 1957). The first group of random numbers represented a stratigraphic thickness, in inches, above the base of the formation. Each section had been previously measured so the largest possible number to be generated for each outcrop was controlled by the thickness of the formation. The second group of random numbers represented some distance, in inches, from the base of the outcrop if the strata were steeply dipping or from the left side of the outcrop, as viewed when facing the outcrop, for horizontal or gently dipping strata. The largest random number to be generated for the second group of numbers depended on the extent of the outcrop or the accessibility of the entire outcrop. The point on the outcrop located by the intersection of the first random number in group one, and the first random number in group two, is the first random sampling point for the outcrop. The remaining random sampling points were established in the same manner. Figure 12 is a diagramatic drawing to illustrate the

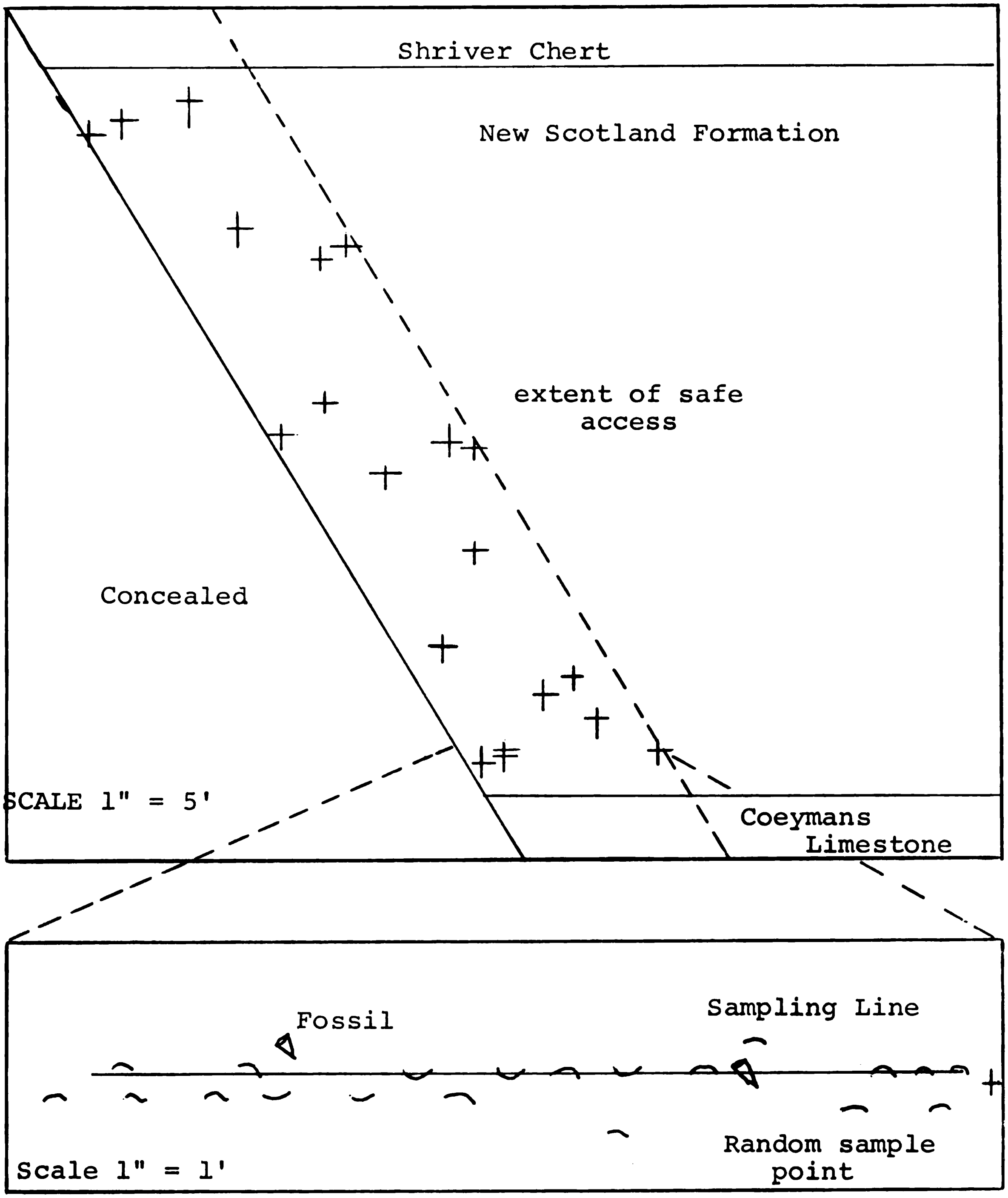


Figure 12.--Hypothetical random sampling point on gently dipping strata. The upper drawing diagramatically illustrates the location of 20 random sampling points in a Helderberg outcrop. The bottom drawing depicts the relationship of the sample line to the location of a given random sample point. Note that the sample line starts on a fossil nearest to the sample point and is parallel to the bedding.

location of some hypothetical random sampling points on gently dipping strata.

If the random sample point did not coincide with a fossil or fragment, the distance from the sample point to the nearest fossil or fragment, either in a stratigraphically vertical, horizontal, or oblique direction, was recorded. If the closest specimen was in a different rock type than that of the random sample point another set of random numbers were generated. This was continued until a random number and the closest fossil were in the same type of lithology.

A chalk line was stretched parallel to the bedding along the face of the outcrop starting at the random sample point, if it coincided with a fossil, or at the nearest specimen. Every specimen which the line crossed was identified to species, of possible, and recorded. This method of sampling is called the line transect method. The following information was also recorded: (1) whole fossil or fragment, (2) if fossil was a bivalve which valve was present where disarticulated, (3) distance between specimens, and (4) type of lithology. Twenty sample lines were investigated in each section.

McIntyre (1953) indicates that the line transect method is well established in theory and practice as giving a level of precision in the estimate for a given effort which compares very favorably with other methods of sampling. There are, however, some limitations with the line transect method. The main deficiencies are (1) the counts made along the line will be proportional not only to abundance but also to the size (diameter) of the specimens and (2) the practicality of the method is void below a certain specimen density (McIntyre, 1953 and Ager, 1963). This method of sampling has been employed successfully by Johnson (1962b) in a paleoecological study of the Millerton Formation at Tomales Bay, California.

In order to compare one section quantitatively with another section a standard unit of sampling length or area must be used. Johnson (1962b) used a sample line of four meters in the Millerton Formation study. Preliminary attempts to use a sample line of four meters in this study proved to be unfavorable because some portions of the outcrops were inaccessible, some lines crossed different lithologies, or some lines extended into highly weathered or concealed portions of the outcrop. Since the length of any sample line is controlled by the accessibility of the outcrop, uniformity of lithology or degree of weathering the longest line possible was used. Each line was roughly evaluated by a species-length of line method, which is discussed below. If a useful minimum length of line was not attained another random point was established.

A species-length of line method was used to determine the necessary minimum length of sample line in this study. This is a modification of the species-area method introduced by Cain (1938).

Braun-Blanquet (1932) introduced an empirical concept for determining the minimum sampling area required to describe a plant community. This method involves plotting the number of species found in a stand on the y-axis coordinate of a graph and the area of the stand on the x-axis coordinate. After several stands of various sizes have been plotted the curve generally rises rapidly from the origin of the graph and then gradually becomes asymptotic with the x-axis. According to Braun-Blanquet (1932) the minimum area corresponds to the point where the species-area curve becomes nearly straight and horizontal.

Cain (1938) has shown, however, that the characteristic shape of the species-area curve depends on the x-y ratio which has been plotted. Therefore, if the same data is plotted twice, but with different x-y ratios, different values for the minimum area will be suggested by the method proposed by Braun-Blanquet (1932). In order to standardize the use of the species-area method Cain (1938) proposed the use of a point on the curve which represents a rate of increase of 10 percent in the total number of species and an increase of 10 percent of the total sample area as the representative minimum sampling area. The location of the point is not affected by the ratio of x to y. This point can be located easily by placing the edge of a triangle so that its edge passes through the origin of the graph and the point which corresponds to 10 percent of the area and 10 percent of the species. Then place a ruler along the right side of the triangle and slide the triangle up or down until its edge is tangent to the curve. The point of tangency corresponds to the minimum area which would contain an adequate representation of an association.

Since a line transect method was utilized in this study rather than a quadrant method, the length of the line was plotted on the x-axis instead of the area of a quadrant. Figure 13 is a diagrammatic drawing to illustrate how the minimum length of line was determined for each sample line.

The minimum length was determined for each sample line. Then the average minimum length was determined for each outcrop. The range of the average minimum length of line for the outcrops was from 1.0 foot for Maysville Gap section to 5.0 feet for Bull Pasture Mountain and New Creek I sections. The average minimum length for the 12 complete sections in the study area is 3.0 feet with a standard deviation of ±.06 foot.

One could use the largest minimum value as a standard length but 114 of 240 lines were not 5 feet in length. Therefore, it was decided to use a line segment of 3.6 feet. This value is the average minimum length for 12 sections plus the positive standard deviation. By using a length of 3.6 feet only 31 lines were shorter. Admittedly some of the data is lost by using the smaller value but

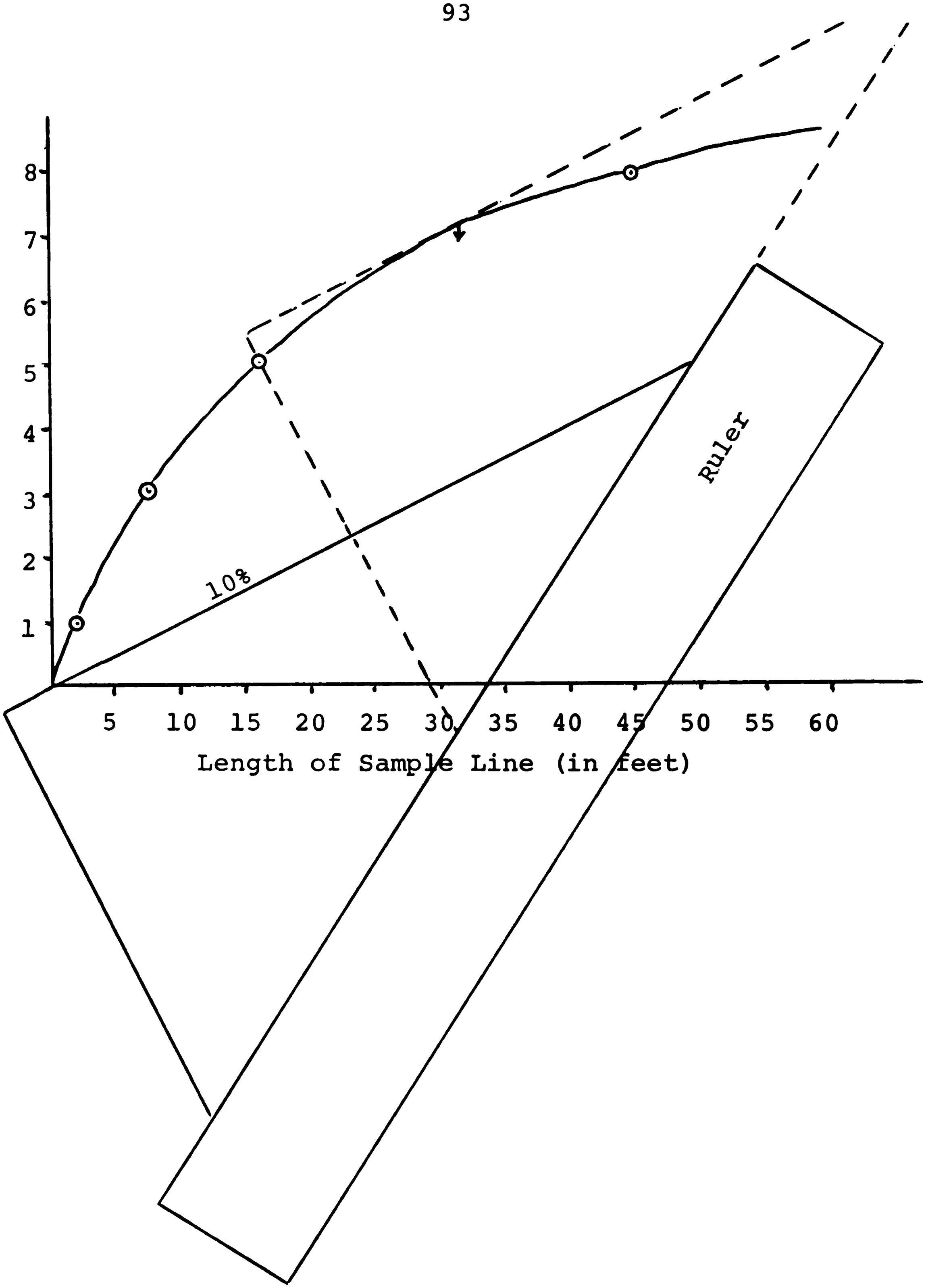


Figure 13.--Species-Length of line curve, showing how the minimum length of line was determined for an adequate sample.

for comparison purposes 3.6 feet is more representative in the study area.

Method of Analysis

Interspecific associations were determined by the use of the chi-square test for independence. Since 34 species were identified there are 561 possible combinations to be analyzed for independence. A computer program[1] which formed a contingency table for each possible combination and then computed the expected values for each cell of the table and the chi square value was used.

Each species was assigned a number from one to 34. Columns one through 34 on the data cards represented a species or variable. Each card represented a sample line or observation. Every species on a sample line was recorded on the data cards by key-punching a one in the appropriate column for the particular species.

The contingency table that the program generates from the input data is a 2 x 2 table based on the presences or absences of two species. Two species are not considered to be associated unless they meet the following requirements: (1) the computed chi square value is greater than $\chi^2_{.95}$ for 1 degree of freedom (for 1 degree of freedom $\chi^2_{.95}$ = 3.84), (2) the minimum expected value for any cell is

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[1] The computer program used in analyzing the interspecific associations is entitled Analysis of Contingency Tables (ACT 1.01) and was written by Alan M. Lesgold of the Computer Institute for Social Science Research at MSU.

greater than 5, and (3) the observed value is greater than the expected value for the cell representing the presence of both species.

If the computed chi square value is greater than the theoretical chi square value the hypothesis of independence is rejected and the result of the chi square test is taken to indicate that two species are associated at the stated level of significance. A relatively low level of significance ($\alpha = 0.05$ and $\alpha = 0.01$) was arbitrarily selected so the rejection of extraneous associations would be increased.

According to Dixon and Massey (1957) the minimum expected frequency for the 2 x 2 table should not be less than 5. Cochran (1954) indicates, however, that the expected frequency of a 2 x 2 table can be less than 5 in certain situations. But it was decided to utilize a minimum expected frequency of 5 as an additional means of excluding extraneous associations.

Some combinations may appear to be associated using a chi square statistic. However, if the expected value exceeds the observed value in the cell representing the presence of both species, a negative association is indicated. Johnson (1962a) indicates that a negative association may reflect the relations of two species with different environmental preferences or the circumstances where the presence of one species excludes the other. It was therefore decided to consider only those statistically associated combinations with the observed value greater than the expected value so that a positive association would result.

Results of the Analysis

Table 1 is a listing of the 34 fossil species identified in this study. No attempt was made to identify crinoid stems and bryzoa to species level. Of the 561 combinations analyzed for interspecific associations 33 combinations were significantly associated at the 0.05 level of significance and 27 combinations were highly significant at the 0.01 level of significance. Ten species plus the undifferentiated crinoid stems account for the 33 significantly associated combinations. The ten species showing positive associations are *Streptelasma strictum*, *Rhipidomella oblata*, *Atrypa "reticularis,"* *Meristella lata*, *Stropheodonta planulata*, *Spirifer cyclopterus*, *Delthyris perlamellosus*, *Macropleura macropleurus*, *Schellwienella woolworthana*, and *Leptaena "rhomboidalis."*

M. macropleurus and *L. "rhomboidalis"* are both associated with eight species. *R. oblata*, *M. lata* and *S. woolworthana* are associated with seven species each. *S. strictum* and *D. perlamellosus* are both associated with six species. *S. planulata* is associated with five species. *A. "reticularis"* and *S. cyclopterus* are both associated with two species. Table 2 is a listing of the species combinations showing positive associations.

TABLE 2.--New Scotland species combinations showing positive associations.

	Streptelasma strictum	Rhipidomella oblata	Atrypa reticularis	Meristella lata	Stropheodonta planulata	Spirifer cyclopterus	Delthyris perlamallosus	Macropleura macropleurus	Schellwienella woolworthana	Leptaena "rhomboidalis"	Crinoid stems
S. strictum		(X)	(X)	(X)	(X)		X	(X)		(X)	
R. oblata	(X)			(X)	(X)		(X)	(X)	(X)	(X)	X
A. reticularis									(X)		X
M. lata	(X)	(X)			(X)		(X)	(X)	(X)	(X)	
S. planulata	(X)	(X)		(X)			(X)	(X)			
S. cyclopterus								(X)		(X)	
D. perlamallosus	X	(X)		(X)	(X)			(X)	X	(X)	
M. macropleurus	(X)	(X)		(X)	(X)	(X)	(X)		(X)	(X)	(X)
S. woolworthana		(X)	(X)	(X)			X	(X)		(X)	X
L. "rhomboidalis"	(X)	(X)		(X)		(X)	(X)	(X)	(X)		X
Crinoid stems		X	X					(X)	X	X	

Note: (X) highly significant, = 0.01
X significant

Recurrent Groups

Recurrent groups were assembled from those species found to be significantly associated by a systematic method of grouping proposed by Fager (1957). Any dichotomous index of relationship between species can be used as a basis for grouping by this procedure (Fager, 1957). Therefore, it is permissible to use the chi square statistic as a basis for grouping.

A recurrent group, as defined by Fager (1957) and recognized in this study is one which satisfied the following requirements:

1. The evidence for affinity (association) is significant at the 0.05 level for all pairs of species within the group.
2. The group includes the greatest possible number of species.
3. If several groups with the same number of members are possible, those are selected which will give the greatest number of groups without members in common.
4. If two or more groups with the same number of species and with members in common are possible, the one which occurs as a unit in the greatest number of samples is chosen.

Table 3 is a trellis diagram displaying the affinity information for the species concerned in this study. Thirty-one groups satisfy requirements 1 and 2. Of the

TABLE 3.--Affinity between pairs of New Scotland fossil species.

	Macropleura macropleurus	Rhipidomella oblata	Leptaena "rhomboidalis"	Meristella lata	Delthyris perlamallosus	Schellwienella woolworthana	Streptelasma strictum	Stropheodonta planulata	Crinoid stems	Atrypa reticularis	Spirifer cyclopterus
M. macropleurus		(X)	(X)	(X)	(X)	(X)	(X)	(X)	(X)		(X)
R. oblata	(X)		(X)	(X)	(X)	(X)	(X)	(X)	X		
L. "rhomboidalis"	(X)	(X)		(X)	(X)	(X)	(X)		X		(X)
M. lata	(X)	(X)	(X)		(X)	(X)	(X)	(X)			
D. perlamallosus	(X)	(X)	(X)	(X)		X	X	(X)			
S. woolworthana	(X)	(X)	(X)	(X)	X				X	(X)	
S. strictum	(X)	(X)	(X)	(X)	X	(X)		(X)			
S. planulata	(X)	(X)		(X)	(X)		(X)				
Crinoid stems	(X)	X	X			X				X	
A. reticularis						(X)			X		
S. cyclopterus	(X)		(X)								

Note: (X) = highly significant, $\alpha = 0.01$
X = significant

31 groups only three groups satisfy requirements 3 when the species interrelationship is examined in detail. The three groups contain the following species:

Group 1. M. macropleurus, L. "rhomboidalis," S. woolworthana, D. perlamellosus, S. strictum, and S. planulata.

Group 2. R. oblata, L. "rhombodalis," S. woolworthana, D. perlamellosus, S. strictum, and S. planulata.

Group 3. M. lata, L. "rhomboidalis," S. woolworthana, D. perlamellosus, S. strictum, and S. planulata.

The original field data were checked to see which group occurred most frequently as a unit. Species of the first group occurred as a unit in 14 sample lines; whereas, those of the second group were present nine times and those of the third group occurred only three times. Based on this information the species of the first group satisfy requirement 4 and are considered as a recurrent group.

After checking the affinity table it is apparent that S. cyclopteris is associated with M. macropleurus and L. "rhomboidalis" of the recurrent group and is not associated with any other species. S. cyclopteris is considered, therefore, as an associate of the recurrent group.

A secondary recurrent group contains R. oblata, M. lata, A. "reticularis" and undifferentiated crinoid stems. All species of the secondary recurrent group are associated with one or more species of the basic recurrent group. Figure 14 diagramatically shows the associations of all the species.

Analysis of Species-Lithology Associations

The chi square test for independence was also used to analyze species-lithology associations. Only those species which showed a positive association with another species were involved in this analysis. Those species not showing an association with another species were excluded because it is not certain whether their presence was due to chance or transportation.

Even though several textural differences are visible in polished sections from the different rock types, they are generally not noticable on weathered surfaces at the outcrop. Therefore, only five general lithologies were recorded during the time of sampling. They are (1) limestone, (2) chert, (3) shaly limestone, (4) siliceous limestone, and (5) limestone with chert nodules or small chert lenses.

Columns 35 through 39 represented the five lithologies on the data cards. A one was punched in the appropriate column for the particular lithology that coincided with the sample lines.

The same computer program which was used to generate contingency tables and compute chi square values in analyzing species associations was utilized in analyzing species-lithology associations.

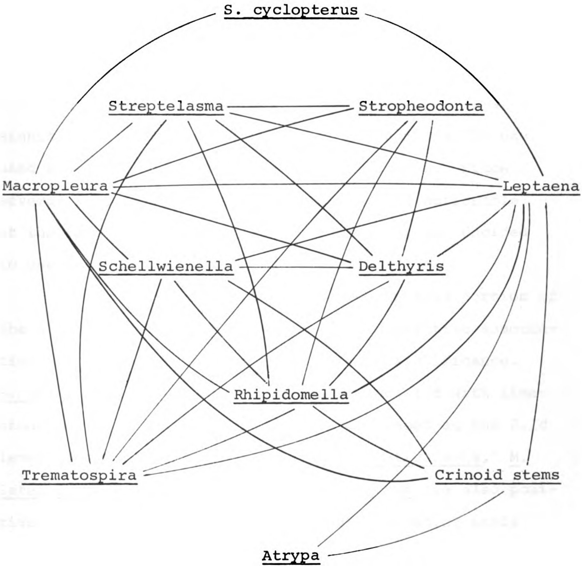

Figure 14.--Species associations in the New Scotland Formation. Lines indicate significant associations.

Before a species was considered to be positively associated with a particular lithology the same requirements had to be met as those designated for determining positive species associations. However, a 0.10 level of significance ($\chi^2_{.90}$ for 1 degree of freedom = 2.71) was used rather than a 0.05 level of significance. Since several textural differences, which are not noticeable at the outcrop, occur for each lithology it was decided to use a larger level of significance.

Of the eleven species concerned in this portion of the study, all except S. strictum have a positive association with limestone at the 0.10 level of significance. S. strictum is, however, positively associated with limestone beds containing chert nodules or lenses at the 0.10 level of significance. R. oblata, A. "reticularis," M. lata, D. perlamellosus, and M. macropleurus are also positively associated with limestone beds containing small nodules or lenses of chert at the 0.10 level of significance. The fact that all species with the exception of S. strictum have a positive association with limestones suggests that they favored a lime mud substrate. S. strictum was, however, always found in the limestone facies of the beds. Therefore, S. strictum probably favored a lime mud substrate also.

All concerned species are negatively associated with beds or large lenses of chert at the 0.10 level of significance. This fact could be explained by either environmental or diagenetic factors. If the chert was a result of primary precipitation the environmental conditions could possibly have been such that the organisms did not live in the vicinity during deposition. Outlines of some fossils were occasionally visible in the chert beds or lenses. Some shells could have been transported into the area of precipitation and deposited or trapped in the silica gel. But, if the chert is a result of replacement the diagenetic processes could have partially or totally obliterated most of the shell material during replacement. As mentioned previously, a replacement origin is favored for the occurrence of chert beds, lenses, and nodules. On this basis the negative association between the species and chert is probably due to diagenetic processes. The negative association could be due to sampling. If more samples had coincided with chert beds a negative association may not have resulted.

None of the species are associated with siliceous limestone beds at the 0.10 level of significance. Based on these samples it is not possible to say whether the occurrence of the concerned species in siliceous limestone horizons is due to environmental factors, transportation or chance.

S. strictum, R. oblata, A. "reticularis," M. lata, D. perlamellosus, and M. macropleurus are negatively associated with shaley limestones. This negative association probably indicates that these species preferred another type of substratum. The other species are not associated with shaly limestone.

Species Diversity

From the analysis of species associations and recurrent groups it is not apparent whether the fossil species are homogeneously distributed or not in the New Scotland Formation. At present, we know that the number of species varies from one organic community to another. By making two assumptions it is possible to evaluate the complexities of species distribution in the New Scotland Formation using the concept of species diversity. First, one assumes that those fossils which are positively associated now occur, at or near their original habitat. Secondly, each outcrop represents a portion of an ancient homogeneous, mixed population or community center.

According to Margalef (1957) the distribution of individuals by species is related to a definite correspondence between the total number of individuals and the total number of species, and the relationship between the number of species and the number of individuals varies according to the type of distribution as the size of the sample increases. Several empirical mathematical expressions have been proposed to describe the distribution of individuals by species. Frequently quoted expressions found in biological literature are the "eometric progression rule" (Yoshirata, 1951), the "lognormal distribution" (Preston, 1948), the "logarithmic series" (Fisher, Corbert, and Williams, 1943) and the indices based on information theory (Margalef, 1957). The parameter obtained from any of these mathematical expressions is called an index of diversity which represents the wealth of species in a given organic community. Margalef (1957) indicates that an index of diversity must be independent of the sample size and the data must be from a homogeneous, mixed population or community.

An index of diversity was calculated for each outcrop, assuming that each outcrop represented a center or near center of an ancient homogeneous, mixed organic community, using the logarithmic series which was proposed by Fisher, Corbert and Williams (1943). Margalef (1957) indicates that the logarithmic series is a good first approximation of species diversity. The equation used in obtaining the diversity value for each outcrop is

$$d = (S - 1)/\ln N$$

where d is the index of diversity, S represents the number of species, and lnN represents the natural logarithm of the number of individuals.

Species Diversity Map

As soon as the index of species diversity has been computed for each sampling location, these values can be recorded next to their respective control points on a map. Isopleths can be drawn through points having equal species diversity values. These isopleths can also represent ecotones or boundaries between different natural communities. In this study a contour interval of 0.5 was arbitrarily used.

Results

Figure 15 shows the spatial distribution of the index of diversity of associated species computed from data on all sample lines at each outcrop of the New Scotland Formation. Two isopleths or ecotones are present which separate three fossil communities. Due to the limited number of favorable outcrops for this type of study the actual position of the ecotone has to be inferred at some localities. The two ecotones appear to be parallel to sub-parallel with each other and display an undulant northeast-southwest trend. The viersity gradient shows a general increase from the northwest toward the southeast.

The relative abundances, expressed as percentages, of each associated species at each outcrop is shown in Table 4. The western-most faunal community is characterized by an abundance of the strophomenid brachipod, <u>Schellwienella woolworthana</u>. Spirifers and a strophomenid, <u>Macropleura macropleurus</u>, <u>Meristella lata</u>, and <u>S. woolworthana</u>, are distinctive fauna of the eastern-most faunal community. The intermediate faunal community between the eastern- and western-most communities is characterized by <u>M. macropleurus</u>, <u>S. woolworthana</u>, and <u>Leptaena "rhomboidalis</u>."

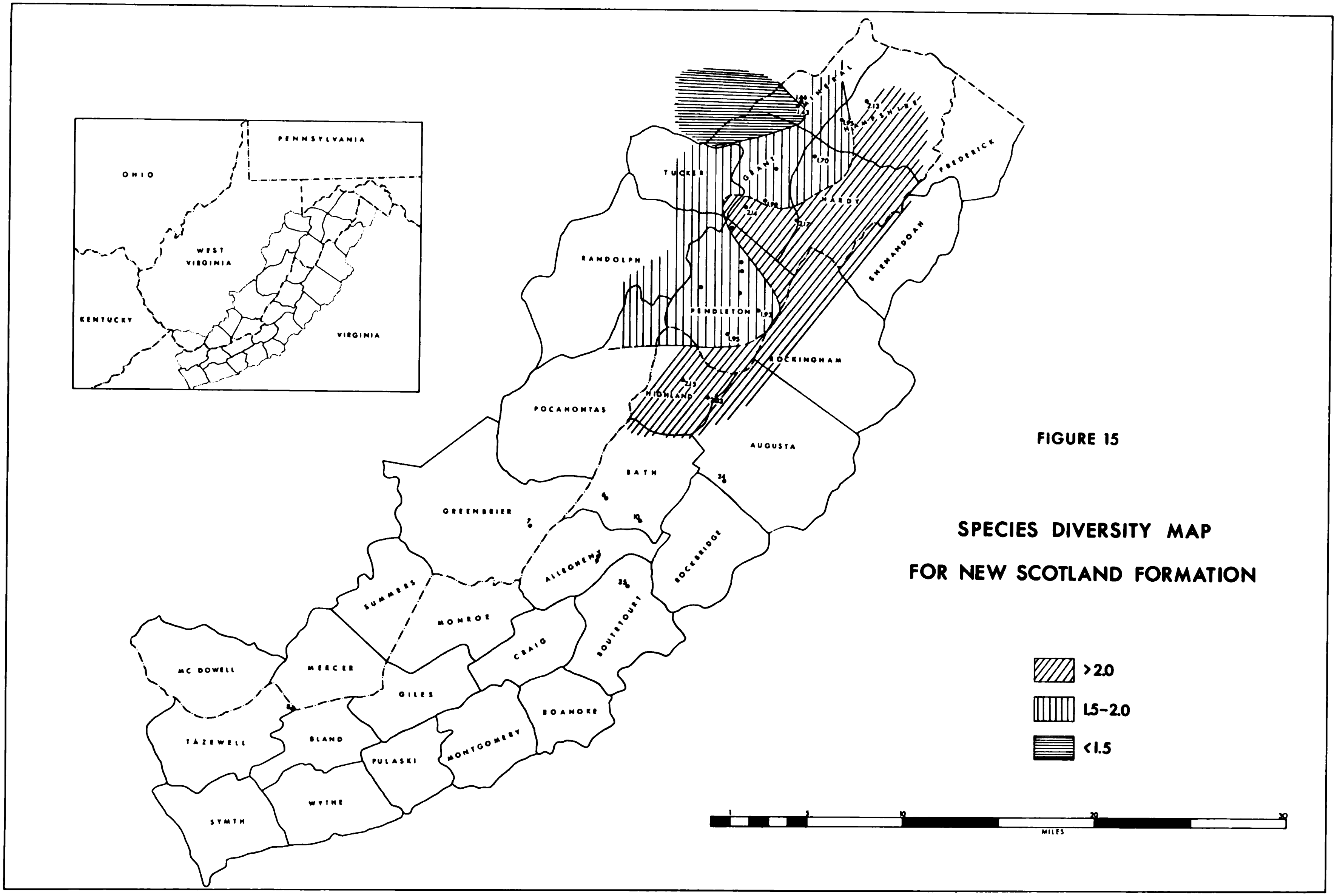

FIGURE 15

SPECIES DIVERSITY MAP
FOR NEW SCOTLAND FORMATION

TABLE 4.--Percent occurrence of New Scotland fossils.

Paleo Community Section	S. strictum	R. oblata	A. reticularis	M. lata	S. planulata	S. cyclopterus	D. perlamallosus	M. macropleurus	S. woolworthana	L. "rhomboidalis"	Crinoid stems
Western-most											
New Creek I	1.49	0.00	13.43	0.00	0.00	8.96	0.00	17.91	34.33	19.40	4.48
Intermediate											
New Creek II	0.00	3.03	21.21	0.00	0.00	6.06	3.03	27.27	18.18	21.21	0.00
Trinity Road	1.92	5.77	21.15	0.00	0.00	3.85	11.54	21.15	25.00	7.69	1.92
Thrasher Spring School	0.00	14.71	8.82	0.00	0.00	0.00	8.82	41.18	11.76	11.76	2.94
Maysville Gap	2.86	14.29	0.00	12.86	5.71	0.00	5.71	14.29	12.86	27.14	4.29
Hively Gap	4.76	7.62	13.33	14.29	3.81	0.00	7.62	16.19	14.29	12.38	5.71
Thorn Creek	3.96	7.92	0.00	19.80	6.93	2.97	18.81	19.80	6.93	11.88	0.99
Eastern-most											
Rocks	1.44	11.59	11.59	0.00	2.90	4.35	17.39	7.25	26.09	14.49	2.90
Petersburg Gap	7.32	10.98	9.76	15.85	4.88	2.44	17.07	10.98	12.20	7.32	1.22
Smoke Hole Cavern	2.77	15.74	3.70	14.63	1.85	3.70	10.19	25.00	21.30	8.33	2.78
Monterey	3.74	9.35	2.80	9.35	15.89	5.61	7.48	27.10	13.08	3.74	1.87
Bull Pasture Mountain	10.22	8.76	0.73	26.28	8.03	5.11	5.11	24.09	5.11	4.38	2.19

Environmental Significance

The concept of species diversity is a means of evaluating quantitatively the degree of structural complexity of each type of community (Margalef, 1957). A large diversity value indicates a faunal community with a high degree of structural complexity. The more complex a community is, as suggested by larger index of diversity values, the more stability that community has attained (MacArthur, 1955). The stability of a given community is a function of the number of species interactions (MacArthur, 1955) and the presence of favorable physical environmental conditions (Odum and others, 1960).

The species diversity map indicates the variation of computed species diversity indices of associated species present. Hypothetical ecotones delineate those areas which possibly had similar environmental conditions. Before any conclusions can be drawn from species diversity concepts, one should consider whether it is possible for two different areas or outcrops to have similar species diversity values but have entirely different species which demand different physical environmental conditions. After checking Table 4 it is apparent that most outcrops in each given fossil community are characterized by the same particular combination of species. Therefore, this does not appear to be a problem. However, certain species appear to be concentrated in a given area and this may represent a transported assemblage of fossils rather than a native population of organisms peculiar to that environment. Figure 16 is a scatter plot on which are plotted the percentage of disarticulation and fragmentation (horizontal axis) and the indices of species diversity (vertical axis). The correlation coefficient value for this data is 0.43 which is not significant at the 0.05 level of significance. Therefore, it may be possible to obtain a high percentage of disarticulated shell material in some locations, and have only a few, if any, of the shells transported. Also, since the species diversity values were computed from those species showing a positive association with one another and associations were determined by the χ^2 statistic using data from random sample lines in each outcrop of the study area, the likelihood of the indices of diversity being affected by transport and depositional conditions should be small.

Another possibility is that some areas have had more favorable conditions for the preservation of shell material than others. No foolproof method exists for evaluating this problem. However, as mentioned in the section concerning petrography and petrology of New Scotland rocks, there is a high degree of similarity with respect to lithology and textures between any two outcrops in the study area, even though each individual outcrop shows some heterogeneity of lithology and texture in both vertical and lateral directions. This similarity of lithology and textures between outcrops suggests that depositional

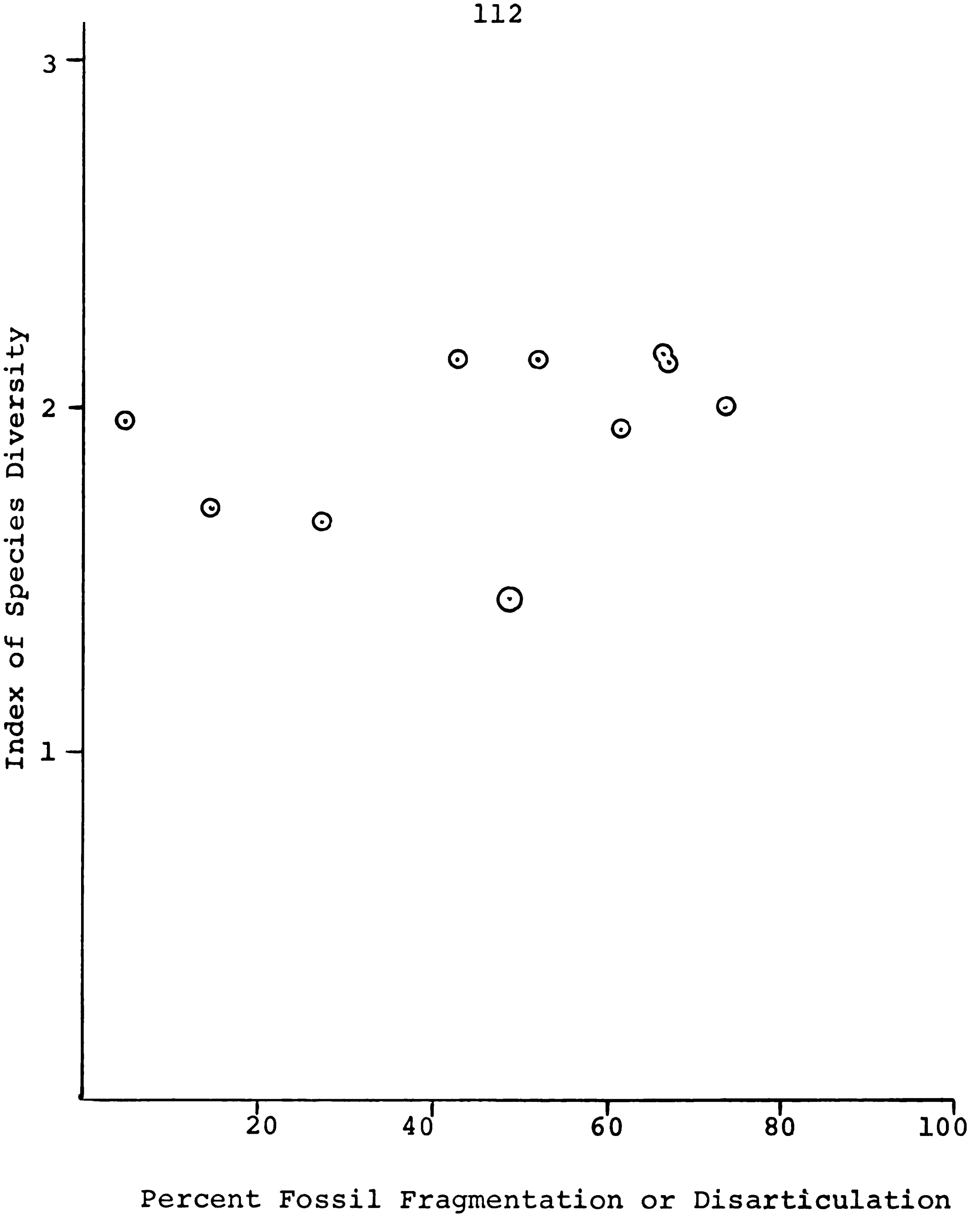

Figure 16.--Percent fossil fragmentation or disarticulation versus index of species diversity.

and post-depositional conditions were similar for the preservation of shell material.

On a larger scale, the index of species diversity in tropical regions at the present time is large compared with that of cooler climatic regions (Fischer, 1961). Superimposed on this hemispheric or worldwide diversity gradient are more localized gradients such as those determined from sampling supratidal through an open marine environment. There is a general increase in the diversity index from supratidal environments through sublittoral environments followed by a decrease in deeper environments for benthonic organisms (Tappan, 1960; Odum and others, 1960; and Ager, 1963).

It is doubtful if any correlation between the distribution of ecotones and paleo latitudes can be established from the species diversity map. (See Figure 15.) However, there is a good correlation between the overall trend of the New Scotland ecotones of this study and the axis of the Devonian depositional basin in this area defined by Woodward (1943). The pattern and distribution of the ecotones may represent irregularities in the basin floor, the geometry of the basin of deposition, and varying ecological conditions within the basin.

Of the many physical and biological factors controlling the diversity of species there are three which can be evaluated with respect to a paleoenvironment. These factors are (1) depth of water, (2) proportion of mud content which is a function of current velocity or proximity to shore and (3) gross salinity.

With respect to water depth low species diversity values can be interpreted two different ways. Low species diversity values can represent either the outcrops (sampling stations) were near the vicinity of the littoral-supralittoral zones or near the edge of the basinal zone. If the outcrops with low species diversity values show a paucity of desiccation features, algal laminations, colites, cross-bedding, and high degrees of sorting this suggests that the outcrops were not near the vicinity of ancient littoral-supralittoral zones. With the exception of one thin bed of cross-bedded crinoidal limestone in the Bull Pasture Mountain section none of these sedimentational features were observed in sections of the New Scotland Formation used in evaluating species diversity. On this basis those outcrops with lower indices of species diversity were not in the vicinity of Helderberg littoral-supralittoral zones. The presence of occasional tabulate corals (Favosites species) and ramose or encrusting bryozoan species showing growth orientations in some of the sections with low diversity values suggest, however, that water depth was not excessive. Therefore, it is questionable if those sections showing lower indices of species diversity can be analogous to modern environments near the edge of the outer sublittoral zones. Since some fossil entities suggest that New Scotland sediments were deposited in a shallow epicontinental marine environment, local irregularities of the basin floor in a sublittoral zone could have possibly altered current conditions and produced slight environmental differences favorable for larger populations of some species. Areas where environmental conditions favored larger populations of certain types of species would show lower species diversity values than other areas with less favorable conditions, even though the same types of species occur in both areas.

Purdy (1962 and 1964) suggests that distribution patterns of aquatic benthos can be correlated with the amount of mud content in a given sedimentary deposit. It is conjectured that most epifaunal benthos, especially brachiopods (Rudwick, 1965) prefer a stable substrate. Substrates with lower proportions of mud content are less stable (Purdy, 1964), but there probably is an upper limit to the amount of mud a sediment can contain and still support epifaunal benthos. Table 5 shows the relationship between the percentage of mud (micrite) content and indices of species diversity for each outcrop of the New Scotland Formation. The linear regression equation for this data as computed by the least squares method, is $Y_x = 2.223 - 0.0112X$ and the value of the correlation coefficient is -0.41 which is not significant at the 0.10 level of significance. Since there is a possibility that the data was not from a population with a normal distribution a rank correlation coefficient was also calculated. The value of

TABLE 5.--Relationship between the amount of lime mud and the index of species diversity in the New Scotland Formation.

Outcrop	Percent Lime Mud	Index of Species Diversity	Rank Mud	Rank Index	d	d^2
New Creek II	65.83	1.66	3	9	-6	36
New Creek I	79.67	1.43	1	10	-9	81
Maysville Gap	60.07	1.98	4	5	-1	1
Smoke Hole Cavern	66.17	2.14	2	3	-1	1
Rocks	53.44	2.13	7	4	3	9
Trinity Road	59.83	1.95	5	6	-1	1
Thrasher Springs School	42.67	1.70	10	8	2	4
Petersburg Gap	53.00	2.27	8	1	7	49
Hively Gap	57.11	1.93	6	7	-1	1
Monterey	48.85	2.15	9	2	7	49
						$\sum d^2=232$

Note:

d = difference between index rank and mud rank

percent lime mud includes microcrystalline calcite and microsparry calcite.

Rank Correlation Coefficient

$$\text{rank} = 1 - 6 \sum d^2/N(N^2-1)$$

$$= 1 - 6(232)/10(99)$$

$$= 1 - 1.406$$

$$= -0.406 \text{ not significant at } \alpha = 0.10$$

the rank correlation coefficient is -0.19 which is also not significant at the 0.10 level of significance. Even though the correlation coefficient and the rank correlation coefficient do not suggest a statistically significant relationship between the indices of species diversity and mud content a general linear trend occurs for these data which is somewhat similar to that obtained by Sanders (1958) for suspension feeders and their relationship to substrate, in that both show a negative slope. A negative slope for the regression curve is not surprising because most of the species involved in calculating the indices of species diversity are brachiopods, which are suspension feeders.

Based on this regression curve there is a possibility that certain benthonic assemblages can be recognized at higher taxonomic levels which show a relationship to amount of mud contained in a given rock unit. Rudwick (1965) suggests that most strophomenids were capable of inhabiting soft muddy substrates whereas most other orders of articulate brachiopods inhabited firmer substrates. Table 6 shows the relationship between the percentage of micrite and the ratio of spirifers and orthids to strophomenids. The value of the rank correlation coefficient for this relationship is -0.509 which is significant at the 0.10 level of significance. When the values for the ratios of spirifer-orthid/strophomenid and percent micrite are plotted on a graph (see Figure 17) there is a general

TABLE 6.--Relationship between the amount of lime mud and the brachiopod ratio in the New Scotland Formation.

Outcrop	Percent lime mud	Brachiopod ratio	Rank mud	Rank ratio	d	d^2
New Creek II	65.83	1.54	3	7	-4	16
New Creek I	79.67	0.75	1	10	-9	81
Maysville Gap	60.07	1.03	4	9	-5	25
Smoke Hole Cavern	66.17	2.00	2	3	-1	1
Rocks	53.44	1.20	7	8	-1	1
Trinity Road	59.83	1.93	5	5	0	0
Thrasher Springs School	42.67	3.13	10	1	9	81
Petersburg Gap	53.00	2.75	8	2	6	36
Hively Gap	57.11	1.94	6	4	2	4
Monterey	48.85	1.89	9	6	3	9
					$\sum d^2=254$	

Note:

Percent lime mud includes microcrystalline calcite and microsparry calcite.
Brachiopod ratio is equal to number of spirifers plus number of orthids divided by number of strophomenids.
d = difference between ratio rank and mud rank.

Rank correlation coefficient $= 1-6 \sum d^2/N(N^2-1)$

$= 1 - 6(254)/10(99)$

$= 1 - 1.539$

$= -0.539$ significant at 0.068α

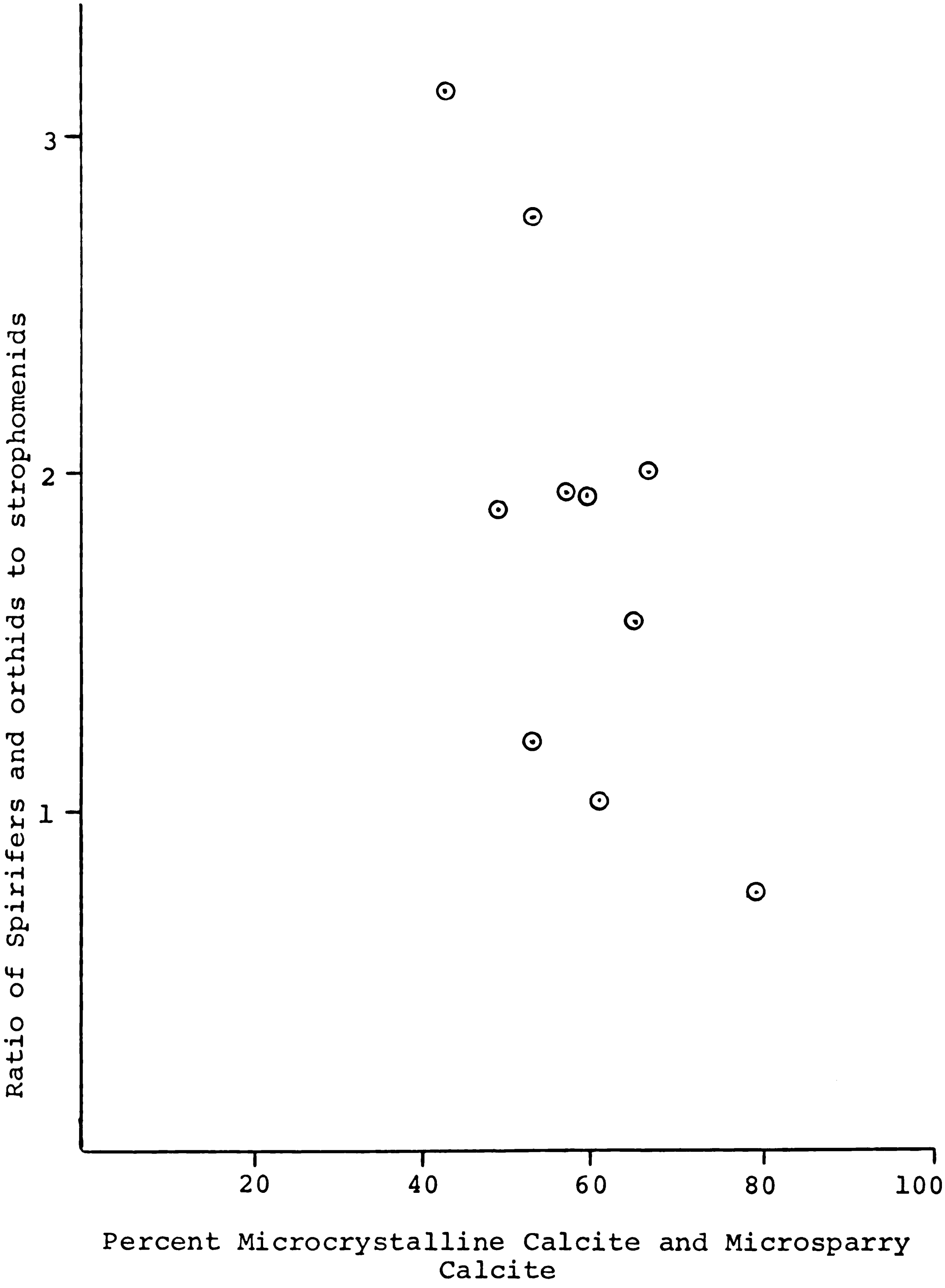

Figure 17.--Percent microcrystalline calcite and microsparry calcite versus ratio of spirifers and orthids to strophomenids.

negative trend of the data points. From an environmental standpoint this could possibly mean that those areas with larger proportions of fine grained sediments making up the substrate supported larger populations of strophomenids than other areas with lower percentages of fine grained sediments in the substrate.

Differences in species diversity values may be due to extreme differences of water salinity in different portions of the basin. Odum and others (1960) have been able to show from a study in the coastal region of the Gulf of Mexico that higher saline water bodies have lower indices of species diversity than normal marine water bodies. The absence of dolomitic or gypsiferous beds, collapse structures, or salt crystal imprints in any of the New Scotland outcrops of the study area suggest that environmental conditions were more open marine rather than hypersaline or hyposaline during deposition.

CHAPTER VI

PALEOENVIRONMENTAL SYNTHESIS

Viewed from a fossil faunal standpoint the sediments of the Helderberg Group were deposited in a marine environment (Woodward, 1943). It is possible, however, to further define the depositional environment by combining petrographic, paleontologic, and stratigraphic evidence. The lithologic and fossil faunal attributes are indicative of specific environments; whereas, the temporal and spatial distributions of the various rocks types are indicative of the areal arrangement of these differing environments at any given time.

In any vertical sequence the Helderberg Group can be subdivided into several smaller stratigraphic units on the basis of lithologic and paleontologic differences. Different rock types or faunal content suggest that depositional conditions changed with time.

The different rock types could be due to mineralogical differences, but since the Helderberg Group is predominantly a carbonate unit in the study area most of the differences are textural ones. As indicated previously, textural differences in carbonate rocks are due primarily to varying proportions of rock components. Figure 18 shows the variation of the rock components plus any significant mineralogical changes displayed in any outcrop containing lithologies typical to each of the Helderberg units. Admittedly there are more compositional variations within a given formation than this diagram depicts, but there are definite trends of textural or lithologic changes from lower to upper Helderberg units in all outcrops of the study area. The most significant aspect of this, with regard to depositional environment, is the varying proportions of microcrystalline calcite contained in the various stratigraphic units. The sediments of those units containing larger amounts of microcrystalline calcite were probably deposited in areas lacking persistent strong currents.

In a vertical section there is also a general increase in the variety of species occurring in the Helderberg units, particularly from the basal units through the New Scotland interval. Few fossils occur in the uppermost micritic beds of the Keyser Limestone. The Coeymans Limestone is characterized by tabulate corals, bryozoa, pelmatozoan debris, and some brachiopods. Spiriferid and strophomenid brachiopods are the dominant fossils of typical New Scotland beds. Fossils are not too common in the Shriver Chert or Licking Creek Limestone.

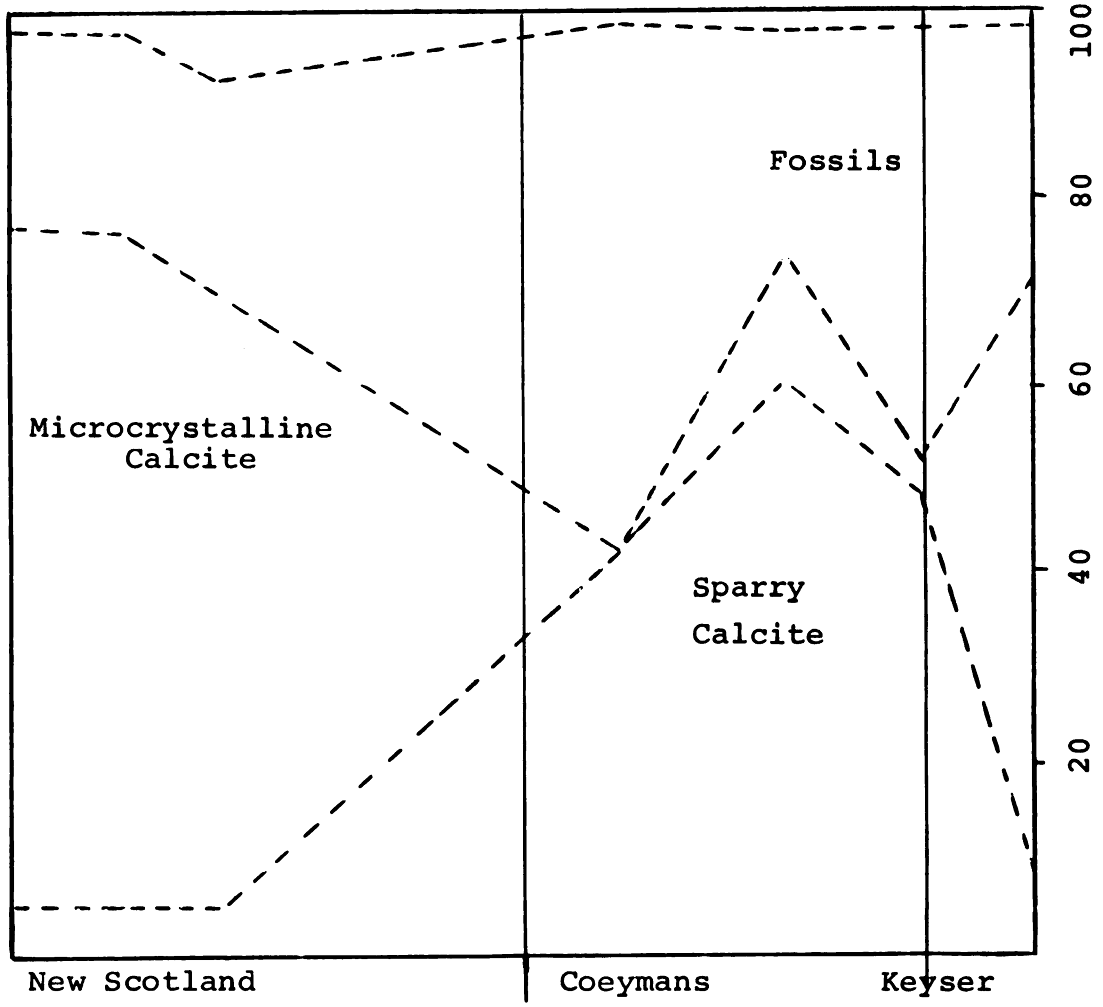

Figure 18.--Vertical variation of rock components in the Helderberg Group.

A reevaluation of the vertical and lateral relationships of the Helderberg units reveals that these units are rock-stratigraphic rather than time-stratigraphic units. Therefore, a stratigraphic unit overlying another unit in a vertical section grades laterally into a subjacent or superjacent unit in another section, and time lines cut through facies. This also indicates that sediments of the various rock-stratigraphic units were probably deposited simultaneously under differing environmental conditions in different parts of the depositional basin. Also, an analysis of several stratigraphic cross-sections strongly suggests that Helderberg sediments were deposited overall in a transgressive sea.

If the stratigraphic units observed in a vertical section actually grade laterally into subjacent or superjacent units and the various units are recognizable through lithologic or textural differences that developed during deposition in different depositional environments, then the various rock components of these units should, at any given time, show distributional patterns similar to those observed in a vertical section. Figure 19 shows the lateral variation of the average proportions for the various rock components plus any other minerals of some environmental significance observed in samples that correspond to a given time line. The lateral distributional pattern for the various rock components of the Helderberg units is very similar to that observed in a vertical section

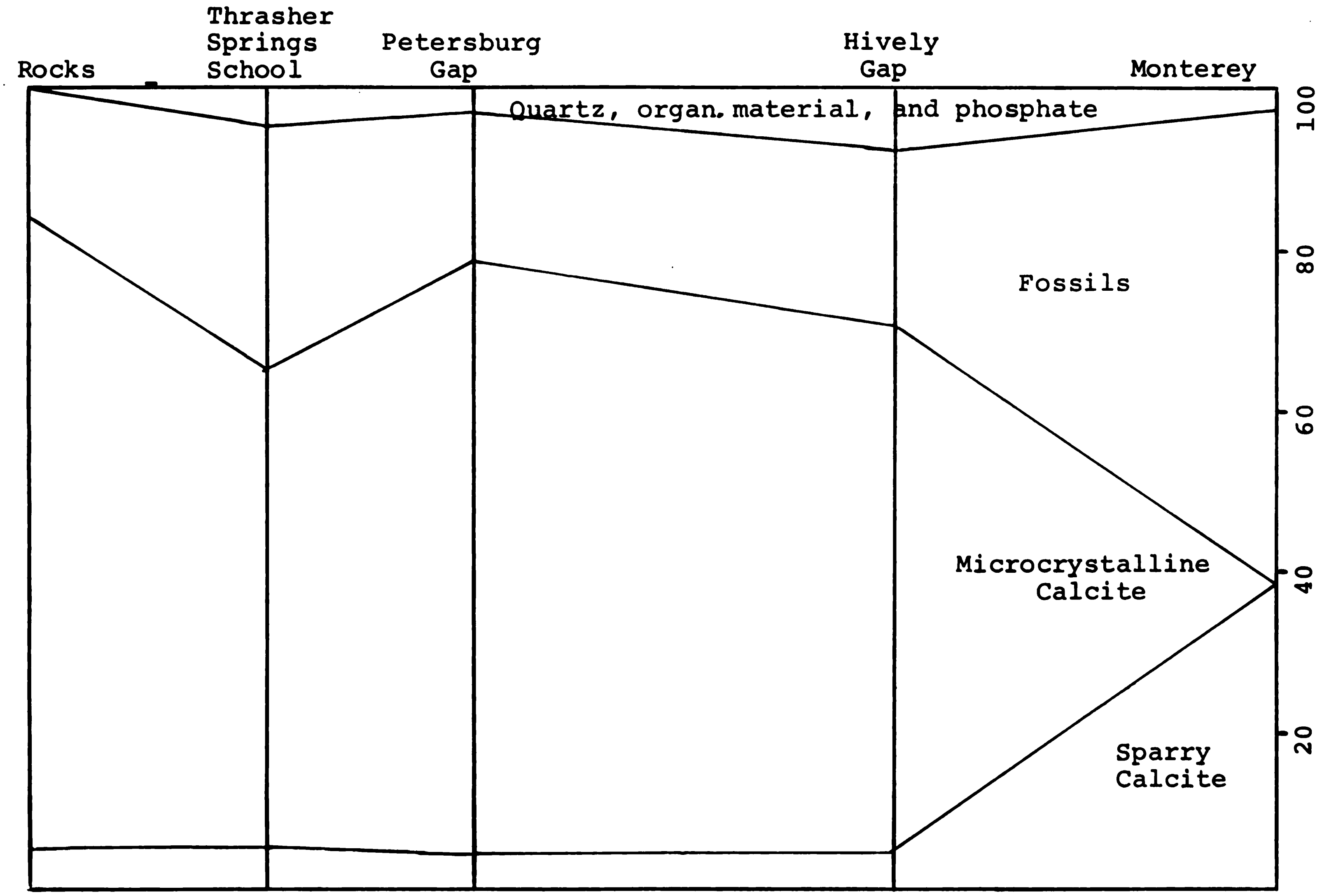

Figure 19.--Lateral variation of rock components in the Helderberg Group.

(compare Figures 18 and 19). This further substantiates the conclusions concerning the vertical and lateral relationships among the various Helderberg units. It also indicates that sediments of the various stratigraphic units were deposited simultaneously in different depositional environments at any given time.

The number of species varies laterally from one stratigraphic unit to another at any given time. Though a detailed analysis of lateral variations of species diversity was restricted to the limestone and chert facies of the New Scotland Formation, a rock-stratigraphic unit, this study indicates that there is a definite northeast-southwest regional trend of species diversity which is of environmental significance.

If lithologic or paleontologic aspects of at least one stratigraphic unit are indicative of a given depositional environment, this unit can be used as a starting point in reconstructing the overall regional distribution of depositional environments at any given time.

The uppermost, micritic beds of the Keyser Limestone suggest that these sediments were deposited in an environment lacking persistent strong currents. Since many of the bedding surfaces of these rocks display mud-cracked surfaces this further suggests that the sediments were deposited in a supratidal, carbonate mud-flat environment. Therefore, the uppermost Keyser beds offer enough information to make logical inferences concerning the direction or directions of possible environmental gradients.

Sediments of the Coeymans Limestone were deposited in an area where currents were rather intense and persistent. This is based on the fact that the units consist of biosparitic packstones and grainstones predominantly. These rock types infer deposition in relatively well agitated water. Since the Coeymans Limestone was deposited laterally adjacent to the Keyser Limestone this indicates that Coeymans sediments are representative of an inner shelf environment adjacent to the carbonate mud-flat. This type of deposition would primarily occur below low tide (subtidal) but above wave base.

The New Scotland Formation is laterally adjacent to the Coeymans Limestone. Sediments of the limestone and chert facies were deposited in somewhat calmer water conditions than those of the Coeymans. This is based on the fact that the units consist of wackestones predominantly. From an environmental standpoint these sediments represent an outer shelf environment which would be subtidal also but below wave base.

Sediments of the crinoidal limestone facies and the crinoidal bearing, quartzose sandstone facies of the New Scotland Formation were deposited under conditons similar to that associated with Coeymans deposition. This is based on the basic textural and structural similarity of these different stratigraphic units.

Sediments of the Shriver Chert were deposited in a more distal location with respect to the carbonate mud flat than those of the New Scotland Formation. They are representative of a slope environment as shown by slump structures observed in the outcrops. This type of sedimentary structure is common in slope deposits (Thomson and Thomasson, 1969).

The sediments of the Licking Creek Limestone were probably deposited under conditions similar to those associated with deposition of the limestone and chert facies. This is indicated by the lithologic similarity of the rocks comprising these two stratigraphic units and the lateral relationship between the Licking Creek Limestone and the crinoidal limestone facies of the New Scotland Formation.

The paleontologic aspects of Helderberg rocks further substantiate the preceding conclusions concerning the various depositional environments. Purdy (1964) indicates that the number of species occupying the shoaling (tidal) zone is less than that occurring in the outer platform of the Great Bahama Bank. Similar relationships occur between the Coeymans Limestone and the limestone and chert facies of the New Scotland Formation. Also, the limestone and chert beds display more evidence for bioturbation than any other Helderberg unit. This corresponds with the conclusions of Moore and Scruton (1957) that burrowing activity increases offshore in the Gulf Coast region.

A summary of the depositional environments which occurred during deposition of Helderberg sediments is shown by Figure 20. The different rock types, sedimentary structures, and faunal assemblages which served as possible indicators for the different environmental conditions are also noted on this figure.

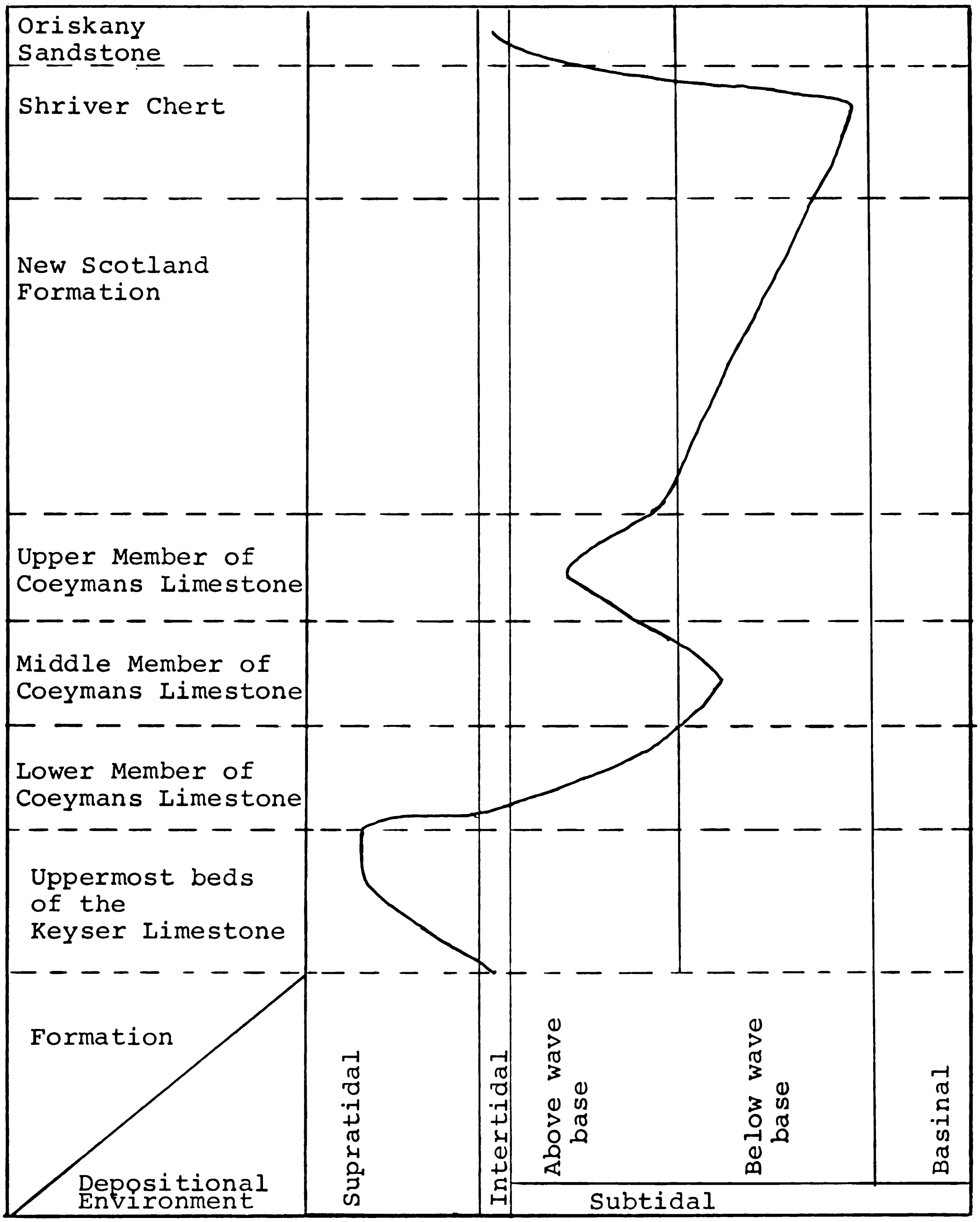

Figure 20.--Interpretation of depositional environments of the Helderberg Group in Virginia and West Virginia.

CHAPTER VII

CONCLUSIONS

The principal conclusions derived from this investigation are as follows:

1. In outcrops north of Monterey, Virginia the Coeymans Limestone can be subdivided into three members: (a) a lower limestone member, (b) a middle limestone member, and (c) an upper limestone member.

2. The middle limestone member is a thin-bedded, finely crystalline, crinoidal limestone with chert nodules and lenses. G. coeymanensis is restricted to the basal beds of the member. The member shows a general thinning from north to south.

3. The midinterval of the middle limestone member of the Coeymans Limestone appears to represent a time plane.

4. Evidence is lacking to indicate that the depositional basin was significantly deformed by any tectonic events during deposition of Helderberg sediments.

5. The formations comprising the Helderberg Group are rock-stratigraphic units rather than time-stratigraphic

units and overall the group represents a transgressive phase of deposition during early Devonian time in West Virginia and Virginia.

6. Calcite, quartz, illite(?), and chert are the dominant mineral components of all Helderberg rock types. Dolomite, collophane, tourmaline, feldspar, zircon, and organic material occur in some samples as accessory components.

7. Based on the type of grain support and the proportion of grains, matrix, and cement the following carbonate rock types can be recognized in the Helderberg Group: micrite, biomicritic wackestone, biomicritic packstone, biosparitic packstone, biosparitic grainstone, pelsparitic grainstone, and intrasparitic grainstone.

8. Petrographic evidence suggests that most of the sparry calcite occurring in Helderberg samples represents a primary pore filling cement. However, some sparry calcite resulted from recrystallization of microcrystalline calcite or from inversion of an original aragonite cement.

9. Petrographic evidence suggests that microsparry calcite represents recrystallized grains of microcrystalline calcite.

10. Field and petrographic evidence suggest that most of the chert occurring in the Helderberg units is of a replacement origin.

11. Thirty-three environmentally significant interspecific fossil associations involving ten of 34 fossil species identified in the New Scotland Formation can be recognized by the chi square test for independence, even though field observations suggest that most of the fossils had been transported or reworked to some degree.

12. The associations can be grouped into a primary recurrent group and a related secondary recurrent group, which may be indicative of the original structure of the biocenoses.

13. All species showing an association with another species with the exception of S. strictum have a positive association with limestone. This suggests that they favored a lime mud substrate.

14. All associated species are negatively associated with beds or lenses of chert. This type of association suggests that the occurrence of chert in the New Scotland Formation is possible a replacement phenomenon.

15. The spatial distribution of the computed indices of species diversity suggest that three fossil communities possibly existed during deposition of New Scotland sediments and the communities had an undulant northeast-southwest trend. There is a general increase from northwest to southeast in the species diversity gradient.

16. Even though there is not a statistically significant relationship between the indices of species

diversity and the mud content in the New Scotland Formation there is a general negative linear trend of the data. This is not surprising since brachiopods are the dominant New Scotland fossils and they were suspension feeders.

17. Depositional sights which experienced larger accumulations of fine grained sediments generally supported larger populations of strophomenids than other areas during deposition of New Scotland sediments.

18. A stratigraphic unit overlying another unit in a Helderberg outcrop grades laterally into a subjacent or superjacent unit in another section and the sediments of the various rock-stratigraphic units were deposited simultaneously under differing environmental conditions in different parts of the depositional basin.

19. Field and petrographic evidence suggest that the micritic beds of the upper Keyser Limestone were deposited in a supratidal, mud-flat environment.

20. Stratigraphic, paleontologic, and petrographic evidences indicate that micrite and wackestone beds of the New Scotland Formation and the Shriver-Chert-Licking Creek Limestone interval were deposited in an open marine environment probably below wave base.

21. Stratigraphic and petrographic evidence suggest the packstone and grainstone beds comprising the Coeymans Limestone, the crinoidal limestone and sandstone facies of the New Scotland Formation were deposited in a high energy environment such as a marginal or beach deposit.

CHAPTER VIII

SUGGESTIONS FOR FURTHER RESEARCH

During the final stages of this investigation it was realized that fossil data were collected in such a way that they could be used to analyze just the lateral variations of fossil distributions. If the fossil data had been collected in such a way that the temporal variations of fossil distributions could be evaluated then this additional information might further define the depositional history of the Helderberg Group in the study area.

A study of the relationship, if any, of the reef horizons in the upper Keyser Limestone and the Coeymans-New Scotland stratigraphic couple might also bring to light additional information that would further define the geometry and topography of the depositional basin for the Helderberg Group in the study area.

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APPENDICES

APPENDIX A

LOCATION OF OUTCROPS

Map Number	Outcrop Name	Location
1.	New Creek II	Abandoned quarry along cut-off between U.S. 50 and U.S. 220-W. Va. 46, Mineral County.
2.	New Creek I	Quarry of Mineral County Stat Road Commission along U.S. 50 (0.1 mile east of junction of U.S. 50 and U.S. 220.
3.	Smoke Hole Caverns	Outcrop in channel of Jordan Run in the vicinity of the entrance to Smoke Hole Caverns, Grant County.
4.	Grant-Pendleton County line	Road cut along W. Va. 28 directly south of the Grant-Pendleton County line.
5.	Nelson Rock	Along the first dirt road (0.6 mile east of the junction with W. Va. 28) turning east off of W. Va. 28 south of the junction between U.S. 33 and W. Va. 28 in the vicinity of Judy Gap, Pendleton, County.
6.	Healing Springs	Along road and creek near west end of gap west of Healing Springs, Rockingham County, Va.
7.	Big Draft	Along Big Draft which is cutting through Bobs Ridge, Greenbrier County.

Map Number	Outcrop Name	Location
8.	Bluefield	Abandoned quarry at end of hill southeast of the ball park at Bluefield, Virginia.
9.	Island Ford	Road cut near old bridge of U.S. 60 between Covington and Clifton Forge at Island Ford, Va.
10.	Millboro Springs	Along Va. 42, 7½ miles south of Millboro Springs, Bath County, Virginia.
11.	Monterey	Quarry ½ mile east of Monterey, Virginia and north of U.S. 50.
12.	Thorn Creek	Along Pendleton County road 23, 0.9 mile east of junction with U.S. 220.
13.	Ruddle	Road cut along an abondoned section of U.S. 220, 0.5 miles east of Ruddle, Pendleton County.
14.	Smoke Hole South	Along road leading from U.S. 220 into Smoke Hole, about 1.5 miles northwest of Upper Tract, Pendleton County.
15.	Smoke Hole North	Along road leading from U.S. 220 into Smoke Hole, about 1.7 miles northwest of Upper Tract.
16.	Maysville Gap	Along Lunice Creek and W. Va. just west of Maysville, Grant County.
17.	Greenland Gap	Along North Fork of Patterson Creek at east end of Greenland Gap, Grant County.
18.	Rocks	Along Baltimore and Ohio Railroad in a water-gap of the South Branch of Potomac River, 4 miles north of Romney, Hampshire County.

Map Number	Outcrop Name	Location
19.	Trinity Road	Along Trinity Road (2.4 miles from the junction with U.S. 220) just southeast of the junction between U.S. 50 and U.S. 220, Hampshire County.
20.	Thrasher Spring School	Along county road between Old Fields and Williamsport, 2.8 miles east of Williamsport on east side of mountain and 1.1 miles northwest of Thrasher Spring School, Hardy County.
21.	Petersburg Gap	Along U.S. 220, two miles east of Petersburg, between the highway bridge over South Branch of Potomac River and the Grant-Hardy County line.
22.	Hively Gap	Along U.S. 33 in Hively Gap, 1.5 miles west of Oak Flat, Pendleton County.
23.	Bull Pasture Mountain	Along U.S. 250, 4 miles eash of McDowell, Virginia, on the east slope of Bull Pasture Mountain.
24.	Fordwick	In abandoned quarry of Lehigh Portland Cement Company at Fordwick, Augusta County, Virginia, 0.4 mile east of Craigsville.
25.	Gala	Along the Chesapeake and Ohio Railway, 1 mile north of Gala, at southwest end of Bill Hill, Botetourt County.