

Petrology of the Alderson Formation (Mississippian)
in Southeastern West Virginia

A Thesis

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of the Requirements for the Degree
Master of Science in Geology

by

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INTRODUCTION

GENERAL STATEMENT

The Greenbrier Group (Upper Mississippian) of West Virginia and Virginia represents the easternmost exposure of a laterally extensive carbonate sequence that extends across the mid-continent of the United States. West of this outcrop belt, Greenbrier sediments occur only in the subsurface until equivalent carbonates crop out in east-central Kentucky. The Greenbrier Group consists mainly of carbonates which are divided on the basis of intervening shale units and subtle changes in carbonate lithology. Originally, eleven formations were described (Reger, 1926), but this number has been reduced to seven formations used by the West Virginia Geological and Economic Survey. These formations are, from oldest to youngest, Hillsdale, Denmar, Taggard, Pickaway, Union, Greenville, and Alderson.

The Alderson Limestone and Greenville Shale are the uppermost formations of the Greenbrier Group in the study area (Fig. 1). They represent a transition in the central Appalachian basin between the last major Paleozoic marine incursion (lower Greenbrier Group) and the deltaic sediments of the overlying Upper Mississippian Mauch Chunk Group. In the study area the Alderson is a mixed terrigenous-carbonate sequence whereas the Greenville is mostly a non-calcareous gray to black shale.

The study area encompasses Mercer, Monroe, Summers, and

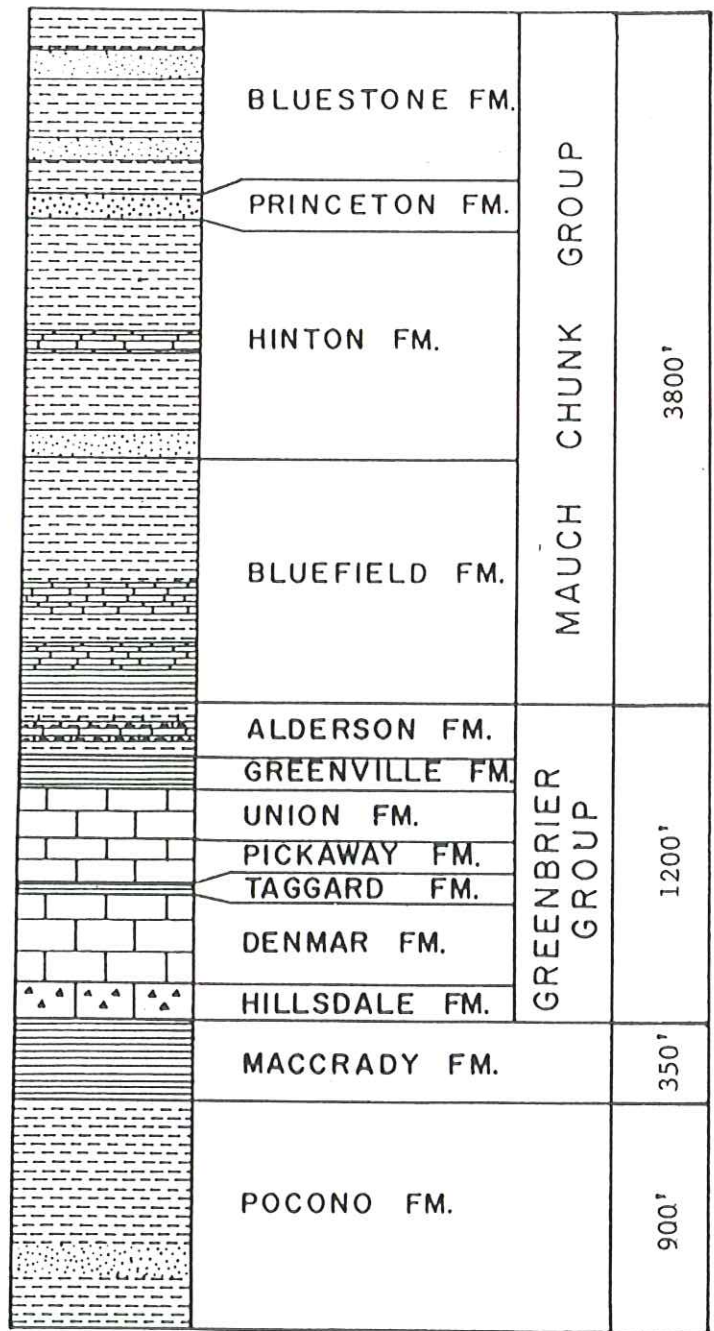
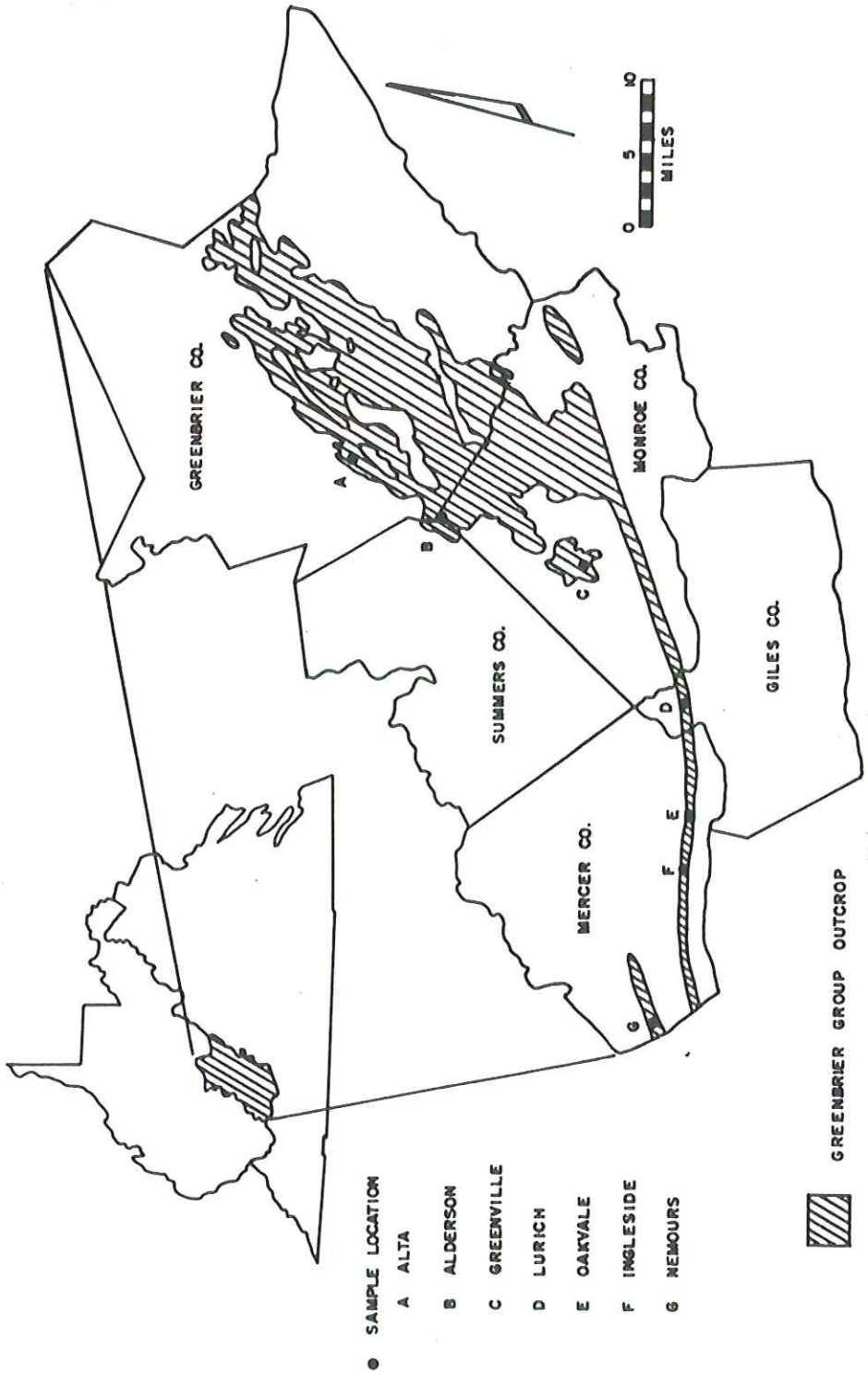


Figure 1. Generalized stratigraphic column for the Mississippian of southeastern West Virginia with estimated maximum thickness.



Greenbrier Counties, West Virginia, and Giles County, Virginia (Fig. 2). This area includes the type localities for each formation in the Greenbrier Group as well as some of its thickest and most complete exposures (Reger, 1926).

PURPOSE

The purpose of this research is to study in detail the Alderson and Greenville Formations, which have been treated previously only in general studies of the entire Greenbrier Group. The objectives of this thesis are: 1) determine mineralogy and petrology and delineate sedimentary facies; 2) characterize diagenetic effects; 3) interpret depositional environments; 4) correlate outcrop and subsurface data; and 5) construct a depositional model for these formations.

PREVIOUS WORK

The Greenbrier Limestone, a thick calcareous unit overlying the Maccrady Formation and overlain by the Mauch Chunk Group, has been given series, group, and formation status. Who actually first applied the name Greenbrier is not known (Reger, 1926). Andrews (1870) used the term Maxville Sandstone and later Maxville Limestone for equivalent strata in Ohio. Stevenson (1878) used Greenbrier as a name for a series of rocks that include the present Greenbrier and Mauch Chunk Groups. Rogers (1879) used Greenbrier Series for limestone

exposures along the Greenbrier River in Pocahontas County, West Virginia. The Greenbrier retained series status until Cooper (1961) used the term Greenbrier Group in order to conform with the stratigraphic code.

Based on general lithologic characteristics, Reger (1926) proposed eleven new formations within Rogers' Greenbrier Series. Reger's new names were used in subsequent West Virginia County Reports (Price, 1929; Reger, 1931; Price and Heck, 1939; and Tilton, Prouty, Price, and Tucker, 1927). Reger's division of the Greenbrier has gone through several changes since his original eleven formations were proposed. Because of similar faunas and lithologies, Wells (1950) proposed a new unit, the Denmark Formation, consolidating Reger's Sinks Grove and Patton Formations. Wells could recognize no basis for dividing these units outside the area of the type section. Kanes (1957) found that the Union and Pickaway Formations cannot be distinguished on faunal content, reconfirming the work of Hickman (1951); but there is a minor lithologic difference between these two units. Kanes proposed the name Gasper Formation and divided it into a lower, impure limestone (Pickaway equivalent) and an upper, pure limestone (Union equivalent). Blancher (1974) could not lithologically differentiate any of the formations above the Hillsdale Formation, so he introduced the name "Gasper-Denmark" Formation. He also included the Little Valley Formation as the lowermost unit of the Greenbrier Group in the Hurricane Ridge Syncline of Virginia.

Various studies on the Greenbrier Group outside the outcrop area

have focused on regional correlation and the importance of this group in petroleum production. Martens and Hoskins (1948) recognized a dolomitic oil-producing zone at the base of the Greenbrier in the subsurface of western West Virginia. Rittenhouse (1949) and Flowers (1955, 1956) studied the Greenbrier in the subsurface throughout West Virginia. Haught (1959) looked at oil and gas production in southern West Virginia and later produced a structural contour map on the Greenbrier for the entire state of West Virginia (Hought, 1968). Correlation of reservoir rocks within the Greenbrier was undertaken by Overby, Tucker, and Ruley (1963) and Overby (1967). Petrology, stratigraphy, structural geology, and hydrocarbon production of the Greenbrier in Lewis, Gilmer, and Braxton Counties, West Virginia was studied by Milner (1968) and Carpenter (1976). Wayne, Lincoln, Mingo, and Logan Counties, West Virginia, were studied by Matthews (1963), Youse (1964), Thomas (1967), and Henniger (1972).

Studies in the Greenbrier outcrop belt have focused on lithostratigraphy, biostratigraphy, and regional correlation problems. Hickman (1951) worked on the biostratigraphy of the Union and Pickaway Formations. Wells (1950) used coral and crinoid biostratigraphy to rename the lower Greenbrier Group. Wray (1951) studied correlation problems of the Greenbrier in northern West Virginia and Pennsylvania, as well as Greenbrier endothyrifid foraminifera (Wray, 1952). Kanes (1957) used blastoid biostratigraphy to group the Union and Pickaway Formations into the Gasper Formation. Slagle (1978) studied the paleontology and paleoecology of the Hillisdale Formation (lower

Greenbrier Group) in the Greendale Syncline of Virginia. Leonard (1968) studied the lithostratigraphy of the Upper Greenbrier Group (Pickaway, Union, and Alderson) from Monroe to Tucker Counties, West Virginia. Blancher (1974) studied the sedimentology of the Maccrady Formation and Greenbrier Group in the Hurricane Ridge Syncline of Virginia and West Virginia. During a hydrologic study Ogden (1976) mapped the formations of the Greenbrier in central Monroe County. Wray (1980) and Wray and Smosna (1982) studied the lithostratigraphy and paleoenvironments of the Greenbrier in Pendleton County, West Virginia, while Yielding (1984) studied Greenbrier stratigraphy in the vicinity of the Pocono Dome.

PROCEDURES

Field methods

This study is based on 10 outcrops of the Alderson Formation and 5 outcrops of the Greenville Formation from 7 generalized locations within the Greenbrier Group outcrop belt of southeastern West Virginia and southwestern Virginia (Fig. 2). All sections were measured, described, and sampled.

The Nemours composite section (Fig. 3), representing the upper 105 feet (samples NN-1 to NN-25) and the lower 146 feet (samples N-1 to N-36) of the outcrop, supplies a nearly continuous section of the Alderson Formation. The stratigraphic gap, due to faulting in the highway section, is estimated to be 75 feet. Ingleside (Fig. 4)

provides a continuous section comprising 388 feet of Alderson sediments (samples I-1 to I-92). Oakvale (Fig. 5) provides the upper 97 feet of the Alderson Formation (samples O-1 to O-21). The thickest exposure of the Alderson Formation, which occurs at Lurich, Virginia (Fig. 6), comprises 542 feet of nearly continuous section (samples L-1 to L-66). The Greenville composite section contains the West and Type sections for the Greenville Formation. The Greenville West section includes the upper 100 feet of the Greenville Formation (not sampled) and 125 feet of the Alderson Formation (samples GW-1 to GW-8) (Fig. 7). The Greenville Type section has been faulted and folded to more than double the section of the Greenville Formation. Its estimated thickness is 175 feet (samples GRA-1 to GRA-79). The Alderson section (Fig. 8) is a composite of four measured sections yielding approximately 125 feet of Alderson Formation (samples A-1 to A-37B and AG-18 to AG-21) and 125 feet of Greenville Formation (samples AG-1 to AG-17 and AB-1 to AB-17). The Alderson South section is incomplete but contains the upper 80 feet of the Greenville Formation (not sampled). The Alta I-64 (Fig. 9) section includes the upper 22 feet of the Alderson Formation (samples AA-2 to AA-12), whereas the Alta Hwy. 60 section (Fig. 9) exposes 93 feet of continuous section in the Alderson Formation (samples ALT-1 to ALT-15). Generalized stratigraphic sections of the Greenville Formation are shown on Fig. 10.

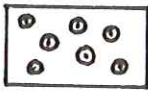
Sampling for this study was carried out on three scales. First, a standard vertical interval of five feet (1.5m) was utilized to give

LEGEND FOR
GENERALIZED STRATIGRAPHIC COLUMNS

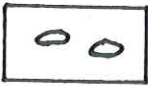
SPARITIC ROCKS



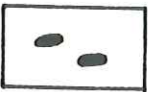
Biosparite



Oosparite

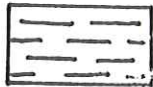


Intrasparite



Pelsparite

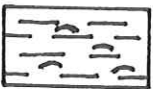
SILICICLASTIC ROCKS



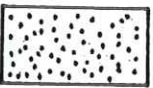
Mudstone



Calcareous
Mudstone



Fossiliferous
Mudstone

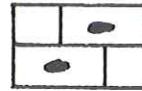


Sandstone

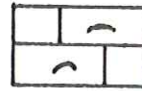


Shale

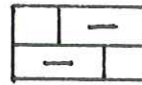
MICRITIC ROCKS



Pelmicrite



Biomicrite



Silty
Micrite



Covered

Sample location

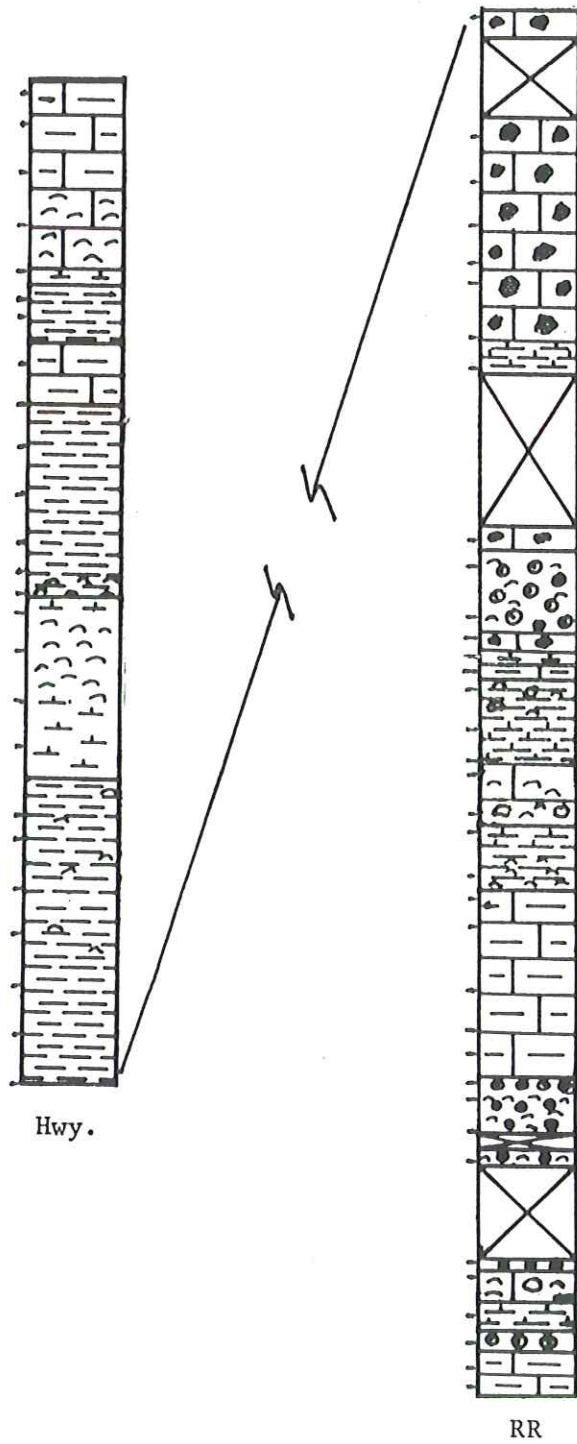


Figure 3. Generalized stratigraphic column of the Alderson Formation, Nemours (Hwy. and Railroad sections), Mercer County, West Virginia. Scale: 1" = 20'.

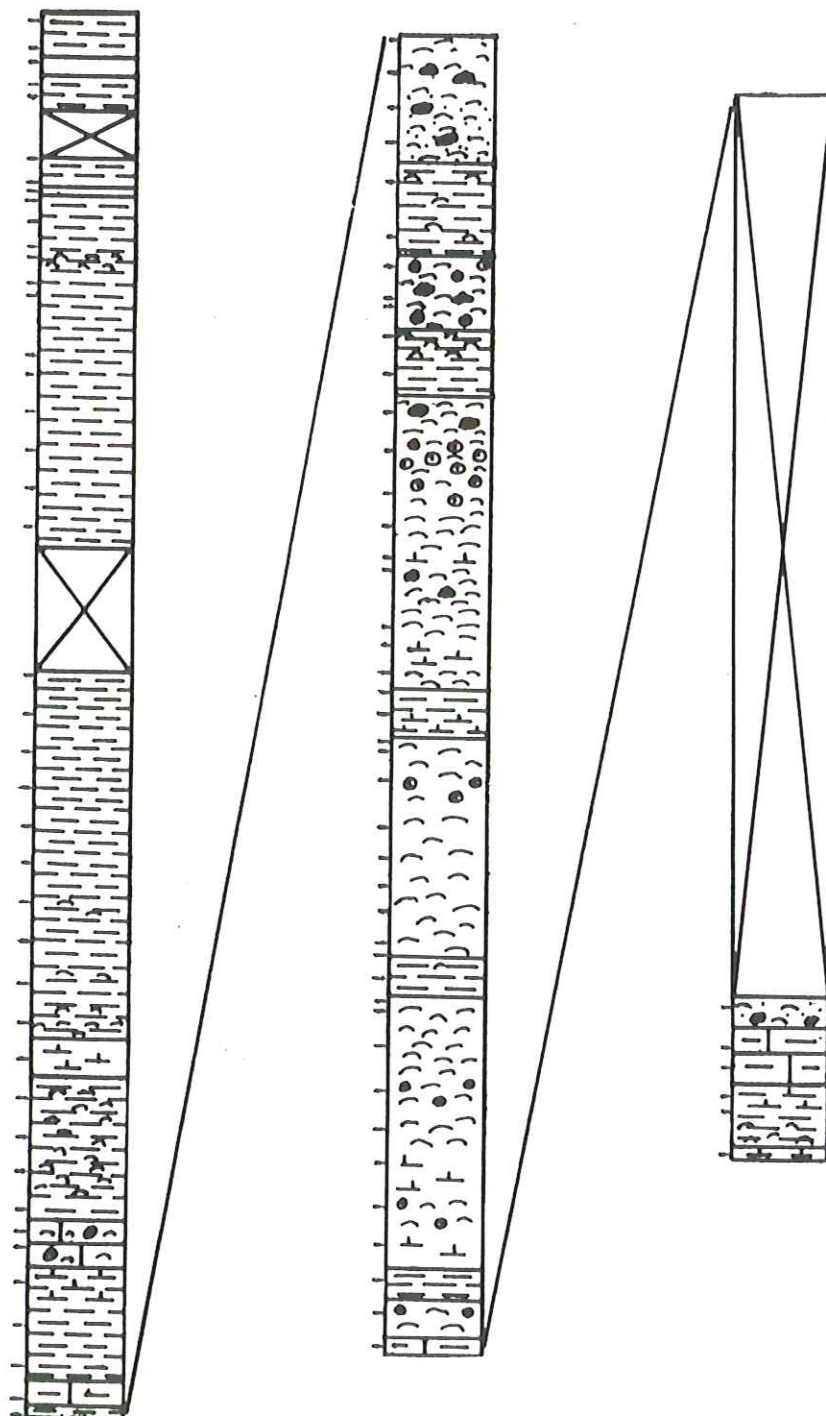


Figure 4. Generalized stratigraphic column of the Alderson Formation, Ingleside, Mercer County, West Virginia. Scale: 1" = 20'.

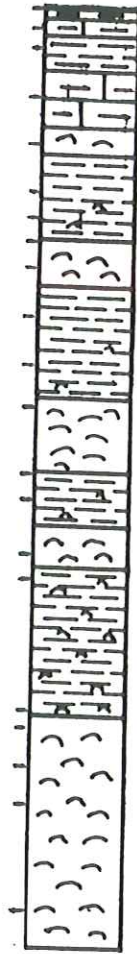


Figure 5. Generalized stratigraphic column of the Alderson Formation, Oakvale, Mercer County, West Virginia.
Scale: 1" = 20'.

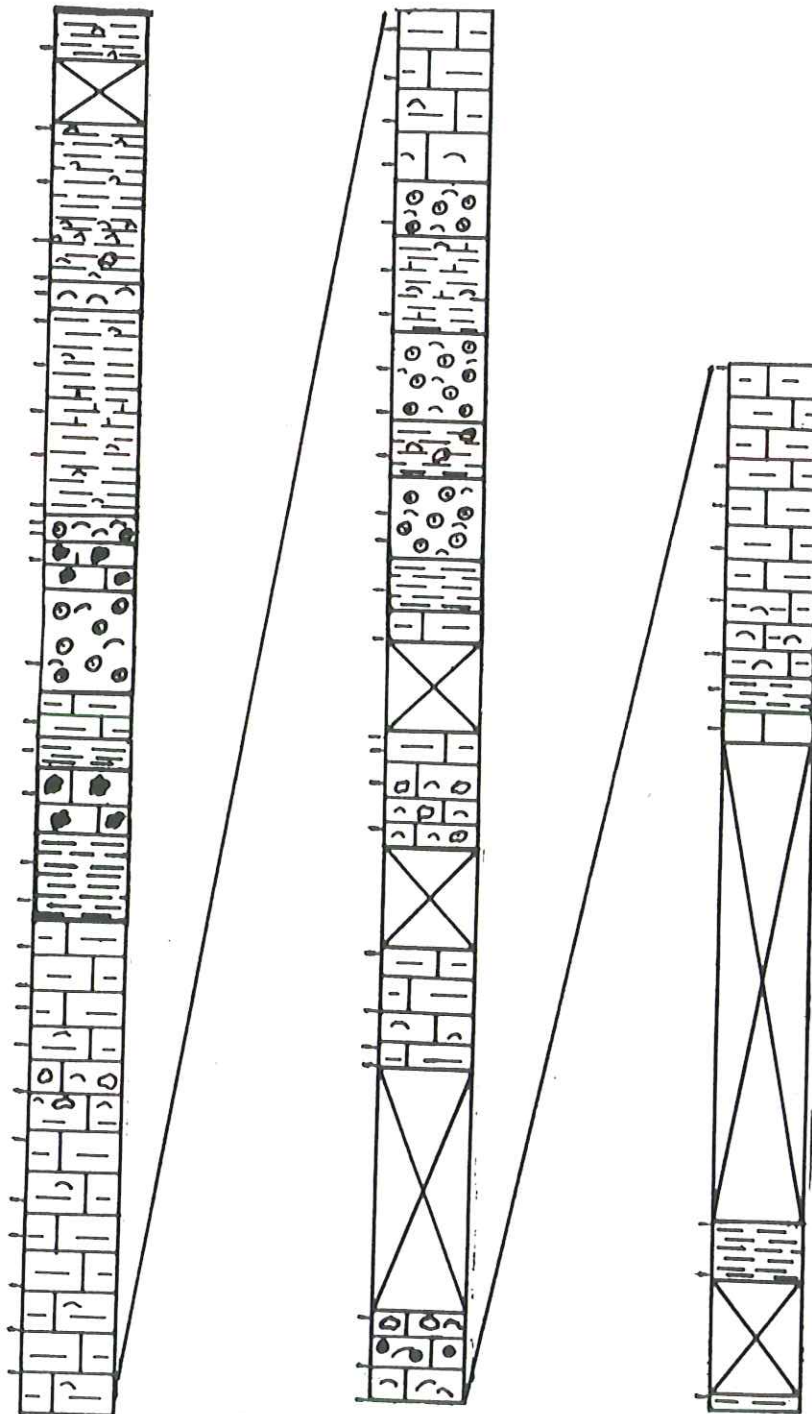


Figure 6. Generalized stratigraphic column of the Alderson Formation, Lurich, Giles county, Virginia.
Scale 1" = 20'.

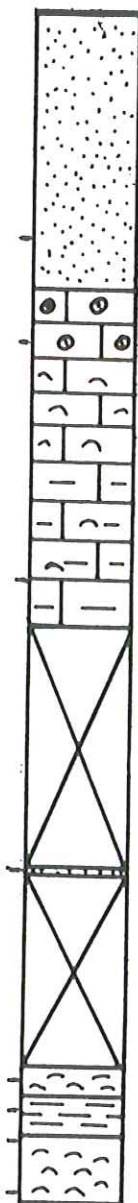
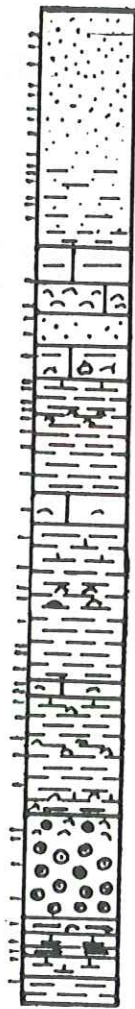
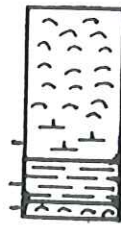


Figure 7. Generalized stratigraphic column of the Alderson Formation, Greenville (West section), Monroe County, West Virginia. Scale 1" = 20'.



Type



Flat Mtn. Road

Figure 8. Generalized stratigraphic column of the Alderson Formation, Alderson (Type and Flat Mtn. Road sections), Monroe County, West Virginia. Scale 1" = 20'.

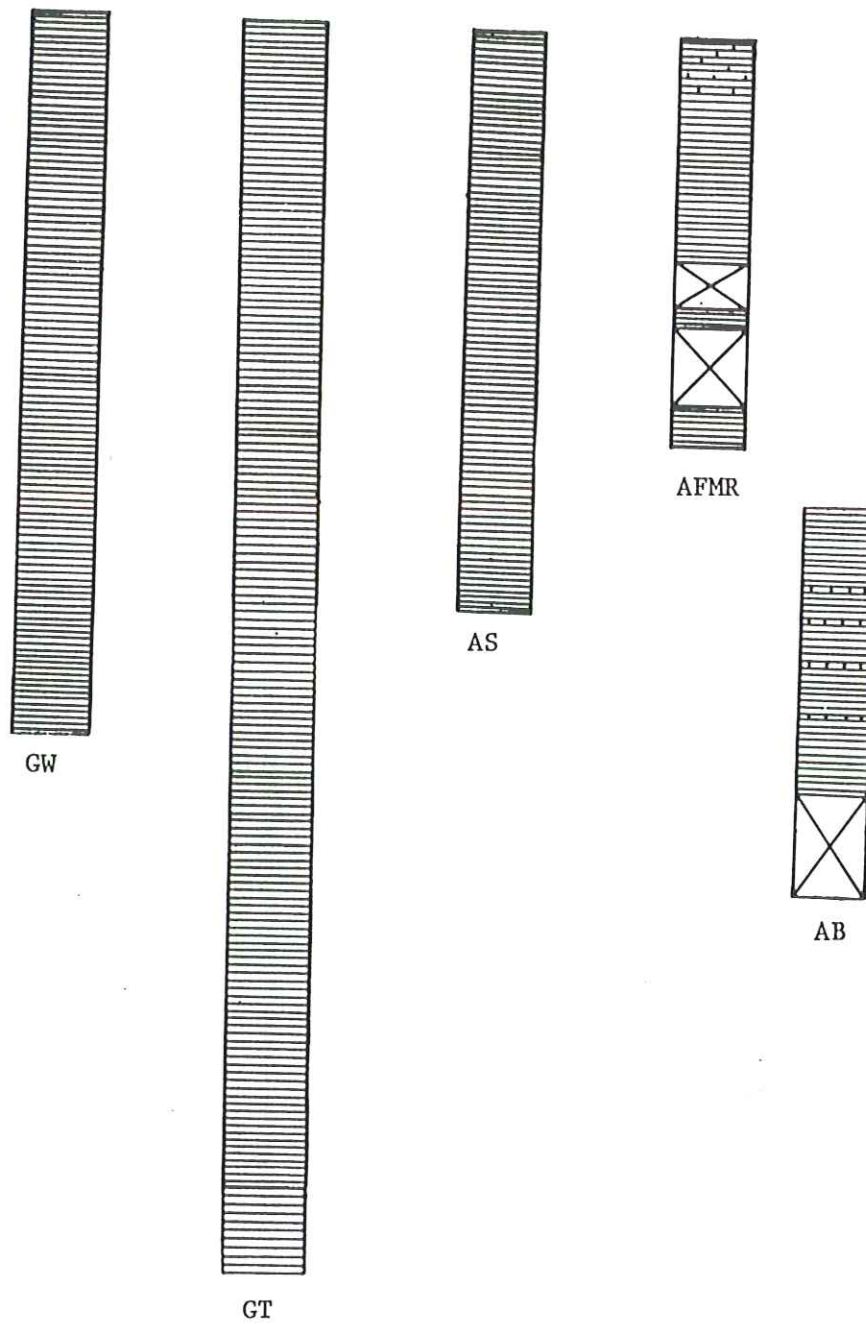


Figure 10. Generalized stratigraphic column of the Greenville Formation. (Greenville West, Greenville Type, Alderson South, Alderson Flat Mtn. Road, and Alderson Bridge sections). Scale 1" = 30'.

general sample coverage throughout informal field units greater than fifteen feet (4.5m) thick. Second, distinct lithologic units three to fifteen feet (1-4.5m) thick were sampled at the bottom, middle, and top. Third, lithologic units less than three feet (1m) thick were sampled near the middle to ensure coverage of all lithologies. A total of 336 samples of the Alderson Formation and 113 samples of the Greenville Formation were collected for study. Measured and described sections are included in Appendix A.

Thin sections

Thin sections were made from 328 samples of the Alderson Formation. Greenville samples were commercially prepared and, due to difficulties encountered in processing, only two thin sections were recovered for petrographic analysis. All other Greenville samples were analyzed using a standard binocular microscope.

Each thin section was stained with a solution of Alizarin Red S and potassium ferricyanide in dilute hydrochloric acid. Using the methods of Evamy (1963) and Friedman (1971), carbonate mineralogy was determined by color.

The slides were then point counted (300 points per thin section), identifying each point by mineralogy and/or allochem type. The grain volume per cent method of Dunham (1962) was used in this study. By this method, voids, cement, and matrix within allochems are counted as part of the allochem. These data are included in Appendix B.

Insoluble residues

240 samples were treated with acid to obtain percentages of carbonate and non-carbonate components, and used as a check on thin section percentages. Samples weighing approximately 15g to 30g were crushed to pea-sized aggregates and placed in a bath of 6.5% (volume) hydrochloric acid. After a 48 hour time period, excess acid was decanted, the residue was washed with deionized water, filtered, dried in an oven at 100°C for three hours, and weighed. From the original weight of the sample and insoluble weight, percent carbonate and non-carbonate material was calculated. These data are included in Appendix C.

X-ray diffraction

20 samples from facies of the Alderson Formation and 20 from the Greenville Formation were analyzed for bulk mineral composition. Samples were powdered and packed into aluminum sample holders and run from 2° 2θ to 60° 2θ at 1° per 30 seconds. Greenville samples and clay-rich Alderson samples were also analyzed for clay mineral content. These samples were powdered and sedimented onto glass slides and then subjected to heat and glycol treatments. Heat treated samples were heated for 1 hour at 100°C and again at 500°C. Glycolated samples were placed in a container and suspended above a solution of ethylene-glycol until moist. Treated samples were then

run at the same settings as bulk mineral runs.

PETROLOGY

INTRODUCTION

The compositional elements of the Alderson and Greenville Formations were identified in hand sample and in thin section. They are divided into two groups: 1) depositional components and 2) diagenetic or post-depositional components.

DEPOSITIONAL COMPONENTS

Carbonate components: skeletal

Bryozoans

Bryozoans, which compose the largest percentage of skeletal material (up to 50% of rock volume) in the Alderson Formation, are represented by Orders Cryptostomata, Trepostomata, and Cyclostomata (Reger, 1926). In hand sample, bryozoans occur as fenestrate fragments and as axial fragments of Archimedes which may attain a length of 7cm. In thin section, they are seen as sections through fenestrate fronds bearing rows of zooecia, as encrusting forms, and as an occasional section through the axis of Archimedes. Bryozoan fragments are preserved in two ways: 1) clean, well-formed fronds with

spar filled zooecia; and 2) worn, micrite coated, irregularly shaped masses that may contain abundant authigenic gypsum. Micrite coatings may have faint laminations that represent algal encrustations (Leonard, 1968), but such laminations were not observed during this study.

Echinoderms

Echinoderms, second only to bryozoans in abundance (up to 32% of rock volume), are represented by Classes Crinoidea, Blastoidea, and Echinoidea (Reger, 1926). They are the principal skeletal components in cleaner carbonates and decrease in abundance in micritic sediments. Echinoderm skeletal material is represented by columnals, plates, and spines.

In outcrop, columnals and plates are resistant to weathering and often accentuate sedimentary structures such as cross bedding and graded bedding in echinoderm rich beds. In places, isolated calyxes of Pentremites can be found, and at the Nemours section, a 0.15m bed composed of calyxes was observed.

Brachiopods

Brachiopods occur throughout the Alderson. They are abundant in some units (up to 13% rock volume), but average only 3%. They are represented by articulate Orders Spiriferida, Strophomenida,

Rhynchonellida, and Terebratulida, and by the inarticulate Order Acrotretida (Reger, 1926).

In thin section, brachiopods are represented by approximately thirty shell types based on shell curvature, surface ornamentation, and shell microstructure. These occur as disarticulated valves, broken and rounded shell fragments, nuclei of ooids, or isolated spines. Smaller articulated shells are sometimes seen and frequently show geopetal fabric.

Mollusks

Mollusks are represented by Classes Gastropoda and Bivalvia. In thin section, mollusks are represented by broken shell fragments and whole gastropod shells. By far, the most abundant and diverse group are the gastropods which may constitute up to 6% of the rock volume. Although no cephalopods were observed in this study, they have been collected from the Greenville Formation (Reger, 1926; Price and Heck, 1939).

Ostracodes

Ostracodes in Alderson sediments occur as two morphotypes; a long, thin-shelled variety predominates in lime mudstones, and a short, thick, robust form that predominates in grainstones. Each occurs as articulated or disarticulated valves less than 1mm in

length. They may make up less than 2% of rock volume and in some sediments are the only fossils present.

Foraminifers

Foraminifers are common in the Alderson but make up less than 1% of the rock volume. The most common genus throughout the Greenbrier Group is Endothyra (Wells, 1950; Wray, 1951, 1952; Leonard, 1968; Slagle, 1978). Climacammina was reported by Flowers (1956), but he noted that it is absent where clastics occur at the top of the Greenbrier Group, which includes the strata examined during this study. Climacammina was not noted in this study. Calcivertella and Calcitornella are common encrusting forms in Alderson sediments and a spherical form, possibly Diplosphaerina, occurs rarely. These genera have been reported from equivalent rocks in Tennessee, Alabama, and Georgia (Rich, 1980).

Algae

Algae are represented by Cyanophyta (blue-green algae), Chlorophyta (green algae) and calcispheres. Chlorophyta are represented by a dasycladacean tentatively identified as Vermiporella (Leonard, 1968). Blue-green algae occurring as stromatolites as well as several fragments resembling Ortonella were observed at the Alta

I-64 location.

Calcispheres are included here with the algae. Although they are of questionable origin, most workers classify them as plants. Stanton (1963) suggested that they represent some type of plant spore or reproductive body. Rupp (1967) and Marszalek (1975) considered calcispheres the reproductive cysts of dasycladacean algae because they closely resemble those of Acetabularia.

Others

Small, solitary rugose corals, seen occasionally in outcrop, were the only anthozoans observed. Rare serpulid worm tube fragments in the Alderson consist of broken fragments of several tubes. Carbonate particles resembling monaxon sponge spicules were observed in some micritic sediments. Various unidentified skeletal particles and many recrystallized skeletal fragments were observed.

Carbonate components: non-skeletal

Micrite

Micrite, a shortened term for microcrystalline calcite, is used for lithified carbonate particles, usually equant crystals in the range of 1-4 μ m (Folk, 1959). Micrite is formed in various ways including: direct precipitation from sea water (Milliman and others,

1969; Berner, 1971; Neuman and Land, 1975); disaggregation of calcareous algae (Cloud, 1962; Stockman and others, 1971; Neuman and Land, 1975) and invertebrate skeletal material (Steiglitz, 1972; Flugel, 1982); and biological abrasion of calcareous particles by borers and sediment ingesting organisms (Chave, 1962; Folk and Robles, 1964; Frydl and Sterns, 1975; Alexandersson, 1979; Torunski, 1979).

Micrite is common in the Alderson. It is mixed with siliciclastic material or has a more or less homogeneous texture, although it sometimes takes on a clotted texture. This may be due to unequal neomorphism to microspar (Schwarzacher, 1961) or from deformation of pelletal material (Illing, 1954; Bachmann, 1973).

Ooids

Ooids are variously shaped carbonate particles, usually spherical or elliptical, with uniform concentric laminae coating a nucleus (Flugel, 1982). Ooid structure and mineralogy have been the subject of much debate. Ooids display three structures: 1) tangential, 2) radial, and 3) radial-tangential. Mineralogically, they can be composed of aragonite, Mg-calcite, or calcite.

Modern ooids occur as two structural types, tangential and

radial. Tangential ooids are always composed of aragonite (Illing, 1954; Newell and others, 1960; Loreau and Purser, 1973). Radial ooids may be aragonite (Eardley, 1938; Friedman and others, 1973; Loreau and Purser, 1973; Kahle, 1974; Sandberg, 1975; Davies and Martin, 1976; Halley, 1977), Mg-calcite (Marshall and Davies, 1975; Milliman and Barretto, 1975) or both (Given and Wilkinson, 1985).

Fossil ooids can have all three types of structures. Some workers believe that fossil radial ooids represent original calcite mineralogy (Sorby, 1879; Sandberg, 1975, 1980; Wilkinson and Landing, 1978; Wilkinson, 1979). Others think that they are a diagenetic feature (Shearman and others, 1970; Swirydezek and others, 1979; Freeman, 1980), or that they indicate hypersalinity (Labecki and Radwanski, 1967).

Ooids can be subdivided on the basis of size, shape, number of laminae, and completeness of formation. Ooids in the Alderson occur as five types: normal, superficial, compound, deformed, and multicycle.

Normal ooids are single carbonate particles with a diameter of less than 2mm that have several concentric laminae. Superimposed on the concentric laminae is a radial structure which predominates in Alderson ooids. The overall size and shape of the ooids are determined by the size and shape of their nuclei, which are generally quartz grains or carbonate skeletal material. In the Alderson, spherical, elliptical, tabular, and crescent shaped ooids are seen. The size ranges from 0.01mm to 1.3mm and averages 0.45mm.

Superficial ooids are carbonate particles surrounded by one or only very few laminae (Flugel, 1982). They equate with proto-ooids of Carozzi (1957) which represent incipient ooid formation, although they have been associated with quiet water environments (Freeman, 1962; Land and others, 1979). Superficial ooids are very common in the Alderson. Size ranges from 0.05mm to 2.2mm and averages 0.7mm

Compound ooids or polyooids are carbonate grains composed of several normal ooids cemented together and surrounded by a common oolitic envelope, building composite particles of variable size and shape (Cayeux, 1935). Internal grains of compound ooids are not exclusively ooids; skeletal fragments are also common. Compound ooids are rare in the Alderson.

Several types of deformed ooids (cracked, broken, and pitted) occur in the Alderson. Cracked ooids form from mechanical stress during which one or several laminae crack and are spalled from the rest of the ooid (Radwanski and Birkenmajer, 1977). Broken ooids are due to mechanical breakup from agitated water (Flugel, 1982). Pitted ooids originate from pressure solution (Radwanski, 1965). Deformed ooids may be of any structural type but, they are rare in the Alderson.

Multicycle or regenerated ooids occur when normal ooid production stops or is interrupted by breaking of grains and then later, ooid production continues. This type of ooid is represented by spherical normal ooids containing several broken or pitted cortices. It rarely occurs in the Alderson.

Peloids

Peloids are spherical to irregularly-shaped carbonate (micrite or microspar) particles of varying size that have no discernable internal structure. They may include fecal pellets, micritized carbonate particles, and pseudo-oids. Pseudo-oids are elliptical or spherical calcareous grains, usually cryptocrystalline and with no coating of concentric layers (Carozzi, 1972). Flugel (1982) recommends that the term peloid be used instead of pseudo-oid. The term peloid is used in place of pellet and is of non-specific origin, whereas pellet implies fecal origin. Peloids are common in the Alderson Formation, range in size from 0.001mm to 4.0mm, and average 0.7mm.

Intraclasts

Intraclast is a shortened term for "intraformational clastic fragment" (Folk, 1959). The intraclasts of the Alderson are micritic to mixed carbonate-siliciclastic composition, rounded to irregular in shape, and typically contain one or more of the following: phyllosilicates, quartz, fossil material, and ooids. They may also contain dolomite and gypsum. Intraclasts are common in the Alderson Formation and are generally larger than peloids, ranging from 0.01mm to 5.0cm and averaging 1.2mm.

Non-carbonate components: skeletal

Trilobites

Trilobites have a segmented exoskeleton characterized by a fine prismatic structure composed of chitin, heavily impregnated with calcite or calcium phosphate (Flugel, 1982). No trilobites were seen in outcrop, but fragments identifiable by their distinctive morphology and sweeping extinction are common in thin section. Two genera have been described from the Alderson, Griffithides and Phillipsia (Price, 1929; Price and Heck, 1939).

Other

Several different types of phosphatic bone fragments were seen in the Alderson. A tooth of the shark Psammodus was found in the Greenville Formation north of Edray in Pocahontas County (Price, 1929).

Non-carbonate components: non-skeletal

Quartz

Quartz is one of the most abundant siliciclastic components within the Alderson and Greenville Formations. It occurs as very fine

silt to medium sand-sized, subangular to rounded grains. The largest grains occur in oolitic grainstones and finest grains occur in the shaly units, which is to be expected with the respective energy regimes. Most quartz grains show straight to slightly undulose extinction, but a minor component shows strongly undulose extinction. Composite grains are locally abundant and occur with metamorphic rock fragments. Most quartz are free of inclusions, but a few have euhedral apatite inclusions. These characteristics suggest a plutonic or reworked sedimentary origin, with subordinate metamorphic and volcanic sources (Folk, 1974b).

Clay Minerals

X-ray studies of clays in the Alderson and Greenville Formations indicate that the most abundant clay mineral is illite, followed by chlorite and montmorillonite. Clays are most common in siliciclastic and mixed carbonate-siliciclastic sediments, but they may also be a minor component of micritic/microsparitic sediments.

Mica

Mica is a common siliciclastic component of the Alderson that can make up to 8.3% of the rock. Two types of mica occur within Alderson sediments. The most abundant is a muscovite-type which occurs as large (up to 0.3mm) bladed crystals in various stages of decomposition

from muscovite to sericite. These micas are oriented parallel to bedding surfaces or are bent due to compaction, suggesting a clastic origin. The second type is a sericite, smaller than the muscovite (up to 0.02mm), which may be oriented parallel to bedding or randomly. Most of this sericite is diagenetic in origin, forming from degradation of other micas; but a minor amount is possibly allochthonous. Sericite is also common along twin lamellae and cleavage planes of the feldspars.

Feldspar

Feldspar was identified optically from the Alderson Formation and from X-ray diffractograms of the Greenville Formation. Most feldspar in the Alderson Formation is microcline and plagioclase, although an untwinned feldspar is present. Feldspar in Greenville Formation samples were not identified to species. The plagioclase has compositions ranging from low labradorite (An 50) to low bytownite (An 71). These identifications were made from samples with good albite twinning using the Michel-Levy method. Plagioclase occurs as small (course-silt to fine-sand), lath-shaped, subangular grains which exhibit little or no deformation. The composition, size, shape, and absence of deformation suggests a mafic plutonic or volcanic source. Similar morphologies and compositions have also been found in the Fido Sandstone, and Girkin and Cove Creek Limestones (Mississippian) of Virginia (D. W. Neal and C. L. Bergren, personal communication),

whereas plagioclase in sandstones of the overlying Bluefield Formation of West Virginia is predominantly intermediate oligoclase (M. Kirkland, personal communication). Geographically, plagioclase is mostly confined to southern Mercer County (Nemours, Ingleside, and Oakvale sections), whereas stratigraphically it is confined to the uppermost Alderson Formation (depositional sequence IV, to be discussed later).

Microcline, exhibiting typical grid iron twinning, and an untwinned feldspar occur as coarse-silt to medium-sand sized, sub-angular to rounded grains. Both types are slightly to strongly deformed, suggesting a metamorphic source. Geographically, microcline generally occurs from Lurich, Virginia northward. Stratigraphically, it occurs in oolitic carbonate sands of the Lurich section and in sandstones from the Alderson section. Carbonate sands of the Lurich section are very similar to the Fido Sandstone (Mississippian) in Virginia (D. W. Neal, personal communication). Alteration is minor and is confined to sericitization along twin lamellae and cleavage planes.

Rock Fragments

Rock fragments, ranging in size from medium sand- to pebble-sized grains, are a minor siliciclastic constituent within the Alderson. Metamorphic fragments are most abundant, but there are minor sedimentary and possibly some volcanic fragments. Metamorphic

fragments are low to intermediate grade, mostly phyllitic and schistose. Some gneissic rock fragments representing a higher grade of metamorphism, dolomitic marble, and a few basaltic fragments are present. Studies of the Bluefield Formation of West Virginia, and of the Girkin, Fido, and Cove Creek Formations of Virginia have noted similar types of rock fragments (D. W. Neal, M. Kirkland, C. Bergren, personal communication). Carbonate rock fragments are represented by oolitic grainstones and microdolomites.

Plant material

Plant material is abundant in siliciclastic sediments, but is rare to absent in cleaner carbonates. Plant fragments have been found at the Alderson, Ingleside, and Lurich sections. Reger (1926) mentioned a plant fossil zone that lies just above the middle of the Alderson Formation, but this does not correlate with plant zones at the Alderson and Ingleside sections. Plant material includes grasslike leaves of the genus Lepidophylloides and stem sections of an unidentified plant with double vascular bundles.

Other Minerals

Phosphate occurs as small, rounded grains but overall is rare in the Alderson. Accessory minerals are very scarce and occur only in sandstones. They include zircon and opaques, possibly illmenite.

POST DEPOSITIONAL COMPONENTS AND PROCESSES

MICRITIZATION

Micritization, a process by which original carbonate material is systematically replaced by microcrystalline carbonate, occurs in the stagnant zone of the marine phreatic environment (Longman, 1980). It may be organic or inorganic in nature, but most micritization is assumed to be organic and occurs by two processes, degrading and aggrading micritization.

Degrading or destructive micritization results from borings made by bacteria, heterotrophic fungi, and various blue-green, green, and red algae (Bathurst, 1966; Freidman and others, 1971; Kobluk and Risk, 1977; Flugel, 1982). The boring zone begins at the sediment/water interface and extends to a depth of approximately one meter. After the organism dies, the vacated boring is infilled with micrite-sized cement by an unknown process. This is repeated many times in a centripetal manner, eventually causing the host grain to lose all original internal structure.

Aggrading or constructive micritization is produced by encrusting organisms, usually algae, which build up concentric layers around a host grain by calcification of filaments protruding from the host (Kobluk and Risk, 1977; Flugel, 1982). This layer will then protect the host from degrading micritization. With time, all internal

structure within the layers will disappear, thus resembling degrading micritization.

Micritization, in the form of envelopes around constituent carbonate grains, is an important diagenetic feature in the Alderson. Envelopes are formed by the degrading process and vary in thickness from a thin film (0.01mm) to approximately 1mm on larger grains. The micritization process has continued, in some rare cases, to produce peloids (cryptocrystalline grains; Purdy, 1963). Micritization preferentially alters aragonitic shell material and endothyrid foraminifers (Fig. 11). Crushed and broken micrite envelopes are locally abundant. Total micritization occurs in some endothyrid foraminifers and some gastropods where shell form is still distinguishable, and in some ooids where structure is barely discernable.

Leonard (1968) cited concentric, algal coatings on fossils and mud fragments and attributed them to aggrading micritization. In the present study, micrite coatings are common on fossils, particularly bryozoans, but no internal structure resembling algal laminations is present.

MICROSPAR

Microspar is composed of equidimensional crystals of calcite that range in size from 5 to 10 μ m (Folk, 1959; Longman, 1977). Most

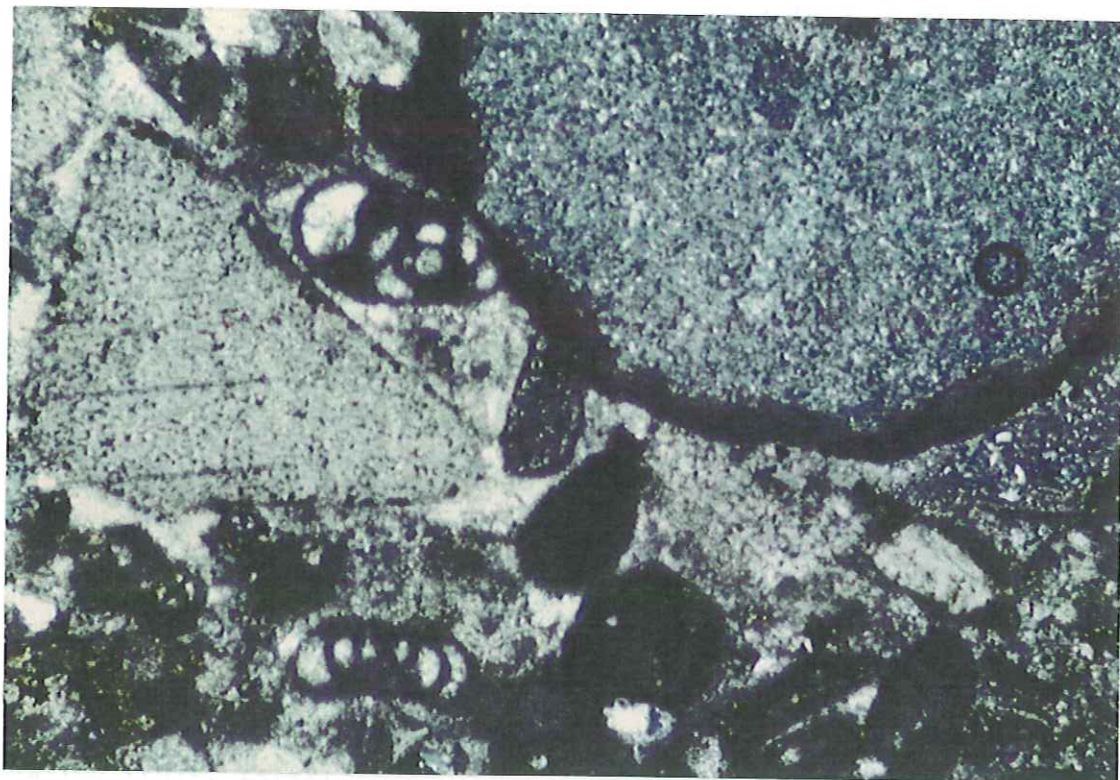


Figure 11. Micritization of endothyrid type foraminifers and partial micritization of echinoderm plates and columnals (63x).

workers agree on the shape and lower size limit, but the upper size limit varies among authors. Upper size limits reported for microspar are: 10 μ m (Folk, 1965; Elf-Aquitaine, 1975), 20 μ m (Dunham, 1962), and 30 μ m (Leighton and Pendexter, 1962). The size range of 4-30 μ m (Micrite II of Bossellini, 1964) will be used in this paper.

Microspar is generally thought to be formed by aggrading neomorphism of micrite (Folk, 1959 and 1965). From an original carbonate mud of high-Mg calcite and/or aragonite, aragonite converts to calcite whereas high-Mg calcite is inverted to low-Mg calcite during the neomorphic process. Inversion of high-Mg calcite frees Mg ions which form a "cage" around low-Mg calcite, inhibit calcite growth, and thus limit crystal size to 2 to 3 μ m. When Mg ions are removed, crystals continue to grow forming microspar and eventually coarser pseudospar (Folk, 1965). Three methods have been proposed for the removal of Mg ions in Folk's model: 1) flushing with fresh water; 2) adsorption/absorption of Mg ions by clay minerals; and 3) dolomitization (Folk, 1974).

Lasemi and Sandberg (1984) suggest an alternative to Folk's theory and use of the term "micrite" for micrite and microspar. They suggest further that micrite and microspar coexist and result from calcitization of an aragonite-dominated mud.

Dunoyer de Segonzac (1970) showed that chlorite and montmorillonite clays can absorb Mg ions from sea water and from sediments during burial diagenesis. This might then allow the micrite-sized calcite to grow to microspar and/or pseudospar. The

action of montmorillonite in the formation of microspar has been well documented in the Bromide Formation of Oklahoma (Longman, 1977).

Longman also cited interbedded shales as Mg sumps in microspar formation. Microspar has also been attributed to porosity differences in sediments (Longman, 1977) and to outcrop weathering (Chafetz, 1972; Folk, 1974a).

The method of microspar formation in the Bromide Formation is a good model for the Alderson Formation even though montmorillonite (and chlorite) are minor to moderate in abundance. Alderson Formation microspar occurs in two ways: 1) microspar patches within sheltered areas of bioclastic material, and 2) pervasive microspar matrix. The sheltered patches may be due to original micrite being neomorphosed during meteoric "flushing". The pervasive microspar matrix is probably due to the influence of clays that occur within the matrix and shaly interbeds.

RADIAL RIM CEMENT

Radial rim cement includes any cement which radiates outward from grain surfaces into an existing pore space. In modern sediments these cements may vary in composition (aragonite, low-Mg calcite, or high-Mg calcite), have various crystal shapes, and are divided into two morphologic groups: 1) isopachous cements and 2) prismatic and bladed cements.



Figure 12. Prismatic radial rim cement forming on ooids with later blocky pore filling cement (63x).

Isopachous cements are first generation void-lining cements which form a thin rim of roughly uniform thickness composed of crystals oriented normal to the pore wall or host grain. Isopachous cements in the Alderson occur as fibrous, prismatic, bladed, or equant crystals, and may be both intragranular and intergranular. Intragranular cements are common in endothyrid foraminifers, articulated ostracodes, and bryozoan zooecia, whereas intergranular cements are common to all grains, carbonate as well as non-carbonate. Intergranular cement does not occur on echinoid plates except where micritization has occurred.

Prismatic and bladed cements are first generation void-lining cements which are more coarsely crystalline than isopachous cements and do not have a uniform thickness. Prismatic (dog tooth) cement equates with dentate cement of Flugel (1982) and occurs as intragranular cement (lining cavities within articulated brachiopods, ostracodes, and bryozoan zooecia) and as intergranular cement (coating some bioclastic material and ooids) (Fig. 12). Bladed cements are lath-shaped with flattened to low angle terminations and are generally smaller than prismatic cements. This type of cement frequently coats ooids but overall is less abundant than prismatic cements.

SYNTAXIAL CEMENT

Syntaxial cement is a sparry calcite overgrowth which is formed in crystallographic and, therefore, optical continuity with the host

grain. It may occur on any carbonate grain with a preferred orientation of its crystallographic lattice (Folk, 1965). Most commonly, syntaxial cement occurs on echinoderm plates and fragments but it can also form on other skeletal grains such as gastropods, corals, brachiopods, and ostracodes.

Evamy and Shearman (1969) showed that syntaxial cement nucleates between the pores of echinoderm plates such that the c-axis of the cement parallels the c-axis of the single crystal that forms the echinoderm plate. Growth is rapid in the c-axis direction but retarded in others, which forms a serrated outline. If the host grain is encrusted or micritized, the cement-to-grain contact is interrupted and no syntaxial cement will occur (Lucia, 1962; Evamy and Shearman, 1969).

Bathurst (1958, 1971) interpreted syntaxial cement in muddy limestones as forming by neomorphic replacement of micrite. Analyzing the same material as Bathurst, Waldken and Berry (1984) repudiated his findings on the basis of cathodoluminescence studies. The syntaxial cements actually occur as solution coronas in which cement fills solution voids in micrite surrounding the echinoderm with several generations of crystal growth.

In grainstones, syntaxial cements will continue to grow until they fill all available pore space and growth is impeded by adjacent grains. In extreme cases, the cement is actually poikilotopic, enclosing many other grains (Lucia, 1962).

Echinoderms and syntaxial cements are common in Alderson

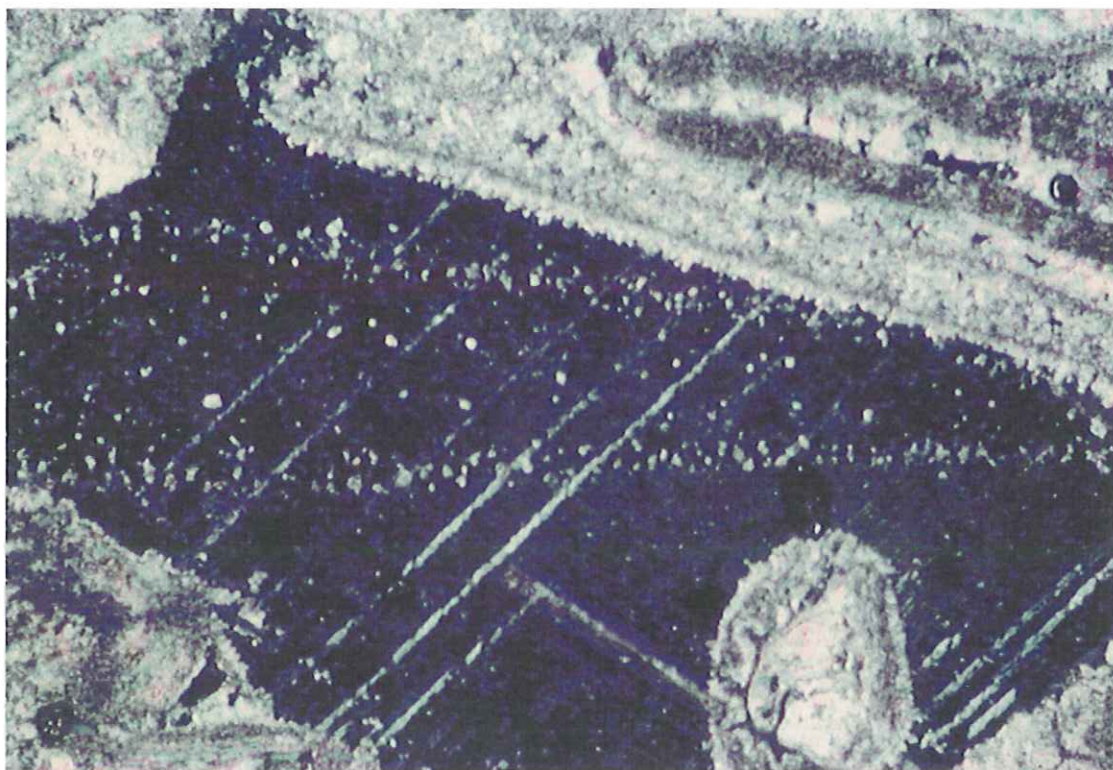


Figure 13. Echinoderm plate with syntaxial cement, showing ghost. Recrystallized mollusk fragment with isopachous radial rim cement at bottom (63x).

sediments. In biosparites, syntaxial cements may constitute up to 60% of the total cement; they encase echinoderm plates and extend 1) to the surface of other grains or their cements (Fig. 13) or 2) to adjacent syntaxial cements, forming compromise boundaries. Where echinoderms have been micritized, growth of syntaxial cement is retarded unless the micrite envelope has been breached, thus providing an avenue for cement formation. If echinoderms are scarce, most cements are blocky and drusy (discussed below). In micrite or fine siliciclastic matrices, no syntaxial cement is present unless there are isolated areas of bioclastic material providing a substrate for cement formation.

PORE FILLING CEMENT

Pore filling cements are second generation cements which occupy primary and secondary interparticle and intraparticle porosity. Two types of pore filling cement occur in the Alderson: 1) blocky, which is equant, anhedral to subhedral in form, and greater than 30 μ m in size; and 2) drusy, in which grain size increases outward from the pore walls. Blocky cement is always preceded by radial rim cement and occludes all porosity. Drusy cement is gradational with radial rim cement, unlike with blocky cement, where contact with the previous cement is abrupt.

Blocky cement forms from pore fluids with a Mg/Ca ratio of 1:1 or

less (Folk, 1973, 1974a; Folk and Land, 1975). This ratio indicates a meteoric environment, although a deep burial environment may account for some of the cement (Badiozamani, 1977; Moore and Druckman, 1981).

Drusy cement may have any crystal form, and ultimate crystal size is determined by the size of the available pore space. In the Alderson, drusy cement is strictly intraparticle, infilling articulated ostracodes and brachiopods.

DOLomite

Dolomite, found in every facies of the Alderson Formation, occurs as four morphologic types: idiotopic-C, idiotopic-P, idiotopic-S, and xenotopic-A. Idiotopic-C dolomite (Gregg and Sibley, 1984) occurs as rhombic crystals with terminations projecting into a pore space. In Alderson sediments, these are typically small, individual or clustered rhombohedral crystals which are clear to white and may be zoned to slightly zoned. Idiotopic-C dolomite always occurs with an intervening isopachous cement layer around the host grains in the carbonate sand facies. The remaining pore space is filled with blocky calcite cement.

Idiotopic-P dolomite (Gregg and Sibley, 1984) occurs as free-floating rhombohedral crystals in a micrite or mixed carbonate-siliciclastic matrix. Crystals are typically small, clear to white, and may be zoned to slightly zoned.

Idiotopic-S dolomite (Gregg and Sibley, 1984) is characterized by straight compromise boundaries and at least 30% preserved crystal face junctions (Gregg and Sibley, 1984). These dolomites are typically subhedral to anhedral and occur in Alderson Formation sandstones as blocky pore filling cement or poikilotopic cement. Blocky dolomite occurs as small, equant crystals with compromise boundaries, whereas poikilotopic cement occurs as large, irregular crystals with few compromise boundaries.

Xenotopic-A dolomite (Gregg and Sibley, 1984) occurs as tightly packed anhedral crystals with mostly curved and irregular intercrystalline boundaries that produce a dolostone composed of 90-100% dolomite. These dolomites are typically clear to white and unzoned, but have a number of inclusions giving a dusty appearance. The remaining material in these dolostones includes quartz, pyrite, and a few fossil fragments. Xenotopic-A dolomite occurs at the Alderson-Lillydale boundary and at other limestone-shaly limestone boundaries within the Alderson Formation.

The exact origin of Alderson Formation dolomites is unknown, but several environmental constraints can be suggested. Gregg and Sibley (1984) have shown that dolomite texture is related to the temperature at which crystals grow. They proposed a "critical roughening temperature" (CRT) for dolomite between 50°C and 100°C. Below this CRT dolomite grows as euhedral crystals producing idiotopic textures. Above this CRT, dolomite grows as anhedral crystals producing xenotopic textures. So it may be inferred that idiotopic-C,

idiotopic-P, and idiotopic-S dolomites formed at low temperatures and correspondingly shallow burial depths, whereas xenotopic-A dolomite formed at higher temperatures and greater depths. Idiotopic dolomite textures may, however, form above the CRT when crystal faces are stabilized during growth by organic material or clay minerals. Consequently, idiotopic-P dolomite in the mixed carbonate-siliciclastic facies may be either low or high temperature dolomite.

Xenotopic-A dolomite is here inferred to have formed by the replacement of micritic sediments at depth. Magnesium was probably derived from the associated shales during the transformation of smectite to illite, which also takes place at higher temperatures. Idiotopic-P dolomite is interpreted to be replacement of micrite at shallow depths in micritic sediments or at greater depths in hybrid sediments. Idiotopic-C dolomite probably originated in shallow mixing environments where changing pore water conditions resulted in slight zonations within the crystals. This occurred after isopachous calcite cementation and before blocky calcite cement formation. Idiotopic-S dolomite formed at low temperatures but its exact diagenetic environment is unknown.

DEDOLOMITE

The terms dedolomite and dedolomitization were first used by Von

Morlot (1847) for replacement of dolomite by calcite, and their use has continued into recent literature. Use of dedolomitization for this process has been rejected in favor of calcitization (Swett, 1965; Smit and Swett, 1969). Calcitization is used throughout this paper for the process, whereas dedolomite is retained for the product.

Early experimental work by Yanat'eva (1955) showed that CaCO_3 should precipitate both from the decomposition of dolomite and from the interaction between gypsum and MgCO_3 . Chillingar (1956) concluded that calcitization is surficial (low temperatures and pressures) and dependent on the presence of gypsum. Subsequent work by DeGroot (1967) confirmed that calcitization is a near surface process associated with the following conditions: 1) a high rate of flow of a Ca-saturated solution (gypsum saturated) to keep the Ca/Mg ratio high; 2) a carbon dioxide partial pressure (PCO_2) less than 0.5atm; and 3) a temperature of less than 50°C. Others have documented the same type of near surface occurrence (Goldberg, 1967; Katz, 1968; and Al-Hashimi and Hemingway, 1973).

Since these works, additional processes for calcitization have been documented: deep burial - Back and others (1983) and Budai and others (1984); contact metamorphism - Wood and Armstrong (1975); schizohaline environment - Margaritz and Kafri (1981); fresh water system along fault zone - Longman and Mench (1978); hot Ca-rich brines moving updip into limestone - Land and Prezbindowski (1981).

Dedolomite in the Alderson Formation is recognized optically by staining having a brownish-red color (in contrast to dolomite which is

clear to white) and by its composite grain structure within the rhombohedral shape (Evamy, 1967). X-ray diffractograms of Alderson samples containing dedolomite show no presence of dolomite. Alderson Formation dedolomite occurs as replacement of idiotopic-E, idiotopic-C, and idiotopic-P dolomite. Idiotopic-S and xenotopic-A dolomite are unaffected. Its occurrence other than in the outcrop area has not been documented. Leonard (1968) did not mention dedolomite, and other studies on the Greenbrier Group focus on the subsurface in areas where the Alderson is absent.

SILICIFICATION

Silicification is the process of introduction of or replacement by silica; introduction implies an external source whereas replacement can be from an internal or external source. Silicification can affect fossils, other carbonate allochems, carbonate cements, and carbonate matrix.

Schmitt and Boyd (1981) divided a descriptive classification of silica based on morphology and optical properties (modified after Folk and Pittman (1971)). Silica is divided into megaquartz (crystals greater than 20 μ m) and microquartz (less than 20 μ m). Microquartz is, in turn, divided into microcrystalline quartz (equant, 1-4 μ m) and chalcedonic quartz (fibrous). Chalcedonic quartz is divided into chalcedonite (length fast), quartzine (length slow), and leutectine

(inclined).

Studies on silicification patterns of calcareous fossils are relatively uncommon (Pittman, 1959; Wilson, 1966; Brown and others, 1969; Jacka, 1974; Meyers, 1977; Schmitt and Boyd, 1981; and Neal and others, 1984). Wilson (1966) based his classification patterns on cement and replacive types of silica, which are divided on the basis of morphology. Schmitt and Boyd (1981) described five patterns of silicification based on quartz types and orientation to the skeletal wall/matrix boundary. Neal and others (1984) examined a wide variety of silicified and partially silicified fossils to determine the effect of various factors (age, location, silica source, silica mineralogy, mineralogy and microstructure of the carbonate host) on the types and patterns of silicification. They found that variation in the type of silica can be attributed to differences in shell microstructure and/or the mineralogy and solubility of original carbonate material. Fibrous shell material (brachiopods, bryozoans, and pelecypods) is predominantly replaced by subhedral to euhedral megaquartz, whereas monocrystalline and microgranular textured organisms (echinoderms, foraminifers, ostracodes, and barnacles) are predominantly replaced by chalcedony and microcrystalline quartz. Chalcedonic quartz is precipitated in solution voids within fossils.

Silicification of fossils in the Alderson Formation produced megaquartz, microcrystalline quartz, and chalcedony (Gray and Neal, 1984). Megaquartz occurs as subhedral to euhedral crystals aligned parallel in one or more layers subjacent to shell boundaries. The

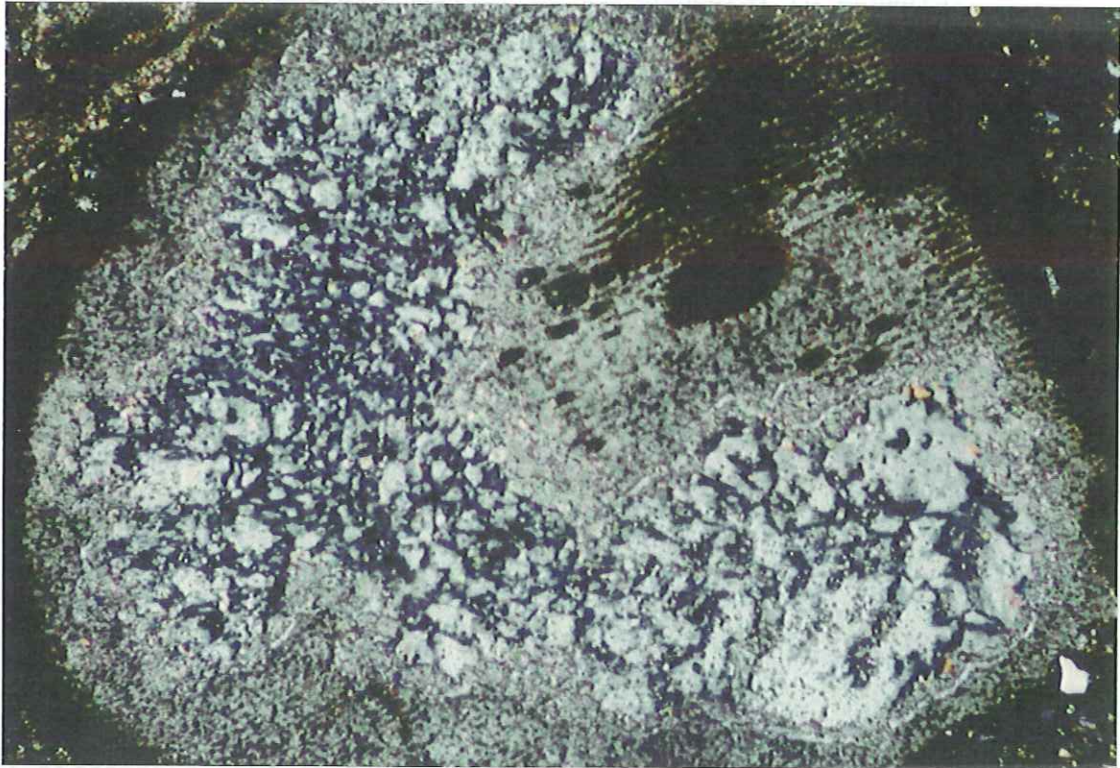


Figure 14. Echinoderm plate showing silicification (63x).

most susceptible organisms to silicification are echinoderms, in which silica occurs as rounded to irregular masses of microcrystalline quartz and/or chalcedony (Fig. 14). Microcrystalline quartz occurs as a replacement, whereas chalcedony occurs as a void filling.

Brachiopods and bryozoans are silicified by subhedral to euhedral megaquartz, which generally parallels shell microstructure (Neal and others, 1984). Silicification of ooids in the Alderson is rare and often incomplete, leaving varying amounts of residual carbonate.

Six major sources of silica have been described in the literature; these include pressure solution, dissolution of silicate minerals, devitrification of volcanic glass, biogenic silica, clay mineral diagenesis, and migration of silica-rich surface waters into the subsurface (Wilson, 1966; Schmitt and Boyd, 1981). In the Alderson, no siliceous organisms were observed although rare, questionable volcanic rock fragments occur. Of possible silica sources, pressure solution, dissolution of silicate minerals, and clay mineral diagenesis seem to be the most likely. The timing of silicification in the Alderson seems to be early and may be porosity related, both in shell structure and in sediments (Neal and others, 1984). Formation of late pore filling cements, compaction, dewatering of clays, and recrystallization of shell material would decrease or occlude porosity sufficiently to restrict movement of silica in solution.

GYPSUM

Gypsum in Alderson sediments is rare, although two morphologic types are seen. One occurs as poikilotopic cement whereas the other, more abundant type occurs as small, euhedral crystals which may be twinned or untwinned. Poikilotopic gypsum cement occurs in pelmicrites as patches of anhedral crystals with individual crystals up to 2mm in diameter. Euhedral gypsum occurs as three crystal forms: small, thin, untwinned crystals; square, polysynthetically twinned crystals; and small, thin, contact twinned crystals.

Small, thin, untwinned euhedral crystals are the most common type in Alderson sediments, and they are restricted to carbonate mud intraclasts. Crystals are small (average 0.005mm) and light gray in color, due to inclusions of micrite or clays. Whether this type of gypsum is syndepositional with the micrite or formed later is unknown.

Square, polysynthetically twinned crystals occur in micrite envelopes of bryozoans and in some carbonate mud intraclasts. Crystals may reach 0.02mm in diameter. Kerr (1977) attributed polysynthetic twinning to heating during thin section preparation, but this is doubtful because such twinning has not affected other types of gypsum. These twins may be pseudomorphs after anhydrite, based on crystal form and twinning type which are common for anhydrite (Phillips and Griffin, 1981).

Small, thin euhedral crystals with simple contact twins occur within micrite envelopes of bryozoans, within the skeletal structure

of bryozoans, within bryozoan zooecia associated with dedolomite, and within dedolomite matrix. Crystals average 0.03mm in length and may result from the breakdown of organic material or from other biological activity.

PYRITE AND HEMATITE

Pyrite, in the Alderson, is most common in micritic, dolomitic, and siliciclastic sediments, whereas hematite is most common in carbonate sands. Hematite occurs as hexagonal crystals in dolomite cemented quartz arenites, as infillings of plant material, as layers within ooids, and as coatings on quartz grains. Pyrite occurs as framboids, individual cubic crystals, irregular masses, and rarely as a replacement of echinoderm fragments.

MECHANICAL COMPACTION

Mechanical compaction, as dealt with here, involves breaking and/or crushing of grains. Three products of mechanical compaction occur within Alderson sediments: 1) compaction of micrite envelopes around dissolved original aragonitic shell material; 2) spalling of micrite envelopes and ooid cortices, and; 3) crushing of fossil grains.

Compaction of micrite envelopes is common in Alderson sediments. Kendall and others (1966) found that micrite envelopes have a high organic content, and that when envelopes were dissolved in acid, the residual organic material possessed great strength. They suggested dissolution of the aragonitic grain left organic material to act as a mold for later reprecipitation of calcium carbonate. This would leave a rigid layer that could be deformed during compaction and could later be infilled with blocky or drusy cement. Longman (1982) stated that dissolution of aragonitic material occurs in the leaching zone of the meteoric phreatic environment. Therefore, micrite envelopes were probably compacted early in the meteoric environment.

Spalling is the breaking of micrite envelopes or ooid cortices parallel to the surface of a grain. Of the two, ooid cortices are easier to detach from the host grain, a process that is dependent on mineralogy of the host grain and cortex. Alderson ooid cortices are more easily spalled from non-carbonate material (quartz) than from other carbonate material (shell material). Typically, only a small portion of material is spalled, and the cortex usually remains attached at one end. Some workers favor a deep burial origin where late cement forms after spalling and pressure solution (Coogan, 1970; Moore and Druckman, 1981). Flugel (1982) suggested a range from shallow to deep burial origin. In the Alderson, however, spalling appears to have occurred early, before most cementation. Partially spalled ooids show infilling by radial rim cement and later are cemented by blocky pore filling cement.

Crushing is another common compaction feature in the Alderson and Greenville Formations. Most of the crushing involves thin ostracode and brachiopod shells. Ostracode valves are typically long, thin-walled forms that are broken in half, whereas brachiopod valves tend to be more fragmented. The timing for the crushing of shell material is uncertain.

PRESSURE SOLUTION

Pressure solution is the process by which a rock or mineral grain undergoes dissolution because static pressures (overburden or tectonic) surpass the hydrostatic pressure of the interstitial fluids. Attempts to classify pressure solution have taken two directions: 1) general pressure solution (Trurnit, 1968; Wanless, 1979), and 2) stylolites (Park and Schot, 1968; Logan and Semeniuk, 1976). In this study, pressure solution is divided in two types: 1) grain-to-grain pressure solution and 2) stylolitization.

Grain-to-grain pressure solution deals only with dissolution between neighboring grains. When grains come into contact with each other, pressures are exerted on them in opposing directions parallel to the direction of stress. Stress is focused on the point of contact between neighboring grains and dissipates away from this point. According to Reicke's Law, mineral grains that are under stress have

higher solubilities and will thus be dissolved preferentially. Dissolution occurs at the grain contact and the ions in solution migrate to areas of less stress to precipitate there as cement.

Trurnit (1968) found that grains of equal pressure solubilities and equal curvature of radii have plane or straight contacts with differentiated or sutured boundaries. Grains that have unequal pressure solubilities and unequal curvature of radii have curved contacts with smooth boundaries.

Grain-to-grain pressure solution may occur between uncemented grains or after formation of rim cements, but not after formation of pore filling cements (Bathurst, 1971). After radial rim cement has formed, the grains still have some ability to move and readjust. The result is interpenetration of grains with an intervening layer of cement.

Stylolites are pressure solution features that involve the whole rock. Two types of stylolites may occur: those parallel to bedding and those at a high angle to bedding (transverse stylolites). Stylolites which parallel bedding are formed due to stresses applied by overburden and may be diagenetically early to late (Park and Schot, 1968). Transverse stylolites are late secondary features, originating as joints formed at high angles to bedding and later transformed into stylolites. Rigby (1953) interprets these as a vector of load acting laterally and downward along arched strata.

In the Alderson Formation, pressure solution is a common feature. It occurs as both grain-to-grain pressure solution and as stylolites.

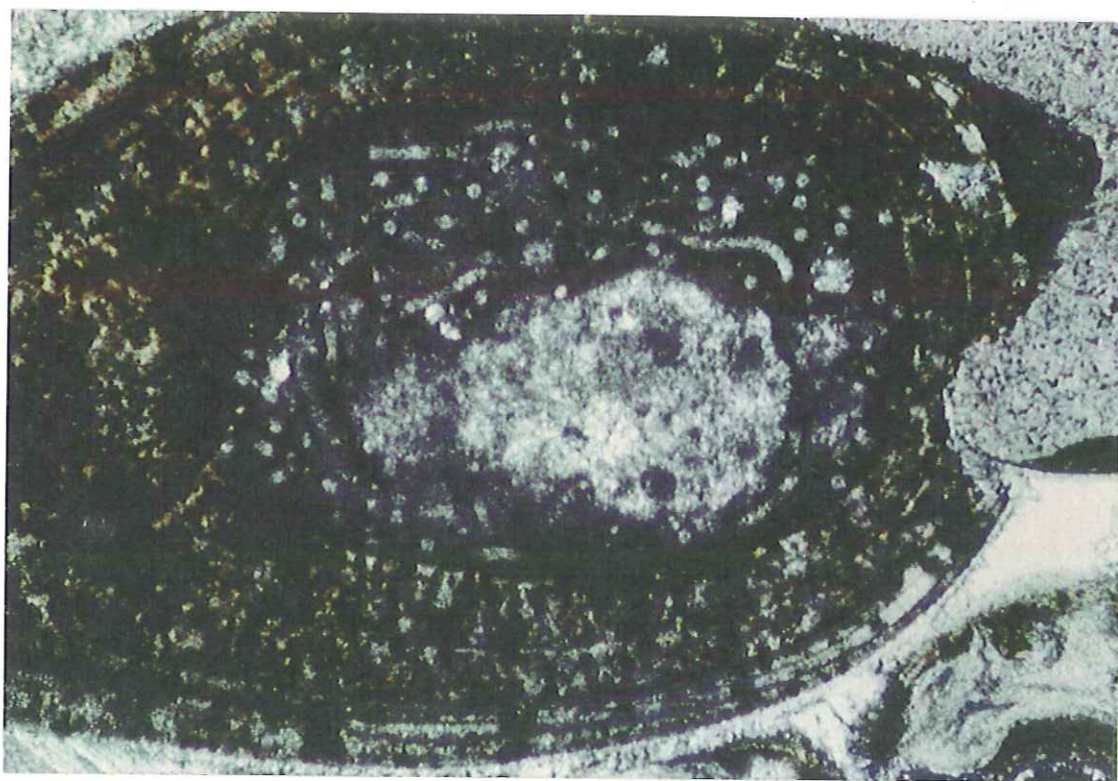


Figure 15. Ooid with algal core showing grain-to-grain pressure solution with echinoderm plate at upper right (63x).

Grain-to-grain pressure solution occurs mostly as sutured boundaries between grains without an intervening cement layer (Fig. 15). Occasionally pressure solution between radial rim cemented grains can be seen. These have smooth, curved boundaries with an intervening cement layer. The absence of a cement layer between grains indicates that most grain-to-grain pressure solution occurred early, whereas grain-to-grain pressure solution with an intervening cement layer occurred later but before syntaxial and pore filling cements. Stylolites occur as 1) sutured boundaries between bioclastic grains that form a sutured mosaic, 2) wavy sutured boundaries between and parallel to limestone beds, 3) stylonodular structures, and 4) irregular transverse boundaries. The timing of stylolitization in the Alderson Formation is uncertain.

FRACTURES

Fractures that have been healed by calcite and, rarely, by other minerals are very common in the Alderson Formation. Experimental deformation of carbonates by Hugman and Friedman (1979) showed that the origin and behavior of fracturing is controlled by the percentage of spar, micrite, and dolomite in the rock. Other factors that contribute to fracturing include grain size and abundance of microfractures.

SUMMARY

The diagenetic sequence interpreted for the Alderson and Greenville Formations is summarized in Table 1. Diagenesis within these sediments began shortly after deposition in the marine environment with micritization of carbonate allochems. Compaction, both mechanical compaction and grain-to-grain pressure solution, and initial cementation by radial rim cements also began soon after deposition. With subsequent burial, other diagenetic processes began, including continued mechanical compaction and stylolitization, formation of syntaxial and pore filling cements, and dolomitization and possible calcitization of dolomite. Continuation of burial resulted in continued stylolitization and compaction of shaly units which may have influenced new dolomitization. Local and areal tectonics resulted in fracturing and faulting of rock units and the formation of transverse stylolites. The timing of formation of microspar, gypsum, pyrite, hematite, and silicification is uncertain, although they appear to have formed early in the diagenetic sequence.

	SYNDEPOSITION	EARLY	BURIAL	LATE
MICRITIZATION		██████████		
COMPACTION		██████████	██████████	██████████
GRAIN-TO-GRAIN PRESSURE SOLUTION		██████████	██████████	██████████
RADIAL RIM CEMENT		██████████		
STYLOLITIZATION			██████████	██████████
SYNTAXIAL CEMENT			██████████	
PORE FILLING CEMENT		██████████		
DOLOMITIZATION			██████████	██████████
CONE-IN-CONE			██████████	██████████

Table 1. Generalized sequence of diagenetic events.

FACIES

INTRODUCTION

Four facies were recognized from 330 thin sections from the Alderson Formation. A data matrix (330 samples x 7 variables) was generated for multivariate analysis by counting 300 counts per thin section. Seven variables (spar cement, micrite, ooids, peloids, intraclasts, fossils and total siliciclastics) were chosen for this analysis. All fossils, including echinoderms, bryozoans, brachiopods, bivalves, gastropods, ostracodes, foraminifers, trilobites, algae, and sponge spicules, were grouped together for statistical purposes. Most fossils are represented by the echinoderms, bryozoans, and brachiopods. Remaining fossil groups account for small percentages, generally less than 1%. Such small percentages are outweighed by the larger groups and are not useful for statistical interpretations. Minor fossils which periodically occur in higher percentages were used for environmental interpretations and are discussed in descriptions of the individual facies. All siliciclastic components were grouped together for the same basic reasons. Siliciclastics, including quartz, feldspar, metamorphic rock fragments, mica, and siliciclastic mud (clay and fine silt), are composed predominantly of quartz and siliciclastic mud. These two occur together in varying amounts, with few "pure" sediments. Any large percentages of normally minor siliciclastic components were used to interpret environment and

provenance, and they will be discussed in descriptions of the individual facies.

Because these samples were not selected at random, nor are the variables normally distributed, the non-parametric technique of cluster analysis was applied. This technique was chosen because 1) it is non-parametric, 2) it is able to analyze large numbers of samples and variables, and 3) it has been used successfully in similar previous studies (Purdy, 1963; Behrens, 1965; Bonham-Carter, 1965; Smosna and Warshauer, 1978, 1979).

Clustering of point count data was accomplished by using Ward's minimum variance hierarchical cluster analysis method (Q-mode) from SAS Institute (Statistical Analysis System). Ward's method uses the sum of squares between the individual clusters for hierarchical clustering. It tends to join clusters within a small number of observations and so is biased toward producing clusters with roughly the same number of observations (SAS Institute, 1984). The resulting dendrogram was too large for inclusion in this paper.

Twenty-three clusters were chosen by plotting the computed Cubic Clustering Criterion (CCC) versus the number of clusters (one-tenth the total number of samples). Each cluster was characterized by determining the two or three important variables that separate it from other clusters. The twenty-three clusters were then grouped into four larger groups (facies), including twelve sub-facies, on the basis of interstitial matrix composition. The ranges and averages for the variables were computed and are arranged by facies in Table 2.

TABLE 2
AVERAGES FOR CLUSTERING CONSTITUENTS

	SPAR	MIC/DOL	OO	PEL	INT	FOSSIL	SILIC
FACIES I (undivided)	0.60	0.62*	-----	0.02	-----	0.53	98.27
FACIES II							
IIA	4.60	-----	0.59	0.58	1.32	17.29	71.89
IIB	16.68	36.16	0.33	2.46	0.44	2.94	40.08
IIC	9.45	37.60*	4.90	3.81	0.18	19.60	26.23
OUTLIER 1	2.28	3.08**	0.36	-----	3.58	66.01	24.71
FACIES III							
INTRACLASTIC	3.31	4.80	4.90	4.37	58.87	13.48	7.37
OOLITIC	19.68	1.38	47.78	1.52	5.10	20.50	2.75
BIOCLASTIC	19.54	7.03**	7.54	4.02	4.45	53.17	2.10
FACIES IV							
PELMICRITE	0.47	11.10	-----	77.78	0.87	9.30	0.32
BIOMICRITE	1.76	50.55	4.98	9.54	6.09	21.65	3.34
MICRITE	0.15	88.82*	0.19	0.54	1.03	4.31	4.22

* Percentage contains both micrite and dolomite

** Percentage is exclusively dolomite

GREENVILLE FORMATION FACIES

The Greenville Formation, as described by Reger (1926), "is a black, fissile, and carbonaceous deposit belonging, when present, between the Alderson and Union Limestones but being quite lenticular and largely confined to a portion of Monroe County where it sometimes reaches a thickness of 100 feet, and containing marine fossils among which there are pelecypods, cephalopods, and gastropods." This is an accurate description of the Greenville Formation for the type location and vicinity, but in other locations it has been described somewhat differently. Price (1929) and Price and Heck (1939) reported brown, calcareous shales from Greenbrier and Pocahontas Counties, West Virginia; but it is not known for certain if these are the Greenville Formation. These shales are more calcareous than the type Greenville and contain a much more diverse and normal marine fauna, similar to that of the Alderson Formation. Hence, these brown shales should probably be placed with the Alderson Formation. Thin, yellow to yellow-green, very fossiliferous, calcareous shales described by Price and Heck (1939) and Price (1929) as the Greenville Formation are also included with the Alderson Formation.

The Greenville Formation is a fissile, largely non-calcareous, dark gray to black shale that crops out from just north of Alderson, southward across Monroe County. The sparse fauna, which includes species of the bivalve Caneyella and an orthocerocone cephalopod Orthoceras (Reger, 1926), suggests a restricted marine environment.

Bioturbation, occurs in only one horizon near the base of the Alderson Bridge Section in the form of finger-like burrow fillings, up to 10cm in length with a tapered lower end. These burrows may be horizontal, vertical, or inclined.

Above the burrowed horizon there are regularly spaced micrite/microspar layers. They are up to 2.5cm thick, unfossiliferous, tabular to nodular, laterally continuous layers which have a vertical spacing of 0.30 to 0.45 meters. Carbonate layers and burrowed zones may represent influx of normal, oxygenated marine water into a largely anoxic bottom environment of the type Greenville Formation.

At Greenville, Monroe County, in both the Type and West sections, the Greenville Formation is composed totally of black shale (Fig. 16). These sections contain the thickest accumulation of Greenville sediments in the outcrop area. The fauna here contains Naiadites (Bivalvia) and Lingula (Brachiopoda) (Reger, 1926). The presence of Lingula suggests a shallow water, near shore, restricted environment. Occasionally there are tan to gray layers within the black shale which indicate periodic influxes of well-oxygenated water.



Figure 16. Outcrop of Greenville Formation (Greenville West section).

ALDERSON FORMATION FACIES

FACIES I

Facies I is strictly siliciclastic, facies, but has a highly variable mineralogical composition. It is the largest of the twenty-three clusters, representing 19.2% of all samples; and it is distinguished by total per cent siliciclastics, not by mineralogy or grain size. Included in this cluster are sandstones, siltstones, and mudstones of the Alderson Formation, and shales of the Greenville Formation. This cluster is characterized by 98.3% siliciclastics and minor sparry calcite (0.6%), dolomite (0.6%), and fossils (0.5%). Other rare constituents include micrite (0.04%) and peloids (0.02%). Most samples in this facies are categorized as mudstones, followed by siltstones and sandstones.

Mudstone sub-facies

Mudstones are composed of a mixture of clay and very fine silt-sized material with varying amounts of medium to coarse silt. Dominant minerals are illite and chlorite (identified from x-ray diffractograms) and quartz. Micas and feldspars are rare. Bioturbation is the predominant sedimentary structure, although there is minor planar lamination of quartz silt.

Siltstone sub-facies

Siltstones are composed of fine to coarse silt with minor clay and organic material, and they may be thinly bedded (up to 0.2m thick) or laminated (laminations up to 3.0mm thick). The silt is composed of angular to sub-rounded quartz, feldspar, rock fragments, and micas. Larger quartz has straight extinction, with few strained and polycrystalline grains. Feldspars are represented by plagioclase in the range of low labradorite to low bytownite. These are generally unaltered and always display albite twinning. Micas are predominantly muscovite with some sericite, and they are oriented parallel to bedding, bent around larger grains, or are randomly oriented due to bioturbation. Organic material is in the form of black amorphous lenses and plant fragments which occur in distinct laminations with micaceous material. The plant fragments are conspicuous in hand samples where they occur as randomly oriented or current oriented leaf and stem parts. The mica and organic laminations (up to 0.1mm thick) create cleavage planes in the siltstones. Sedimentary structures are highly varied and include macroscopic ripples and crossbeds, microscopic crossbeds, graded bedding, planar laminations, and bioturbation structures. Diagenesis included only porosity reduction, caused by grain-to-grain pressure solution and very minor sparry calcite or dolomite cementation.

Sandstone sub-facies

Sandstones include quartz arenites, lithic arenites, and quartz and lithic wackes, but they account for only a small percentage of the facies. Quartz arenites and lithic arenites resemble one another in outcrop and in hand sample. They are typically fine to medium grained, tabular, and thin bedded with shaly stringers between the beds. Sedimentary structures include wavy bedding and cross bedding in outcrop, and graded bedding, planar bedding, and cross bedding in thin section. Diagenesis is predominantly porosity reduction due to grain-to-grain pressure solution and/or dolomite cementation.

Wackes differ from arenites in color, texture, bedding, and lithology. Wackes are distinguishable in hand sample by a yellowish color, an abundance of clays and micas in the matrix, and their porous nature. They are uniform, fine to medium grained, thicker bedded than arenites. Sedimentary structures are lacking due to abundant bioturbation.

Environments of deposition

Sandstones, siltstones, and mudstones of this diverse facies represent the most shoreward facies of the Alderson Formation. They formed in shallow marine subtidal to marine/fluviol intertidal environments. These sediments were deposited under differing hydrodynamic conditions within the same broad nearshore environment.

Due to the lack of characteristic sedimentary evidence, a definitive depositional environment is not proposed. Although exact depositional environments are unclear, some general hydrodynamic conditions may be assumed.

Sandstones were deposited in the highest energy environments as evidenced by larger grain sizes, megascopic cross bedding, and graded bedding. Arenites were deposited in higher energy systems than wackes because they lack the fine silt and clays that predominate in wackes. Sandstones may represent fluvial to marine tidal channel, beach, and/or bar sands.

Siltstones were deposited in intermediate energy conditions within shallow sub-tidal to intertidal environments. This is evidenced by smaller grain size, abundance of clays, presence of ripples, small scale cross beds, abundant plant material, and lamination of the sediments. These may represent tide-influenced clastics analogous to those of the North Sea (Reineck, 1967).

Mudstones, the most abundant sediment type in facies 1 were probably deposited in low energy, sub-tidal marine environments, basinward of the siltstones. Lack of sedimentary structures indicates a low energy environment, and the ubiquitous burrows indicate that there was abundant feeding activity by mobile organisms. The absence of any significant fauna indicates this environment may have been, for the most part, inhospitable for sessile fauna.

FACIES II

Facies II is composed of mixed siliciclastic-carbonate sediments representing a transition zone between the shoreward siliciclastics of facies I and the basinward carbonates of facies III and IV. Facies II contains nine of the twenty-three clusters, and can be divided into three sub-facies on the basis of siliciclastic, fossil, carbonate mud, and dolomite content.

Sub-facies IIA

Sub-facies IIA contains three clusters and accounts for 15.2% of all samples. It is composed of siliciclastic mudstones and minor fine sandstones with varying amounts of fossils, other carbonate allochems, and carbonate cement. Siliciclastic material composes 81.5% to 59.8% of the sediment and is dominated by mud (clay to fine silt-sized material), medium silt- to medium sand-sized quartz, plagioclase feldspar, micas, and minor metamorphic rock fragments. Quartz is sub-angular to sub-rounded and has straight to slightly undulose extinction. X-ray diffractograms show that clays are predominated by illite, with minor amounts of chlorite and montmorillonite.

Fossils compose 2.2% to 37.1% of the sediment and are predominantly bryozoans. Echinoderms and brachiopods are secondary in abundance, and minor fossils include foraminifers, ostracodes, and trilobites. Bryozoans show signs of abrasion and fragmentation,

whereas brachiopods, foraminifers, and ostracodes are all well preserved and appear to be indigenous. Other carbonate allochems are absent or minor in abundance; ooids (0-1.5%), peloids (0.2-1.3%), and micritic intraclasts (0-3.4%). Ooids and intraclasts probably represent influx during storm activity.

The orthochemical carbonate component consists of scattered patches of sparry calcite and microspar in mudstones (0.2-12.8%) whereas in fine sandstones the cementing agent is sparry calcite and dolomite occurring as blocky pore filling and poikilotopic cements. Most primary sedimentary structures have been destroyed by extensive bioturbation, resulting in an unsorted sediment. Structures that survived bioturbation include minor graded bedding and laminations of alternating fine silt/clay and coarse silt/fine sand. Small, low angle ripple cross bedding and graded bedding occurs in fine sandstones.

Sub-facies IIB

Sub-facies IIB contains three clusters and accounts for 3.6% of all samples. It is composed of transition sediments from calcareous mudstones/sandstones to silty, argillaceous micrites. Siliciclastic content ranges from 31.0% to 55.9% and is dominated by muds (clay to fine silt-sized material) with minor fine to medium sand. The orthochemical carbonate component ranges from 41.9% to 66.6% and is composed of micrite, microspar, and sparry calcite cement.

Calcareous mudstones contain 41.9% micrite/microspar and 55.9% siliciclastics. Minor constituents include 1.7% sparry calcite cement, 1.3% intraclasts, and 0.5% fossils. Bryozoans, largely unabraded, are the only fossils present. Intraclasts are composed of matrix material and are interpreted as rip up clasts. The orthochemical carbonate is evenly dispersed within the siliciclastic matrix and bioturbation has destroyed much of the original sediment lamination.

Silty, argillaceous micrites average 33.3% siliciclastics and 66.6% micrite/microspar. No carbonate allochems were observed in this sub-facies. Siliciclastics are clays and silt-sized quartz randomly dispersed within the micrite or sometimes concentrated in planar laminations. Some of the original texture has been destroyed by bioturbation.

Calcareous sandstones contain 31.0% siliciclastics and 48.4% sparry calcite cement. Minor constituents include 1.0% ooids, 7.4% peloids, 8.4% fossils, and 1.4% dolomite. Siliciclastics are predominantly quartz with minor plagioclase, mica, and organics. Quartz sand is fine to coarse, sub-angular to sub-rounded, and has straight to slightly undulose extinction. Peloids and fossils are the predominant carbonate allochems. Fossils are mostly bivalves and brachiopods, with minor foraminifers and ostracodes. Bioturbation is rare and sedimentary structures are predominated by graded bedding and small scale cross bedding.

Sub-facies IIC

Sub-facies IIC contains two clusters and accounts for 3.6% of all samples. It is composed of fossiliferous, argillaceous to sandy dolostones and is characterized by 6.6% to 32.7% fossils, 19.3% to 33.2% siliciclastic mud and sand, and 30.8% to 40.3% dolomite. Minor constituents include sparry calcite cement (5.8-13.2%), micrite (0.1-0.7%), ooids (1.5-8.3%), peloids (0.4-7.2%) and intraclasts (up to 0.3%).

Fossils are mostly bryozoans and echinoderms, with minor brachiopods, foraminifers, trilobites, and bivalves. Brachiopods are the most diverse of the faunal groups. Most fossils are abraded and broken, although occasional whole, articulated brachiopods are found.

The siliciclastic component is composed of clay-sized material with lesser silt- and sand-sized material. The clay fraction is predominantly illite with minor chlorite, whereas the silt and sand fraction is predominantly quartz. Quartz is sub-angular to angular with many elongated grains that have straight to slightly undulose extinction, which is typical of schistose and stretched metamorphic quartz (Folk, 1974b).

Dolomite occurs mostly as idiotopic-P and idiotopic-E dolomite, but xenotopic-A dolomite does occur in quartz-rich zones with minor sparry calcite. Idiotopic dolomites are cloudy and inclusion rich. In some cases, dolomite rhombs have been calcitized. The origin of idiotopic dolomite is not known, but xenotopic dolomite appears to

have been a primary pore filling cement.

Sedimentary structures are largely bioturbation in the muddy sediments, which are generally poorly sorted. Sandy zones have graded bedding, small scale ripple cross bedding, and no bioturbation.

Outlier 1

Outlier 1 contains one cluster, which is composed of very fossiliferous mudstones and constitutes 1.8% of all samples. This cluster is characterized by 66.0% fossils and 24.7% siliciclastics. Minor constituents include 3.4% intraclasts and 2.35% sparry calcite.

Fossils include bryozoans and echinoderms with minor brachiopods, all of which show signs of abrasion and transport. Intraclasts are micritic and contain fossil material. The siliciclastic component is predominantly a mud matrix composed of clays, mica, and silt-sized quartz. The remaining siliciclastic material is composed of coarse silt and fine sand-sized quartz and plagioclase. These grains are sub-rounded to rounded, poorly sorted, and randomly dispersed in the mud matrix. Sedimentary structures include planar laminations and minor burrows.

Environment of deposition

The mixed siliciclastic-carbonate transition facies is one of highly variable composition. Because this is a transition sequence,

sediments range from predominantly siliciclastic (muds and sands) to predominantly carbonate (micrites and dolomites).

Overall, this facies is mostly fine grained muds, either siliciclastic or carbonate, reflecting a low energy environment in which currents were gentle enough not to disturb or winnow fine particles and to allow formation of laminated sediments. Bioturbation is ubiquitous and, in most cases, has destroyed the original laminated nature of these sediments, resulting in poorly sorted, highly bioturbated muds. Organisms indigenous to this facies were brachiopods, foraminifers, ostracodes, and some bivalves. Bryozoans and echinoderms, based on abrasion and breakage of skeletal remains, appear to have been introduced by storm activity. Salinities ranged normal to hyposaline, probably due to fluvial mixing, resulting in the presence of some restricted faunas. Sandstones and siltstones reflect somewhat higher energy levels, as evidenced by the absence of mud, larger grain size, graded and cross bedding, and high percentage of abraded and broken fossils.

The environment of deposition of facies II may include both a tidal flat and a lagoon. Energy levels were low throughout, was shallow, salinities ranged from normal marine to brackish, and carbonate content increased basinward. Benthic faunal communities became more diversified basinward and were widespread, as evidenced by the ubiquitous bioturbation. Typical carbonate and siliciclastic tidal flat sedimentary structures and diagenetic features are lacking. Simonson and Walker (1984) indicated that mixed

carbonate-siliciclastic tidal flat complexes are greatly affected by argillaceous content. Clays would retard sediment stabilizers such as early cementation, dolomitization, and algal mat development. Clays would also tend to hold water longer than pure carbonates, thus acting as a soft sediment longer and allowing for soft sediment deformation and diffuse burrowing.

Sub-facies IIA represents the most shoreward environment of this facies. It contains the highest siliciclastic content, lowest carbonate mud content, lowest proportion of carbonate allochems, and lowest fossil content. Sessile fauna were stressed by the influx of fine siliciclastics, possible lower salinities, and low current activities, all of which prohibited filter feeding epifauna. Mobile organisms were ubiquitous.

Sub-facies IIB represents a change to more normal marine, carbonate-rich waters resulting in sediments with subequal amounts of carbonate and siliciclastic muds. Current activity was still low, salinities closer to normal marine, and water depth was shallow. The absence of shelled fauna suggests that this environment was unsuitable for most sessile forms, although mobile forms were ubiquitous. This sub-facies is similar to shallow submerged mudflats. Sandstones of this sub-facies indicate slightly higher energy regimes in which muds have been winnowed, but micas and organic material have been retained. Energy levels were, however, sufficient to locally accumulate peloids and fossils.

Sub-facies IIC contains a high percentage of carbonate and low

percentages of siliciclastics. Its fauna is the most diverse in facies II with brachiopods being the most diverse faunal group. Water depths were at a maximum for the facies, salinities were normal to near normal, and current activity was mild.

Outlier 1 is an anomalous cluster which may represent the accumulation of shelled organisms due to storm or high current activity. This was deposited perhaps in the form of mounds or bars and was probably located in sub-facies IIA.

FACIES III

Facies III is composed of carbonate sands of varying composition representing a moderate to high energy depositional environment. This facies comprises three sub-facies: 1) intraclastic sub-facies (one cluster), 2) bioclastic sub-facies (four clusters), and 3) oolitic sub-facies (two clusters).

Intraclastic sub-facies

This sub-facies is characterized by 59.0% intraclasts, 13.5% fossils, 7.0% siliciclastics, 8.0% spar cement, and it represents 2.1% of all samples. Intraclasts are varied in composition including micrites, pelmicrites, biomicrites, oomicrites, and siliciclastic mudstones. Boundaries of the intraclasts may be sharp or they may resemble stylolitic pressure solution boundaries. Siliciclastic

material is composed of patches of silty mud or silt rich in quartz and mica. Fossils include bryozoans, echinoderms, and brachiopods. Sedimentary structures include graded bedding and minor bioturbation.

Bioclastic sub-facies

The bioclastic sub-facies is composed of poorly washed biomicrites, oobiosparites, biosparites, and peloid and ooid bearing biosparites. It represents 18.6% of all samples.

Poorly washed biomicrites contain sub-equal amounts of spar cement and micrite (6.6% and 7.0%, respectively) and 63.2% fossil material. Minor constituents include 1.7% ooids, 1.2% peloids, 2.7% intraclasts, and 3.3% siliciclastics. Fossils represent a normal marine fauna composed of bryozoans, echinoderms, brachiopods, thick shelled ostracodes, gastropods, bivalves, trilobites, and foraminifers. Most fossils are broken and abraded, implying transport and/or high energy conditions. Ooids and thick-shelled ostracodes indicate high energy conditions and were probably deposited into lower energy environments during storms. The original micrite matrix was partially winnowed leaving pore spaces for spar cement to form. These sediments were located on the distal fringes of the carbonate sand belt and represent a transition between facies III and facies IV.

Oobiosparites are characterized by 14.4% ooids, 10.5% intraclasts, 53.3% fossil material, and 13.0% spar cement. Minor constituents include 1.4% peloids and 0.7% siliciclastics. Ooids are

predominantly normal, exhibiting radial and/or tangential structures, which are typical of high energy conditions. Intraclasts are micritic and unfossiliferous to fossiliferous. Fossil material represents a normal marine fauna of bryozoans, echinoderms, and minor brachiopods, ostracodes, and trilobites. All fossil material shows signs of breakage and wear due to transportation and/or high energy conditions. Ooids and intraclasts represent periods of environmental mixing possibly due to periodic storm conditions.

Biosparites, which form the bulk of the bioclastic sub-facies, are characterized by 58.6% fossil material and 26.3% spar cement. Minor constituents include 4.5% ooids, 3.1% peloids, 2.1% intraclasts, and 3.4% siliciclastics. Fossils include bryozoans, echinoderms, and brachiopods with minor bivalves, gastropods, trilobites, ostracodes, foraminifers, and rare vertebrate material. This fauna is the most diverse within Alderson sediments, but it is predominated as all other sediments, by bryozoans and echinoderms. All fossil material shows breakage and abrasion due to the mobility of the sediment. Foraminifers, ostracodes, and some bivalves and brachiopods are thin-shelled forms indicative of quiet water environments. These fossils were transported into the higher energy carbonate sand environment and mixed these taxa with more robust forms. Ooids include normal and superficial types. Peloids and intraclasts are both micritic, but intraclasts are larger and contain quartz silt. Siliciclastics are rounded to sub-rounded, coarse silt- to sand-sized quartz and rare plagioclase grains that are randomly dispersed in the

sediment.

Peloid and ooid bearing biosparites average 37.0% fossil material, 32.0% spar cement, 10.4% peloids, and 9.6% ooids. Minor constituents include 2.4% intraclasts, 0.9% siliciclastics, and 6.5% micrite. Fossils are predominantly echinoderms and bryozoans with fewer brachiopods, bivalves, gastropods, foraminifers, and trilobites. All fossil material is abraded or broken, indicating transport and/or high energy conditions. Ooids occur as both normal and superficial types. The type of nucleus seems to have influenced the type of ooid formed. Normal ooid nuclei are small and contain fossil fragments, quartz grains, or are unidentifiable; whereas superficial ooid nuclei contain larger fossil fragments such as echinoderm plates. Both types of ooids attain the same maximum size. Peloids contain both pellets and totally micritized fossil material in which the morphology is still discernable. Intraclasts are larger than peloids and may be composed of micritic or mixed sediments. Peloids represent quiet water environments, whereas ooids and abraded fossils indicate more agitated water. The presence of interstitial micrite also indicates quiet water conditions. The sediments are, however, grain supported and interstices are occupied by sparry calcite cement. Interstitial micrite was, therefore, either present as a principal component of the sediment and subsequently winnowed away, or was washed in secondarily. This sediment may result from environmental mixing and inadequate washing, or it may be the product of mixing and deposition in a localized area of lesser current activity, such as in troughs between

energy conditions, probably represent the distal fringe of this sand belt.

FACIES IV

Facies IV is composed of micritic sediments of varying composition that represents a quiet, shallow (below wave base), carbonate mud environment. It can be divided into three sub-facies: 1) pelmicrite (one cluster), 2) biomicrite (three clusters), and 3) micrite (two clusters).

Pelmicrite sub-facies

Pelmicrites compose 2.7% of all samples and are characterized by 78.0% peloids, 11.0% micrite, and 9.0% fossil material. Peloids are probably fecal in origin and, judging from the low abundance of shelled organisms, were produced by soft bodied organisms. An inorganic origin is doubtful because of their uniform size and shape. Peloids may occur as individual grains, or they may be fused to form a micrite-like matrix. Larger peloids are partially to totally micritized oncolites, suggesting exposure on the sea floor for long periods of time. Faunal diversity is low and predominant types are endothyrid foraminifers and calcareous sponge spicules. Other faunal elements include algae (oncolites), thin-shelled brachiopods and ostracodes, and rare echinoderms and bryozoans. Calcareous sponge

spicules, the only identifiable sparry remains, are prevalent in all samples, and endothyrid foraminifers attain their maximum abundance in this sub-facies.

Biomicroite sub-facies

The biomicroite sub-facies is composed of intrabiomicroites, biomicroites, and oobiomicroites which collectively represent 8.4% of all samples.

Intrabiomicroites are characterized by 53.2% micrite, 11.2% intraclasts, and 29.7% fossil material. Minor constituents include 2.0% sparry calcite, 1.0% peloids, and 2.1% siliciclastics. The micrite matrix includes both micrite and microspar, which were grouped together for clustering purposes due to their similar genesis. Patches of sparry calcite occur as geopetal fabrics and also as possible "birdseye" structures. Faunal diversity is moderate to moderately high and fossils include echinoderms, bryozoans, and brachiopods with minor foraminifers, gastropods, and bivalves. Some whole fossils show signs of abrasion. Intraclasts are micritic in composition, rounded, and contain few fossils. Siliciclastics occur as quartz silt randomly dispersed in the micrite matrix.

Biomicroites are characterized by 66.0% micrite, 19.5% fossil material, and 4.2% siliciclastics. Minor constituents include 0.9% sparry calcite, 1.9% ooids, and 0.7% peloids. Faunal diversity is low to moderate and fossils include bryozoans, echinoderms, thin-shelled

brachiopods, bivalves, ostracodes, and foraminifers. Foraminifers, which are most abundant, include endothyrid, calcitornellid, and diplosphaerinid forms. There is usually only one type in any particular sample. One sample is predominated by productid brachiopod spines and calcitornellid foraminifers, whereas another sample is predominantly endothyrid foraminifers and thin-shelled ostracodes. Siliciclastics in this sub-facies are silt and fine sand-sized quartz, plus minor clay and mud mixed with the micrite. Burrows, which concentrate fossils and pellets, occur in most samples.

Oobiomicrites are characterized by 32.5% micrite, 13.0% ooids, and 15.7% fossil material. Other constituents include 7.8% peloids, 6.1% intraclasts, 2.3% sparry calcite, and 3.7% siliciclastics. Faunal diversity is moderate and fossils include echinoderms, brachiopods, trilobites, foraminifers, gastropods, and ostracodes. Brachiopods and ostracodes include both thick and thin-shelled forms. In one sample, thin-shelled forms occur in micritic laminae whereas the thick-shelled forms occur in ooid laminae. This indicates mixing of two totally different energy regimes. Ooids are mostly normal and well formed, but some superficial ooids are present. Intraclasts are micritic and usually contain fossils. Siliciclastic material occurs as silt to coarse sand-sized quartz dispersed within the micrite matrix. Peloids may be fecal in origin and may occur as distinct grains, but they also constitute a large part of the matrix.

Micrite sub-facies

The micrite sub-facies, composed of dolostones and micrites, represents 17.1% of all samples. It was deposited on a carbonate ramp in deeper, quiet water sub-tidal environments. Despite the fact that dolomite was not one of the variables used in clustering, these samples clustered well and do form a distinct lithologic group. The clustering was affected by the low abundance of fossil and siliciclastic material, the virtual absence of spar and micrite, and high dolomite percentages.

Dolostones are characterized by 85.6% dolomite, 4.9% fossil material, and 4.3% siliciclastics. Minor constituents include 0.2% sparry calcite, 1.2% micrite, 0.1% ooids, and 1.3% intraclasts. These minor constituents occur sporadically, as only one sample contains micrite, one contains ooids, and three contain intraclasts. The dolomite matrix is made up of idiotopic-S and xenotopic-A dolomite of variable grain size. In most samples, silt and clay-sized siliciclastics are interspersed within the dolomite. Two samples are totally dolomite and two are totally dedolomite. Excluding the pure dolomites and dedolomites, all samples contain minor quartz silt or fine sand, clay minerals, and mica. Quartz is rounded, well sorted, and evenly dispersed throughout the matrix. Faunal diversity is low and the fauna is predominated by bryozoans and echinoderms with minor brachiopods and foraminifers. The most important diagenetic process was the formation of dolomite. Its sediment precursor was micritic mud that was dolomitized easily. Most samples were subjected to

bioturbation which may have enhanced dolomitization by providing porous conduits for dolomitizing fluids (Choquette and Steinen, 1980). The second most important diagenetic effect was calcitization of dolomite, resulting in formation of dedolomite. All sedimentary structures except burrows have been destroyed by dolomitization. Burrows occur as lense-shaped dark patches and circular patterns of quartz grains.

Micrites are characterized by 88.8% micrite and/or microspar. Other constituents include 0.3% ooids, 1.5% peloids, 0.8% intraclasts, 3.7% fossil material, 0.1% spar cement, and 4.1% siliciclastics. Micrites are relatively pure but are slightly contaminated with siliciclastics, predominantly quartz, and organics. Siliciclastics are dispersed throughout the micrite, although some laminations and clotting occur. Organic material occurs as dark lenses parallel to bedding, with some hematite staining and some individual hematite (after pyrite) framboids. Faunal diversity is low and fossils include bryozoans, echinoderms, thin-shelled brachiopods and ostracodes, calcareous sponge spicules, and foraminifers. Fossils are randomly dispersed throughout the micrite, except where they have been concentrated by bioturbation. Sedimentary structures are predominantly burrows and planar laminations of siliciclastics and organics.

Environments of deposition

Pelmicrites are characteristic of carbonate deposition in quiet water, below wave base with semi-restricted to restricted circulation. Their probable environment of deposition is, therefore, one of restricted circulation located on a ramp shoreward of the carbonate sands. The Alderson pelmicrites are similar to pelletal muds of the Great Bahama Bank (Purdy, 1963). Water depth was greater than that for the higher energy, sparry sediments, as indicated by the presence of interstitial micrite, and current action was evidently not strong enough to winnow the carbonate mud. The types of organisms found indicate a quiet water, possibly semi-restricted to restricted environment. Other parts of this sub-facies were even more restricted as indicated by very low diversity and very high predominance by a limited number of genera.

The biomicrite sub-facies represents a quiet water, open marine environment located below wave base, and basinward of the carbonate sand facies. Intrabiomicrites represent a well oxygenated, open marine environment with mild current activity. This is evidenced by moderate to moderately high faunal diversity. Rounded micritic clasts may have been ripped up and redeposited as the result of storm activity, which may also be the source for some fossil and siliciclastic material.

Low diversity and high faunal predominance indicate, perhaps, a deeper water environment. The lack of bryozoans and echinoderms

indicates that the bottom conditions may not have been conducive to filter feeding and attaching organisms. Low current activity may have brought little oxygenated water and nutrients to these organisms, or carbonate mud may have choked their feeding structures. Active feeding and grazing by soft-bodied and mobile organisms is indicated by the abundance of fecal pellets and bioturbation.

Abundant, well-formed ooids of the oobiomicrorites may be the result of sediment mixing during storms. Ooids were probably formed on the ooid shoals of facies III, and then redeposited downslope in quieter, deeper micrite facies during storms.

Sediments of the micrite sub-facies average 85.6% micrite or 88.8% dolomite. Because dolomite is considered to be a diagenetic mineral that forms in a variety of ways, it is not useful as an indicator of depositional environment. Dolomite occurs as an interlocking network of small crystals containing abundant bioturbation structures, which suggests that the sediment precursor was micrite.

The abundance of micrite and absence of sparry calcite indicates an environment of low energy below wave base. Sparsity of epifaunal and infaunal taxa suggests restriction of water circulation, or that the carbonate mud substrate was not suitable for many marine organisms such as mollusks, brachiopods, and echinoderms. Sponges and several types of foraminifers were the only abundant organisms. Such forms probably preferred the quiet, deeper water environment and carbonate mud substrate.

Typical environments for micrite deposition are moderate to deep waters or restricted lagoons located peripheral to some type of barrier. In the case of the Alderson Formation, there is no prominent barrier. Therefore Alderson Formation micrites probably accumulated offshore in the deeper part of the ramp.

DEPOSITIONAL MODEL

Four facies, representing distinct depositional environments, have been identified in the Alderson and Greenville Formations of southeastern West Virginia. These formations represent siliciclastic to carbonate sediments deposited on a homoclinal ramp (Fig. 17).

A ramp is defined as a gently sloping platform (generally less than 1°) that extends basinward without a pronounced break in slope (Ahr, 1979). Ramps differ from rimmed shelves in that: 1) higher energy sediments are deposited at the nearshore zone and pass downslope (basinward) into deeper water low energy sediments, whereas in rimmed shelves, high energy sediments occur far from shore and low energy sediments occur nearshore (Ahr, 1973; Read, 1982); 2) continuous reef trends are absent and carbonate buildups are separate and discrete; 3) ramps are continuous, gently sloping features whereas rimmed shelves contain an abrupt break in slope at the shelf edge; 4) ramps generally develop at times of tectonic or climactic crises during which reef formers are poorly preserved (James, 1979); 5) ramps generally lack significant gravity flows and slumps in deeper water sediments (Read, 1982); and 6) ramps are located well landward of the continental-ocean crust boundary on continental margins, on underthrusting continental crusts in foreland basins, or in continental interiors (Read, 1985).

The siliciclastic facies is composed of sandstone, siltstone, and mudstone sub-facies. These are interpreted as the most shoreward

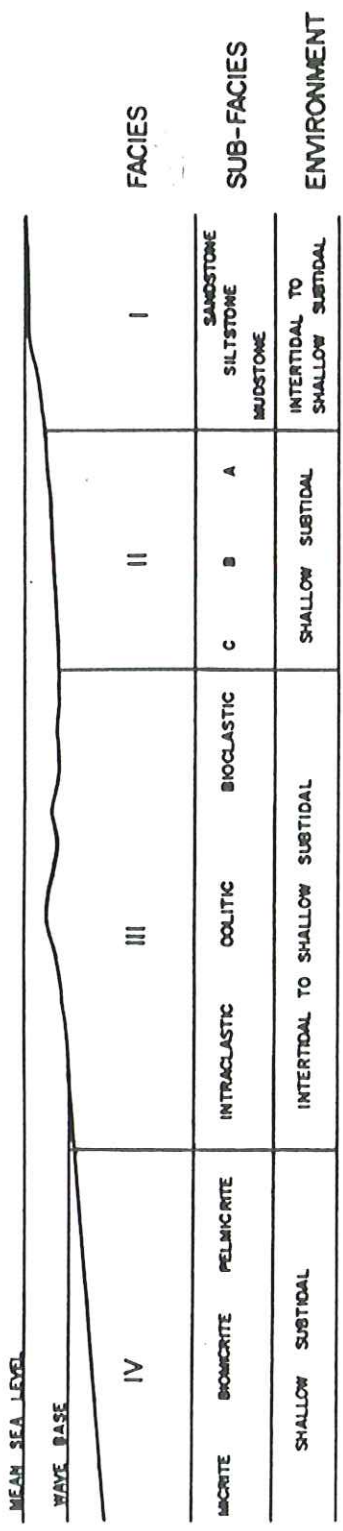


Figure 17. DEPOSITIONAL MODEL FOR THE ALDERSON FORMATION

facies, deposited in shallow, high to low energy conditions. Due to a lack of characteristic sedimentologic and diagenetic evidence, definitive depositional environments are not proposed. These may, however, represent tidal flat environments similar to those of the North Sea.

The mixed carbonate-siliciclastic sediments are interpreted as shallow, generally low energy, nearshore deposits representing a transition from siliciclastic to carbonate sedimentation within tidal flat or lagoonal environments. Carbonate content increases basinward, as does fossil content. Typical tidal flat characteristics are absent due to the clay content (Simonson and Walker, 1984).

The carbonate sand facies is composed of intraclastic, bioclastic, and oolitic carbonate sand sub-facies representing shallow (subtidal to intertidal), high energy sediments. These are interpreted as coalescing sand bars, shoals, and sheets forming a highly mobile carbonate sand environment.

The micritic facies is composed of pelmicrite, biomicrite, and micrite (including dolostones) sub-facies. These sediments, which contain normal marine to restricted marine faunas, are interpreted as being shallow subtidal, quiet water environments similar to lagoonal sediments. They form the most basinward facies.

STRATIGRAPHY

OUTCROP ANALYSIS

The generalized outcrop stratigraphy of the Alderson and Greenville Formations was obtained by measuring sections throughout the Greenbrier Group outcrop belt in Mercer, Monroe, and Greenbrier Counties in West Virginia, and Giles County, Virginia. The Alderson Formation is lithologically very complex, whereas the Greenville Formation is more uniform.

To facilitate construction of a cross section and correlation of the outcrop data, minor lithologic variations were suppressed in favor of four larger lithologic groups: carbonate sand facies, micritic facies, mixed carbonate-siliciclastic facies, and siliciclastic facies (Plate I). These units were chosen on the basis of cluster analysis and hand sample description.

SUBSURFACE ANALYSIS

Subsurface stratigraphic analysis of the Alderson Formation was based on gamma-ray logs from selected wells (Plate II). All logs

were provided by the West Virginia Geological and Economic Survey. The purpose of this aspect of the study was to ascertain, if possible, the areal extent and lithologic character of the Alderson Formation west of the existing outcrop belt. The wells were selected to obtain uniform spacing.

Gamma-ray logs record the natural radioactivity of rock units. Such radioactivity is due to concentrations of radioactive isotopes in argillaceous minerals, feldspars, and organic material, and to naturally occurring radioactive minerals. It can be used to delineate the gross lithology of a particular sequence of rocks. Radiation measurement used on well logs is the American Petroleum Institute (API) unit.

The Greenbrier Group carbonates are distinguished on gamma-ray logs by having lower API unit and bulk density signatures than the surrounding shale units. The Greenbrier-Maccrady contact is marked by a change in the API reading from 240 (Maccrady) to 20 (Greenbrier) within the lower 30 meters of the Greenbrier carbonates. This represents a transition from shales of the Maccrady Formation to "pure" carbonates of the Greenbrier Group. The gamma-ray signature is also accompanied by a bulk density signature change from 2.92 to 2.68g/cc over the same 30 meter interval.

The Greenbrier-Bluefield contact (coincident with the Alderson Formation-Lillydale Shale Member contact) is less distinctive. This is due to the high siliciclastic content of the Alderson Formation. The gamma-ray signature is quite varied in the Alderson because of

it's highly variable lithology. Greenbrier Group sediments have API ranges of 20 to 40 (minimum) for limestones, but shaly units range from 80 to 120 (maximum). The overlying Lillydale Shale Member of the Bluefield Formation has an API range of 100 to 160. The Alderson-Union boundary is somewhat easier to define. This transition from "pure" limestone (Union) to shaly limestone (Alderson) is represented by a drop of 80 API units (110 for Alderson to 30 for Union).

When formational units can not be differentiated easily by gamma-ray signatures, the accompanying bulk density signature may be used to delineate slight changes in lithology, which may then be used in correlation. This facilitates identification of units having roughly the same gamma-ray signature but slightly different lithologies. Figure 18 represents a well log from southeastern West Virginia (Mercer 39) containing both gamma-ray and bulk density logs. The Alderson-Lillydale contact is detected here by a very subtle, but characteristic, change in bulk density. The Lillydale has a continuous 2.67 to 2.69g/cc signature. The signature decreases to 2.64g/cc at the Alderson contact and then increases to 2.75g/cc within a span of 4.5 meters downward. Bulk density values remain nearly constant although the thickness of these strata varies within southeastern West Virginia.

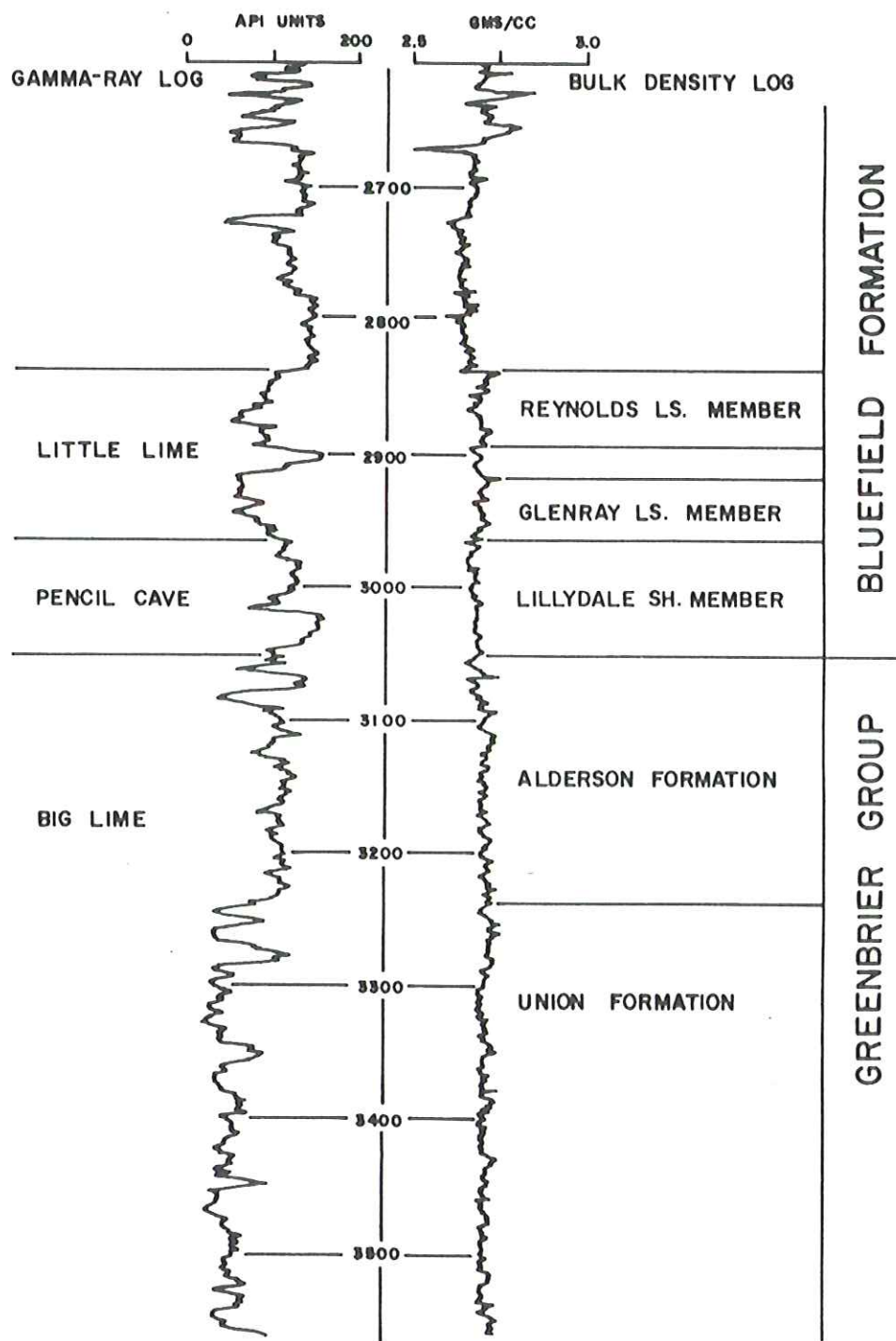


Figure 18. Gamma-ray and bulk density log (Mercer 39) typical of the Alderson Formation and related units in southeastern West Virginia. Included are formational and driller's terms. Base of the Greenbrier Group is not shown and Greenville Formation is absent.

UNION FORMATION

The Union Formation is composed of biomicrites and oosparites that represent shallow water environments during a tectonic standstill (Wray, 1980). It ranges in thickness from 30 to 84 meters (Reger, 1926). Leonard (1968) divided the Union into an Oolitic Calcarenite Member and a White Oolite Member. The White Oolite Member occurs as pure oosparites forming prograding bars and shoals. This member occurs only from central Monroe County to southern Randolph County (Leonard, 1968). In the present study area, the Union is oolitic in places but is predominantly a biomicrite representing subtidal carbonate muds and local oolitic shoals.

GREENVILLE FORMATION

The Greenville Formation, which lies between the Union and Alderson Formations, represents a period of subsidence and subsequent siliciclastic sedimentation from an easterly source. The Greenville is thickest near the type locality of Greenville, Monroe County, where it attains a true thickness of approximately 60 meters. Exact measurements are impossible because of covered lower contacts and thrust faulting accompanied by folding of the incompetent shale, which more than doubles the Greenville's apparent thickness. This thickness contrasts with the type section described by Reger (1926), which lies on the east limb of the Abbs Valley Anticline and was estimated to be

30 meters thick. The Greenville West Section lies on the west limb of the anticline and is estimated to be approximately 37 meters thick. These two sections represent the thickest accumulations in the area. The Greenville Formation thins rapidly to the northeast and is not recognized north of Alderson, Monroe County.

Vertical and lateral relationships of the Greenville to the Alderson and Union Formations are still not well understood. The lower contact (Greenville-Union) is usually covered and has been observed only once (Greenville type section, where it was very sharp). The upper contact (Greenville-Alderson) is better exposed but is less well defined. The upper contact is sharp at the Greenville West and Alderson South sections, whereas it is gradational at the Alderson Flat Mtn. Road and Bridge sections and the Alta Hwy-60 sections.

To the southwest, the Greenville Formation is thought to interfinger with micritic sediments of the Lower Alderson Formation (Fig. 20a). This facies change occurs in the vicinity of Lurich, Giles County, Virginia. The Greenville thins to the northeast where it grades into mixed carbonate-siliciclastic sediments of the Lower Alderson. The westward extent of the Greenville Formation is approximately the Monroe-Summers County line (Fig. 19).

The Greenville Formation has been considered a part of the Alderson Formation in some previous investigations (Leonard, 1968; Wray, 1980). The Greenville should retain formational status, given by Reger (1926), but it should be restricted to the black shale.

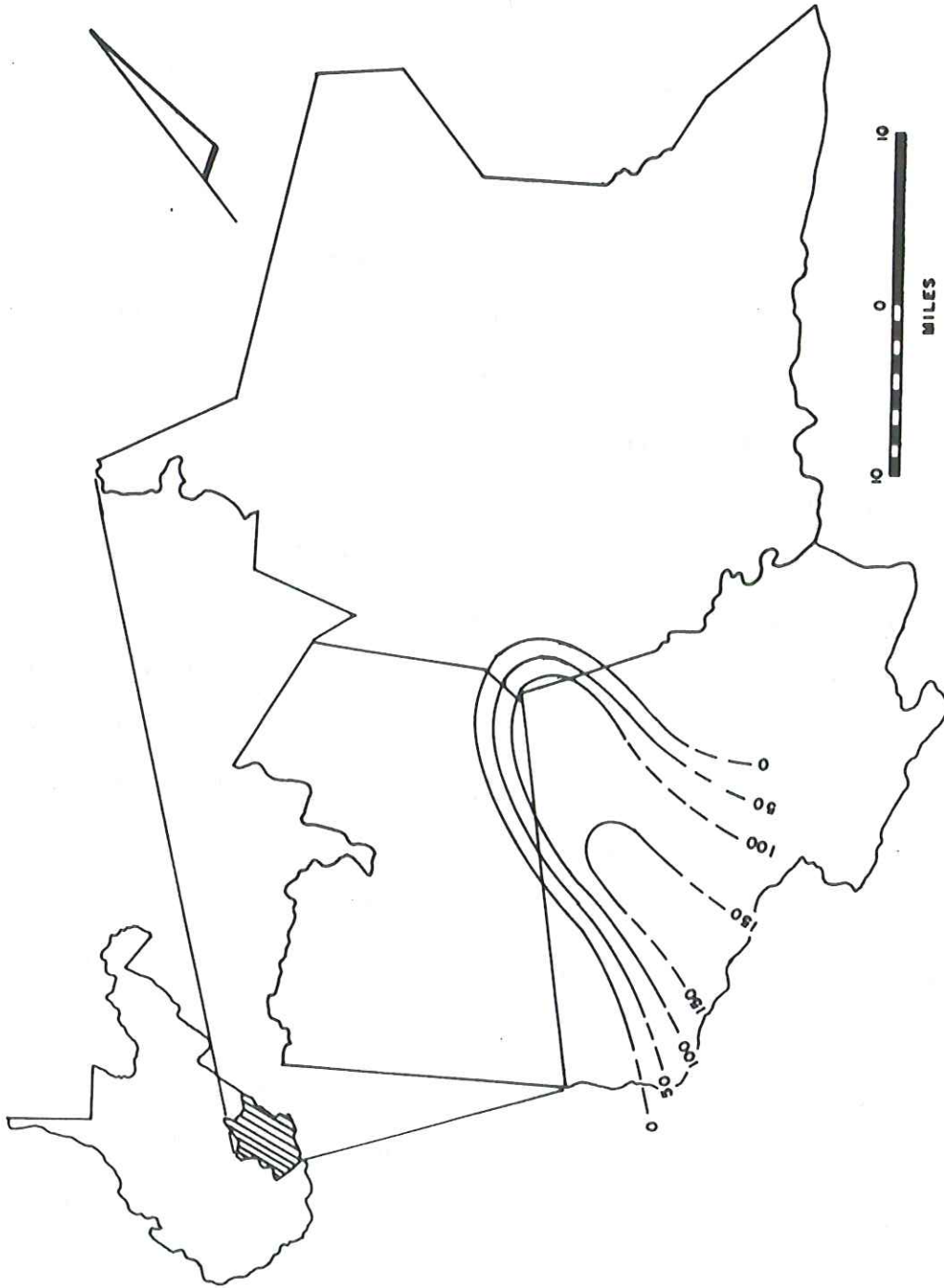


Figure 19. Isopach map of the Greenville Formation. Contour interval is 50 feet.



Figure 21. Basal yellow shaly marker bed of Alderson Formation. Alderson Formation is overturned (Ingleside section), Union Formation is at upper right.

The Alderson and Greenville Formations of depositional sequence I represent an area of local subsidence on a broad, gently dipping ramp or unrimmed shelf in which sedimentation was roughly equal to subsidence. Basal siliciclastics of depositional sequence I represent shallow water sediments, derived from an southeasterly source, accumulating along the distal portion of a clastic wedge. They grade upward into progressively basinward mixed sediments and carbonate muds. The overall depositional sequence is transgressive.

Depositional sequence II is represented by carbonate sands composed of intraclastic, bioclastic and oolitic sands. These developed on the ramp as sand shoal complexes and sand sheets during a period of regression or sea-level standstill. Two shoal complexes are separated by an intervening sand sheet. These sands are predominantly bioclastic, but they also include thick oolitic sands. The thickest accumulation occurs at the Ingleside section (49m), from which sands thin to 7m at the Nemours and Lurich sections. The second, smaller shoal occurs at the Alderson section where sands attain a thickness of 17m. To the north and south, this thins to 3m (Greenville and Alta Hwy. 60 sections).

Depositional sequence III, containing siliciclastic, mixed, and micritic sediments, represents a transgressive sequence with episodic regressive phases. The lower portion is composed of mixed carbonate-siliciclastic sediments with an intervening clastic wedge which prograded from the north. Mixed sediments are capped by a predominantly micritic facies deposited during cessation of clastic

influx. The micritic facies is thinnest at Ingleside, generally thickens to the north, and has a maximum thickness at Lurich.

Depositional sequence IV is a complex regressive sequence containing siliciclastic, mixed, micritic, and carbonate sand sediments. Micritic sediments predominate the southwestern outcrop area (Nemours). A large siliciclastic wedge (mudstones and siltstones) predominates the southern area (Ingleside) and a siliciclastic sand wedge forms the north-central outcrop area (Alderson to Greenville). Both clastic wedges prograded from easterly/southeasterly sources. The central outcrop area, between the two clastic wedges, is composed of carbonate shoal sands and mixed sediments. Depositional sequence IV is thickest in the south and thins to just north of Alderson, where it disappears.

In the subsurface, the Alderson Formation thins to the west and can be traced into McDowell, Wyoming, Raleigh, and Fayette Counties (Plate II) where it loses its typical gamma-ray character. Its westward boundary parallels a "hinge line" along which the uppermost Greenbrier unit is Union or Pickaway (Carpenter, 1976). The boundary along this line is interpreted to be the westward depositional extent of the Alderson Formation (Fig. 22). Westward of this line, formations of the Greenbrier Group become lithologically indistinguishable. Here the Greenbrier should be given formational status.

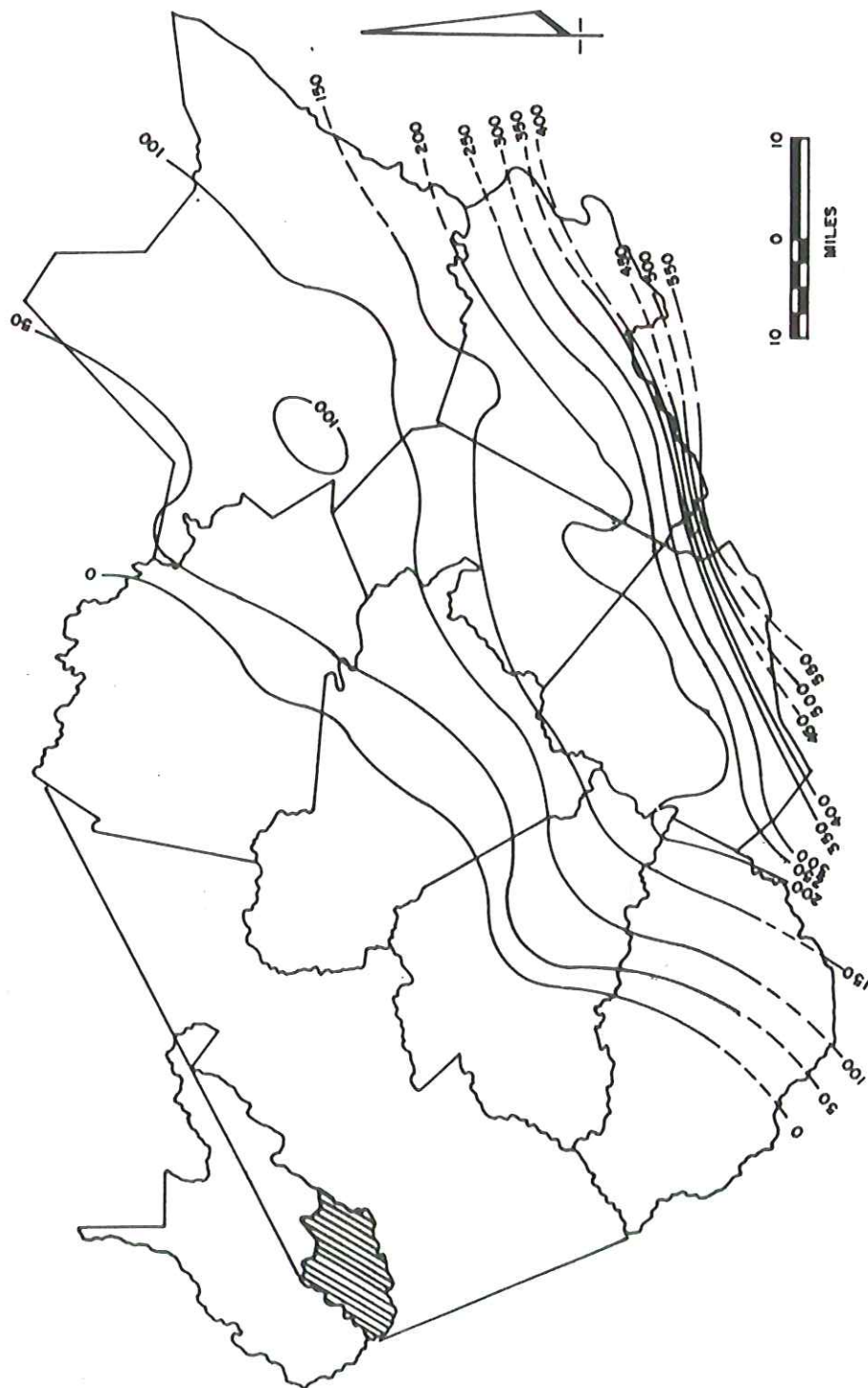


Figure 22. Isopach map of the Alderson Formation. Contour interval is 50 feet.

LILLYDALE SHALE MEMBER OF THE BLUEFIELD FORMATION

The lower Bluefield Formation represents a period of reactivated subsidence in the south, with emergence and erosion in the north (Carpenter, 1976). The subsidence in the south drowned the carbonate ramp of the Greenbrier Group as distal clastics of the southward prograding Mauch Chunk Group deposited the overlying Lillydale Shale Member. In the study area the shale is black, uniform, contains marine fossils, and attains a thickness of approximately 30 meters. The Lillydale thins to the west and north where it changes to gray and green shales. The Lillydale-Alderson contact is transitional in southern Mercer County, whereas it is sharp from central Mercer County northward.

SUMMARY OF CONCLUSIONS

1. The Greenville Formation is a gray to black, fissile, mostly non-calcareous, silty shale forming a distinct lithologic unit in southeastern West Virginia. This shale unit can be traced across its outcrop area but is absent in surrounding regions. It is a localized but distinct unit which has been included within the Alderson Formation by several workers. The formational status of the Greenville should be retained but it should be restricted to the gray to black shale of the type area in Monroe County, West Virginia.

2. Sediments of the Alderson Formation were grouped into 23 clusters by statistical methods. Clusters were subsequently grouped into four facies, containing 12 sub-facies, based on gross lithology. Facies I is a siliciclastic sequence containing sandstone, siltstone, and mudstone sub-facies. It is interpreted to represent a complex nearshore environment. Facies II is a mixed siliciclastic-carbonate sequence containing three sub-facies, that represent a transition from siliciclastic to carbonate sedimentation. Facies III contains intraclastic, bioclastic, and oolitic sub-facies that represent a high energy, mobile, carbonate sand complex. Facies IV is a micritic sequence containing pelmicrites, biomicrites, and micrite/dolostone sub-facies, which represents a low energy sub-tidal environment.

3. The Greenville and Alderson Formations represent intertidal to shallow sub-tidal sediments deposited in four sequences along a homoclinal ramp. The Greenville Formation represents an area of localized subsidence on the ramp in which siliciclastics from a southeasterly source were deposited during a transgressive phase. The Greenville Formation grades laterally into the lowermost Alderson Formation, and both form depositional sequence I. Depositional sequence II is composed of carbonate sands representing shoal complexes formed during a period of regression or sea-level standstill. Depositional sequence III contains siliciclastic, mixed, and micritic sediments representing a transgressive phase with episodic regressive sequences. Depositional sequence IV contains siliciclastic, mixed, micritic, and carbonate sand sediments representing a complex regressive sequence.

4. The Alderson Formation is a valid stratigraphic unit in southeastern West Virginia, mappable in outcrop and traceable into the subsurface. It extends westward, in the subsurface, to a line running roughly NE-SW through McDowell, Wyoming, Raleigh, Fayette, and Greenbrier Counties, West Virginia. This line is interpreted to be the westward depositional extent of the Alderson Formation. Along this line the Alderson Formation loses its gamma-ray character and the Greenbrier Group becomes indistinguishable on gamma-ray logs. Here, the Greenbrier Group should be given formational status.

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APPENDIX A

Nemours (Railroad): Beaver Pond District, Mercer County, West Virginia. Measured on the west limb of the Abbs Valley Anticline along the Norfolk and Western Railway on the north side of the Bluestone River. Starting 0.2 miles west of the quarry. Section measured from base of Alderson and extending westward until section is covered.

	Unit Thick <u>Feet</u>	Cum. Thick <u>Feet</u>
1. <u>Union Fm.</u> Oolitic grainstone. Medium light gray (N6) fossiliferous oolitic grainstone. Weathers light olive gray (5Y6/1). Sample N-1.	Not Measured	
2. <u>Alderson Fm.</u> Mudstone. Dusky yellow (5Y6/4) and medium gray (N5) laminated and slightly fossiliferous and oolitic mudstone. Weathers yellowish gray (5Y7/2) and light gray (N7). Fossils and ooids concentrated in laminae. Sample N-2.	0.5	0.5
3. Mudstone. Light olive gray (5Y6/1) mudstone. Weathers light gray (N7). Spar filled vert. burrows (2.5-3.5 ft.). Sample N-3.	4.5	5.0
4. <u>Union Fm.</u> Oolitic grainstone. Medium gray (N5) oolitic grainstone. Weathers medium light gray (N6). Sample N-4.	2.0	7.0
5. <u>Alderson Fm.</u> Mudstone. Medium gray (N5) mudstone. Weathers light olive gray (5Y6/1). Slightly fossiliferous. Samples N-5 to N-7.	6.0	13.0
6. <u>Union Fm.</u> Oolitic grainstone. Medium light gray (N6) oolitic grainstone. Weathers light gray (N6). Slightly fossiliferous. Sample N-8.	1.5	14.5
7. Covered	10.0	24.5
8. <u>Alderson Fm.</u> Fossiliferous wackestone. Medium gray (N5) fossiliferous wackestone. Weathers light yellowish gray (5Y7/1). Ostracodes, brachiopods, echinoids, Vertical stylolites. Sample N-9.	1.5	26.0
9. Covered	1.5	27.5

Nemours (Highway): Beaver Pond District, Mercer County, West Virginia. Measured along WV Hwy 102 on the west limb of the Abbs Valley Anticline, south side of the Bluestone River. Starting at the intersection of Hwy 102 and Hwy 659 continuing East to the Lillydale-Alderson contact and extending eastward. Section measured from top to bottom.

	Unit Thick <u>Feet</u>	Cum. Thick <u>Feet</u>
1. <u>Lillydale Shale Mbr., Bluefield Fm.</u>	Not measured	
2. <u>Alderson Fm.</u> Silty mudstone. Medium gray (N5) slightly fossiliferous silty mudstone. Weathers light olive gray (5Y6/1). Echinoids, bryozoans, brachiopods. Samples NN-1 to NN-3.	15.0	15.0
3. Silty mudstone. Medium gray (N5) finely laminated silty mudstone. Weathers very light gray (N8). Sample NN-4.	5.0	20.0
4. Skeletal grainstone. Medium light gray (N6) skeletal grainstone. Weathers light olive gray (5Y6/1). <u>Archimedes</u> , echinoids, brachiopods. Dark yellow orange (10YR6/6) intraclasts. Sample NN-5.	1.5	21.5
5. Silty mudstone. Light olive gray (5Y6/1) silty mudstone. Weathers olive gray (5Y4/1). No fossils. Sample NN-6.	6.5	28.0
6. Silty mudstone. Light olive gray (5Y6/1) silty mudstone. Weathers olive gray (5Y4/1). Bryozoan molds. Samples NN-7 and NN-8.	6.0	34.0
7. Silty mudstone. Medium dark gray (N4) silty mudstone. Weathers light olive gray (5Y6/1). Abundant mica. Samples NN-9 to NN-12.	18.0	52.0
8. Silty wackestone. Medium gray (N5) fossiliferous silty wackestone. Weathers light olive gray (5Y6/1). Echinoids and plant fragments. Sample N-13.	2.0	54.0
9. Oolitic grainstone. Light gray (N7) fossiliferous oolitic grainstone. Weathers very light gray (N8). Echinoids, brachiopods, bryozoans. Samples NN-14.	2.0	56.0

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| 10. Skeletal grainstone. Medium gray (N5) skeletal grainstone. Echinoid fragments and brachiopods most abundant. Weathers greenish gray (5GY6/1). Cross bedding dipping East from 67-71 ft. Samples NN-15 to NN-18. | 17.0 | 73.0 |
| 11. Silty mudstone. Olive gray (5Y4/1) silty mudstone in a sheared zone. Weathers light olive gray (5Y5/2). Fenestrae bryozoans present. Sample NN-19. | 7.0 | 80.0 |
| 12. Silty mudstone. Medium dark gray (N4) silty mudstone. Weathers medium light olive gray (N6). Mica abundant, minor bryozoan fragments. Samples NN-20 to NN-25. | 25.0 | 105.0 |
| 13. Highly faulted zone. | | |

Ingleside: East River District, Mercer County, West Virginia. Measured along Norfolk and Western Railway on the south side of the East River adjacent to Hwy 112. Starting approximately 0.1 mi. southward of the Railroad trestle at the Union-Alderson contact and extending to the trestle.

	Unit Thick <u>Feet</u>	Cum. Thick <u>Feet</u>
1. <u>Union Fm.</u> Fossiliferous mudstone.	Not measured	
2. <u>Alderson Fm.</u> Brownish gray (5YR4/1) skeletal packstone. Weathers light olive gray (5Y6/1). Fossils include echinoids, brachiopods, bryozoans, and gastropods. Sample I-91.	0.5	0.5
3. Skeletal packstone. Olive gray (5Y4/1) skeletal packstone. Weathers yellowish gray (5Y7/2). Fossils include bryozoans, brachiopods, and echinoids. Sample I-90.	1.5	2.0
4. Silty mudstone. Olive gray (5Y4/1) silty mudstone. Weathers light olive gray (5Y6/1). Fossils include bryozoans and echinoids. Sample I-89.	4.0	6.0
5. Silty mudstone. Dark gray (N3) fossiliferous silty mudstone. Weathers medium gray (N5). Fossils include bryozoans, echinoderms, and brachiopods. Some horizontal burrows. Sample I-88.	1.0	7.0
6. Skeletal packstone. Olive gray (5Y4/1) silty bryozoan packstone. Weathers yellowish gray (5Y7/2). Predominately fenestrate bryozoans. Others include brachiopods, echinoids, and ostracodes. Sample I-87.	5.0	12.0
7. Silty mudstone. Olive gray (5Y3/2) laminated silty mudstone. Weathers light olive gray (5Y6/1). Bottom is burrowed, some cross laminations, abundant mica seen of fracture surfaces. Top has distinct silt layers (quartz, mica, some fossil fragments), horizontal burrows. Samples I-85 and I-86.	5.0	17.0
8. Covered	95.0	112.0

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| <p>9. Skeletal grainstone. Dark gray (N3) skeletal grainstone. Weathers moderate yellowish brown (10YR5/4). Slightly oolitic. Abundant dark yellowish orange (10YR6/6) iron stained alterations. Fossils include echinoids, brachiopods, and bryozoans. Vertical stylolites. Samples I-80 to I-84.</p> | 15.0 | 127.0 |
| <p>10. Skeletal grainstone. Similar to unit 9. More oolitic, more stylolites (vertical and horizontal). Planar and cross laminated in outcrop. Samples I-75 to I-79.</p> | 21.0 | 148.0 |
| <p>11. Skeletal grainstone with calcareous siltstone laminations. Dark gray (N3) skeletal grainstone with light olive gray (5Y5/2) calcareous siltstone laminations and flaser bedding. Weathers same. Abundant burrows. Fossils are mostly echinoids with minor brachiopods. Samples I-72 to I-74.</p> | 6.0 | 154.0 |
| <p>12. Skeletal grainstone. Medium dark gray (N4) skeletal grainstone. Weathers grayish brown (5YR3/2). Slightly oolitic. Abundant iron alteration. Abundant vertical and horizontal stylolites. Laminated in outcrop due to fossil layers. Fossils are mostly eciods, others include brachiopods, bryozoans, and rugose corals. Samples I-65 to I-71.</p> | 21.0 | 175.0 |
| <p>13. Silty mudstone. Medium gray (N5) silty mudstone with olive gray (5Y4/1) calcareous siltstone laminations. Weathers light olive gray (5Y6/1) and brownish black (5YR2/1). Sample I-64.</p> | 2.0 | 177.0 |
| <p>14. Skeletal grainstone. Medium gray (N5) skeletal grainstone with moderate brown (5Y4/4) silty mudstone flaser bedding. Weathers yellowish gray (5Y7/2). Fossils mostly echinoids, others brachiopods. Samples I-62 and I-63.</p> | 4.0 | 181.0 |

15.	Skeletal grainstone. Medium dark gray (N4) skeletal grainstone. Weathers olive gray (5Y4/1). Slightly to very oolitic (samples I-54 to I-57). Echinoids most abundant, others include brachiopods, corals, molluscs, and bryozoans. Stylolites very abundant (vertical and horizontal). Calcite filled fractures. Laminations in outcrop. Iron stains along micro fractures. Samples I-54 to I-61.	37.0	218.0
16.	Silty skeletal wackestone. Dusky yellow (5Y6/4) silty skeletal wackestone. Weathers same. Fossils include bryozoans, echinoids, and brachiopods. Samples I-52 and I-53.	4.0	222.0
17.	Skeletal packstone. Medium gray (N4) laminated skeletal packstone. Weathers light olive gray (5Y6/1). Fossils mostly echinoids, others brachiopods, <u>Archimedes</u> , molluscs, and corals. Slightly oolitic. Abundant stylolites and laminations. Samples I-49 to I-51.	8.0	230.0
18.	Silty skeletal wackestone. Medium dark gray (N4) and olive gray (5Y4/1) silty skeletal wackestone. Weathers olive gray (5Y4/1). Fossils mostly echinoids and <u>Archimedes</u> , others brachiopods. Few <u>intraclasts</u> . Sample I-48.	4.0	234.0
19.	Silty skeletal grainstone. Dark gray (N3) silty skeletal grainstone. Weathers olive gray (5Y4/1). Has distinct silt laminations (planar and cross). Silt layers are olive gray (5Y4/1) and weather dark yellowish brown (10YR4/2). Abundant vertical stylolites. Samples I-44 to I-47.	18.5	252.5
20.	Skeletal grainstone. Dark gray (N3) skeletal grainstone. Weathers moderate yellowish brown (10YR5/4). Fossils mostly echinoids, others brachiopods. Sample I-43.	1.0	253.5
21.	Silty mudstone. Medium dark gray (N4) silty mudstone. Weathers moderate yellowish brown (10YR5/4). Abundant plant fossils. Samples I-37 to I-42.	19.5	273.0

22.	Oolitic packstone. Medium dark gray (N4) fossiliferous oolitic packstone. Weathers light olive gray (5Y6/1). Minor bryozoan bafflestone layer lin. thick. Fossils include echinoids, brachiopods, bryozoans, and corals. Sample I-36.	0.75	273.75
23.	Bryozoan bafflestone. Medium dark gray (N4) silty bryozoan bafflestone. Weathers moderate yellowish brown (10YR5/4). Other fossils include brachiopods, echinoids, and corals. Samples I-33 to I-35.	11.5	285.25
24.	Shaly mudstone. Medium gray (N5) shaly, silty mudstone. Weathers light olive gray (5Y6/1). Fossiliferous at base. Samples I-27 to I-32.	11.5	297.75
25.	Shaly mudstone. Olive gray (5Y4/1) silty, shaly mudstone. Weathers light olive gray (5Y6/1). Highly burrowed (horizontal). Samples I-23 to I-26.	16.0	313.75
26.	Shaly mudstone. Same as unit 25 but no burrows. Samples I-21 and I-22.	6.0	319.75
27.	Covered	13.0	332.75
28.	Shaly mudstone. Same as unit 26. Samples I-18 to I-20.	12.0	344.75
29.	Shaly mudstone. Same as unit 25. Samples I-14 to I-17.	14.0	358.75
30.	Silty skeletal wackestone. Medium dark gray (N4) silty skeletal wackestone. Weathers olive gray (5Y4/1). Fossils include echinoids, bryozoans, and brachiopods. Samples I-12 and I-13.	4.5	363.25
31.	Calcareous shale. Light olive gray (5Y5/2) calcareous shale. Weathers yellowish gray (5Y7/2). Abundant plant fossils on bedding surfaces. Samples I-9 to I-11.	7.0	370.25

<p>32. Skeletal grainstone. Medium dark gray (N4) intraclastic skeletal grainstone. Weathers grayish orange (10YR7/4). Fossils include echinoids, brachiopods, bryozoans, corals, and trilobites. Intraclasts are lime mudstone which weathers dark yellowish orange (10YR6/6). Minor pyrite. Sample I-8.</p>	0.5	370.75
<p>33. Calcareous shale. Same as unit 31. Samples I-6 and I-7.</p>	3.0	373.75
<p>34. Covered.</p>	5.0	378.75
<p>35. Calcareous shale. Same as unit 31. Samples I-1 to I-5.</p>	10.0	388.75
<p>36. Covered.</p>		

Oakvale: East River District, Mercer County, West Virginia. Measured along Hwy. 112 2.1 mi. west of the town of Oakvale. Starting at the Alderson-Lillydale contact at the roadside quarry and extending westward until section ends. Measured from top to bottom.

	Unit Thick <u>Feet</u>	Cum. Thick <u>Feet</u>
1. <u>Lillydale Shale Mbr., Bluefield Fm.</u>	Not measured	
2. <u>Alderson Fm.</u> Oolitic grainstone. Medium dark gray (N4) oolitic grainstone. Minor echinoid, bryozoan, and brachiopod fragments. Abundant pyrite. Samples 0-1 and 0-2.	3.5	3.5
3. Silty mudstone. Medium dark gray (N4) thinly bedded, laminated silty mudstone. Some cross laminations. Mica and organic (plant fragments) on bedding surfaces. Laminations are undulatory and discontinuous. Sample 0-9 has a skeletal wackestone bed 2 in. thick. Beds average 8 in. thick. Flute casts and ripple marks common. Weathers light olive gray (5Y6/1). Samples 0-3 to 0-10.	28.0	31.5
4. Silty mudstone. Medium dark gray (N4) thick bedded silty mudstone. Slightly micaceous. Weathers yellowish gray (5Y7/2). Samples 0-11 to 0-15.	26.0	57.5
5. Sheared zone. Very shaly with grainstone lenses. Badly weathered. Fault breccia at top contact. Clasts are oolitic grainstone. Sample 0-16.	16.0	73.5
6. Skeletal grainstone. Medium dark gray (N4) skeletal grainstone. Weathers light olive gray (5Y6/1). Echinoid fragments and oolites predominate. Dark yellow orange (10YR6/6) material in interstices. Samples 0-17 to 0-21.	24.0	97.5

Lurich: Giles County, Virginia. Measured along Norfolk and Western Railway on west side of the New River. Approximately 0.9 miles east of the town of Lurich. Starting approximately 300 feet from the intersection of Norfolk and Western Railway and Highway 649. Extending southeastward to the Alderson-Union contact. Alderson-Lillydale contact is covered.

	Unit Thick <u>Feet</u>	Cum. Thick <u>Feet</u>
1. <u>Alderson Fm.</u> Silty Mudstone. Light gray (N7) shaly silty mudstone. Thinly beaded (0.5"). Weathers light olive gray (5Y6/1). Abundant carbonaceous plant material. Sample L-1.	2.0	2.5
2. Covered	7.0	7.9
3. Silty Mudstone. Light gray (N7) silty mudstone. Thinly beaded (3-4"). Weathers light olive gray (5Y6/1). Abundant carbonaceous plant material. Sample L-2.	5.0	14.0
4. Silty Mudstone. Medium dark gray (N4) slightly fossiliferous silty mudstone. Abundant carbonaceous plant material. Fossils include brachiopods and <u>Archimedes</u> . Sample L-3.	5.0	19.0
5. Wackestone. Medium gray (N5) massive foss. wackestone. Weathers light olive gray (5Y6/1). Fossils include brachiopods, bryozoans and echinoid fragments. Samples L-4, L-5.	6.0	25.0
6. Skeletal grainstone. Medium gray (N5) massive oolitic skeletal grainstone. Weathers gray (N7). Laminated and cross laminated. Fossils include brachiopods. Samples L-6, L-7, L-8.	13.0	38.0
7. Skeletal packstone. Medium gray (N5) skeletal packstone with fine grained yellowish gray (5Y7/2) laminated silty mudstone lenses and (sandstone) stringers. Fossils mostly echinoid fragments and columnals. Sample L-9.	1.75	39.75
8. Calcareous sandstone. Medium light gray (N6) top to dusky yellow (5Y6/4) bottom medium bedded (1') laminated and cross laminated calcareous fine sandstone. Samples L-10, L-11.	10.25	50.0

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| 9. | Pelletal packstone. Medium dark gray (N4) foss. pelletal packstone. Weathers light gray (N7). Fossils include echinoid and brachiopod fragments. Sample L-12. | 3.0 | 53.0 |
| 10. | Mudstone. Medium dark gray (N4) slightly fossiliferous mudstone. Weathers light gray (N7). Fossils include echinoid fragments. Horizontal stylolites. Sample L-13 | 12.0 | 65.0 |
| 11. | Pelletal packstone. Medium dark gray (N4) foss. pelletal packstone. Weathers light gray (N7). Fossils include echnoid and brachiopod fragments. Sample L-14 | 2.0 | 67.0 |
| 12. | Mudstone. Medium dark gray (N4) mudstone. Weathers very light gray (N8). Few fossils (bryozoans). Samples L-15, L-16. | 10.0 | 77.0 |
| 13. | Skeletal Wackestone. Medium gray (N5) skeletal wackestone weathers light gray. Fossils are echinoid fragments which stand out in relief. Samples L-17, L-18. | 11.0 | 88.0 |
| 14. | Silty Mudstone. Medium gray (N5) silty mudstone. Weathers light gray (N7). Slightly laminated. Samples L-19, L-20, L-21, L-22, L-23, L-24, L-25, L-26, L-27, L-28, L-29, L-30, L-31, L-32. | 69.0 | 157.0 |
| 15. | Bafflestone. Medium gray (N5) bryozoan bafflestone. Weathers very light gray (N8). Other fossils include brachiopods and echinoid fragments. Samples L-33, L-34. | 10.0 | 167.0 |
| 16. | Oolitic grainstone. Medium gray (N5) sandy fossiliferous oolitic grainstone. Weathers light gray (N7). Very light gray (N8) mudstone clasts 188' to 196' fossil zone 190' to 191'. Samples L-35, L-36, L-37, L-38, L-39, L-40, L-41. | 33.0 | 200.0 |
| 17. | Silty mudstone. Light gray (N7) silty mudstone. Weathers light olive gray (5Y6/1). Samples L-42, L-43. | 10.0 | 210.0 |
| 18. | Covered | | |

19.	Skeletal wackestone. Medium dark gray (N4) skeletal wackestone. Weathers medium light gray (N6) to light gray (5Y6/1). More fossiliferous at bottom. Fossils include bryozoans, brachiopods and echinoid fragments. Samples L-44, L-45, L-46.	12.0	222.0
20.	Covered	21.0	243.0
21.	Silty mudstone. Medium dark gray (N4) silty laminated mudstone. Weathers light olive gray (5Y6/1). Samples L-47, L-48, L-49, L-50.	14.0	257.0
22.	Covered	16.5	273.5
23.	Silty mudstone. Medium dark gray (N4) silty mudstone. Weathers light olive gray (5Y6/1). Sample L-51.	2.0	275.5
24.	Oolitic packstone. Medium dark gray (N4) oolitic packstone. Weathers medium gray (N5). Some echinoid fragments. Samples L-52, L-53.	7.0	282.5
25.	Covered	148.0	430.5
26.	Silty mudstone. Medium dark gray (N4) laminated silty mudstone. Weathers light olive gray (5Y6/1). Samples L-54, L-55, L-56, L-57, L-58, L-59.	39.0	469.5
27.	Oolitic grainstone. Medium dark gray (N4) oolitic grainstone. Weathers light gray (N7). Samples L-60, L-61.	2.5	472.0
28.	Covered	50.5	522.5
29.	Silty mudstone. Light olive gray (5Y6/1) laminated silty mudstone. Weathers same. Samples L-62, L-63.	6.0	528.5
30.	Covered	12.0	540.5
31.	Silty mudstone. Light olive gray (5Y5/2) silty mudstone. Weathers light olive gray (5Y6/1). Fossils include echinoid fragments. Sample L-64.	1.0	541.5

32. Silty wackestone. Light olive gray (5Y6/1) silty wackestone. Weathers same. Fossils include brachiopods, bryozoans, and echinoid fragments. Sample L-65. 0.5 542.0
33. Union Fm. Oolitic grainstone. Medium gray (N5) fossiliferous oolitic grainstone. Weathers very light gray (N8). Fossils are echinoid fragments. Sample L-66. 53

Greenville (Type): Springfield District, Monroe County, West Virginia. Measured along Hwy 785 1.9 mi. southeast of Greenville on the north side of Indian Creek (east limb of Abbs Valley Anticline). Starting at the Union-Greenville contact and extending along highway to the bridge over Indian Creek. Section is folded and thickness more than doubled. Estimated thickness 200-250 ft.

	Unit Thick Feet	Cum. Thick Feet
1. <u>Union Fm.</u>	Not measured	
2. <u>Greenville Fm.</u> Covered	21.8	21.8
3. Shale. Dusky yellowish brown (10YR2/2) fissile shale. Weathers same. Sample GRA-1.	2.2	24.0
4. Shale. Grayish black (N2) fissile shale. Weathers same. Samples GRA-2 to GRA-8.	24.0	48.0
5. Covered	24.0	72.0
6. Shale. Grayish black (N2) fissile shale. Weathers medium dark gray (N4). Samples GRA-9 to GRA-14.	20.0	92.0
7. Covered	8.0	100.0
8. Shale. Grayish black (N2) fissile shale. Weathers medium dark gray (N4). Samples GRA-15 to GRA-17.	8.0	108.0
9. Covered	28.0	136.5
10. Shale. Grayish black (N2) fissile shale. Weathers medium dark gray. Some grayish orange (10YR7/4) layers approximately 2 in. thick. This unit contains thrust fault induced folds making actual thickness less than measured. Samples GRA-18 to GRA-79.	241.5	377.5
11. <u>Alderson Fm.</u> Oolitic grainstone. Medium dark gray (N4) oolitic grainstone. Weathers olive gray (5Y4/1). This unit wedges out due to thrust fault. Sample GRA-80.	3.0	380.5
12. Thrust fault		

13.	Greenville Fm. Shale. Medium dark gray (N4) shale. Weathers medium gray (N5). Sample GRA-81.	1.5	382.0
14.	Alderson Fm. Fault breccia. Medium dark gray (N4) oolitic grainstone fragments with calcite cement. Weathers grayish orange (10YR7/4). Sample GRA-82.	1.0	383.0
15.	Oolitic packstone. Medium dark gray (N4) oolitic packstone. Weathers medium light gray (N6). Samples GRA-83 to GRA-85.	5.0	388.0
16.	Skeletal wackestone. Dusky yellow (5Y6/4) skeletal wackestone. Weathers moderate yellowish brown (10YR5/4). Fossils include echinoids, brachiopods, and bryozoans. Samples GRA-86.	3.0	391.0
17.	Oolitic grainstone. Medium dark gray (N4) oolitic grainstone. Weathers moderate yellow brown (10YR5/4). Samples GRA-87 and GRA-88.	2.5	393.5
18.	Covered		

Greenville (West): Springfield District, Monroe County, West Virginia. Measured at a road cut on Hwy 122 approximately 1 mile west of Greenville. Starting at road and extending to top of hill.

	Unit Thick <u>Feet</u>	Cum. Thick <u>Feet</u>
1. <u>Greenville Fm.</u> Shale. Grayish black (N2) fissile shale. Weathers same. Scarce fossils include <u>Lingula</u> brachiopods and bivalves. Not sampled.	20.0	20.0
2. Shale. Grayish black (N2) fissile shale. Weathers same. Not sampled.	80.0	100.0
3. <u>Alderson Fm.</u> Skeletal grainstone. Medium gray (N5) skeletal grainstone. Echinoid fragments and brachiopods most abundant. Weathers greenish-gray (5GY6/1). Samples GW-1 and GW-2.	7.0	107.0
4. Silty mudstone. Olive gray (5Y4/1) silty mudstone. Weathers light olive gray (5Y5/2). Some bryozoans present. Sample GW-3.	4.0	111.0
5. Skeletal grainstone. Medium gray (N5) skeletal grainstone. Fossils include bryozoans, brachiopods, and echinoids. Weathers greenish gray (5GY6/1). Sample GW-4.	3.0	114.0
6. Covered	20.0	134.0
7. Sandstone. Dusky yellow (5Y6/4) medium sandstone. Weathers yellowish gray (5Y7/2). Some mica and organics. Sample GW-5.	1.0	135.0
8. Covered	25.0	160.0
9. Silty skeletal wackestone. Light olive gray (5Y5/2) silty skeletal wackestone. Weathers medium olive gray (5Y5/1). Fossils include bryozoans, echinoids and brachiopods. Sample GW-6.	17.0	177.0
10. Skeletal wackestone. Same as above. No sample.	11.0	188.0

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| 11. | Oolitic grainstone. Medium dark gray (N4) oolitic grainstone. Weathers grayish orange (10YR7/4). Sample GW-7. | 7.0 | 195.0 |
| 12. | Sandstone. Light gray (N7) micaceous sandstone. No fossils. Sample GW-8. | 29.0 | 214.0 |
| 13. | Covered | | |

Alderson (Bridge): Wolf Creek District, Monroe County, West Virginia. Measured along road west of Alderson leading to Federal Women's Correctional Institution. Starting at base of roadcut and extending to top of hill.

	Unit Thick <u>Feet</u>	Cum. Thick <u>Feet</u>
1. <u>Greenville Fm.</u> Shale. Brownish-black (5YR2/1) to black (N1) fissile, slightly silty shale. Contains a 5.0 foot zone of horizontal, vertical and randomly oriented burrow fillings. Samples AB-1 to AB-3.	8.0	8.0
2. Shale. Brownish-black (5YR2/1) to black (N1) fissile, silty shale. Contains thin (0.5 to 1.0 in.), olive-black (5Y2/1) silty, lime mudstone, nodular and tabular layers. Samples AB-4 to AB-15.	49.0	57.0

Alderson (Flat Mountain Road): Wolf Creek District, Monroe County, West Virginia. Measured along Flat Mountain Road leading from intersection of Highway 3. Starting approximately 200 feet from intersection.

	<u>Unit Thick</u> <u>Feet</u>	<u>Cum. Thick</u> <u>Feet</u>
1. Covered		
2. <u>Greenville Fm.</u> Calcareous shale. Olive Brown (5Y2/1) fissile slightly calcareous shale weathers dusky yellowish brown (10YR2/2). Irrescent iron staining. Samples AG-1, AG-2.	5.0	5.0
3. Covered	10.5	15.5
4. Calcareous shale. Medium dark gray (N4) fissile slightly calc. shale. Weathers medium gray (N5). Minor small (1/2") fossils. Sample AG-3.	3.0	18.5
5. Covered	6.5	25.0
6. Calcareous shale. Medium gray (N5) well cemented calcareous shale. Weathers same. Samples AG-4, AG-5.	4.5	29.5
7. Shale. Olive gray (5Y4/1) non-calcareous shale with 4" thick medium gray (N5) calcareous shale layers and hard mudstone lenses. Weathers same. Samples AG-6, AG-7, AG-8.	8.0	37.5
8. Shale. Olive gray (5Y4/1) non-calcareous shale. Weathers same. Increases to calc. shale at top. Samples AG-9, AG-10, AG-11, AG-12, AG-13, AG-14, AG-15, AG-16, AG-17.	19.0	56.5
9. <u>Alderson Fm.</u> Skeletal packstone. Moderate yellowish brown (10YR5/4) skeletal packstone. Weathers grayish orange (10YR7/4) fossils include echinoids, <u>Archimedes</u> and other bryozoans, brachiopods & rugosa. Sample AG-18. A 0.75' olive gray (5Y4/1). Sl. calc. foss. shale (Greenville Fm.) tongue splits this unit. Sample AG-19.	1.5	58.0
10. Skeletal packstone. Olive gray (5Y4/1) silty skeletal packstone. Weathers same. Fossils are bryozoans. Sample AG-20.	5.0	63.0

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| 11. | Skeletal wackestone. Moderate yellowish brown (10YR5/4) silty skeletal wackestone. Weathers dark yellowish orange (10YR6/6). Fossils mostly bryozoans, others echinoids, brachiopods, and algae. Sample AG-21. | 2.75 | 65.75 |
| 12. | Silty mudstone. Light olive gray (5Y5/2) silty mudstone. Weathers same. No sample | 13.0 | 78.75 |

Alderson (Type): Wolf Creek District, Monroe County, West Virginia. Measured along West Virginia Highway 3 leading south from the town of Alderson along the axis of the Alderson anticline starting at base of hill extending to top of hill.

	<u>Unit Thick</u> <u>Feet</u>	<u>Cum. Thick</u> <u>Feet</u>
1. Covered		
2. <u>Alderson Fm.</u> Fossiliferous siltstone. Light olive gray (5Y5/2) fossiliferous non-calcareous siltstone. Weathers yellowish gray (5Y7/2). Fossils mostly bryozoans, some brachiopods, some organic materials. Sample A-1.	5.0	5.0
3. Skeletal wackestone. Moderate olive brown (5Y4/4) skeletal wackestone. Weathers dusky yellow (5Y6/4). Fossils include echinoids, bryozoans, corals, brachiopods. Sample A-2	0.25	5.25
4. Silty skeletal wackestone. Light olive gray (5Y5/2) silty skeletal wackestone. Weathers yellowish gray (5Y7/2). Fossils mostly bryozoans, some brachiopods. Sample A-3	0.75	6.0
5. Skeletal wackestone. Dark yellowish brown (10YR4/2) skeletal wackestone. Weathers moderate yellowish brown (10YR5/4). Fossils include echinoids, brachiopods, bryozoans and corals. Sample A-4.	0.25	6.25
6. Skeletal wackestone. Light olive gray (5Y5/2) skeletal wackestone. Weathers pale yellowish brown (10YR6/2). Fossils include echinoids, bryozoans, and brachiopods. Sample A-5.	3.25	9.50
7. Oolitic grainstone. Medium dark gray (N4) oolitic grainstone. Weathers grayish orange (10YR7/4). Thick bedded. Cross bedded, vert. stylolites. Samples A6-A, A6-B, A6-C	8.0	17.50
8. Silty skeletal wackestone. Light olive gray (5Y5/2) silty skeletal wackestone. Weathers med. olive gray (5Y5/1). Fossils include bryozoans, echinoids, brachiopods, and ostracodes. Cross bedded (channel). Samples A-7, A-8, A-9.	9.0	26.50

9.	Silty skeletal packstone. Light olive gray (5Y5/2) silty skeletal packstone. Weathers yellowish gray (5Y7/2). Some organic material cross bedded. Skel. material v. fine, some larger echinoid material. Mudstone intraclasts between beds. Sample A-10.	1.25	27.25
10.	Shaly lime. Lense. No sample.	0.75	28.50
11.	Silty skeletal packstone. Light olive brown (5Y5/6) laminated silty skeletal packstone. Weathers grayish orange (10YR7/4). Skeletal material v. fine. Silt/skel. material 50/50. Sample A-11, A-12. Horiz. and undulose laminations, some cross reading. Top more fissile, less calcite, less fossils, more silty.	3.0	31.50
12.	Fossiliferous siltstone. Light olive gray (5Y5/2) fissile fossiliferous slightly calcareous siltstone. Weathers same. Plant fossils abundant a small discontinuous 2" silty skeletal wackestone lense. Samples A-13, A-14, A-15, A-16, A-17, A-18, A-19.	11.0	42.50
13.	Silty skeletal packstone. Olive gray (5Y4/1) silty skeletal packstone. Weathers light olive gray (5Y6/1). Fossils include echinoids, bryozoans, brachiopods, corals, ostracodes. Samples A-20A, A-20B, A-20C, A-20D, A-20E.	15.0	57.50
14.	Silty mudstone. Medium dark gray (N4) silty mudstone. Weathers medium light gray (N6). Highly burrowed. Sample A-21.	1.0	58.50
15.	Calcareous siltstone. Light olive gray (5Y5/2) calcareous siltstone. Weathers moderate yellowish brown (10YR5/4). Abundant black organic matter. Sample A-22.	2.0	60.50
16.	Silty mudstone. Medium dark gray (N4) silty mudstone. Weathers yellowish gray (5Y7/2). Burrowed. Some brachiopods. Sample A-23.	1.0	61.50
17.	Laminated mudstone. Olive gray (5Y3/2) laminated mudstone. Weathers light olive gray (5Y5/2). Some burrows. Small diapiric compaction structures. Samples A-24, A-24A, A-24B, A-24C.	3.0	64.50

18.	Fossiliferous pelletal packstone. Dark gray (N3) foss. pelletal packstone. Weathers yellowish gray (5Y7/2). Fossils mostly echinoids. Others brachiopods and bryozoans. Sample A-25.	3.0	67.50
19.	Skeletal wackstone. Dark gray (N3) skeletal wackstone. Weathers yellowish gray (5Y7/2). Fossils are bryozoans, echinoids and brachiopods. Samples A-25A, A-25B.	2.5	70.0
20.	Silty mudstone. Olive gray (5Y4/1) silty mudstone. Weathers dusky yellow (5Y6/4). Highly burrowed. Sample A-25E.	1.5	71.5
21.	Silty mudstone. Olive gray (5Y4/1) silty sl. foss. mudstone. Weathers dusky yellow (5Y6/4). Fossils occur as laminae. Mostly echinoids, bryozoans and brachiopods. Samples A-25C, A-25D.	8.0	79.5
22.	Laminated siltstone. Olive gray (5Y4/1) laminated siltstone. Weathers. Yellowish gray (5Y7/2). Laminae show diapiric compaction structures. Some organic material on laminae planes. Sample A-25G.	2.5	82.0
23.	Laminated siltstone. Colors same as Unit 22. Bedding laminations and cross laminations. Abundant plant material on bedding planes. Sample A-29	0.5	82.5
24.	Laminated sandstone. Light olive gray (5Y5/2) cross laminated v. fine grained sandstone. Weathers yellowish gray (5Y7/2). Abundant organics and mica on bedding planes. Interstratified finely laminated siltstones. Samples A-30A, A-30B, A-30C, A-30D.	4.0	86.0
25.	Fossiliferous shale. Light olive gray (5Y5/2) foss. silty shale. Weathers yellowish gray (5Y7/2). Fossils include bivalves and ostracode casts. Sample A-31.	2.5	88.5
26.	Laminated sandstone. Light olive gray (5Y5/2) cross laminated massive sandstone. Weathers yellowish gray (5Y7/2). Calcareous cement. Abundant mica and organic material. Sample A-32.	2.5	91.0

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| 27. Laminated siltstone. Light olive gray (5Y5/2) laminated siltstone. Weathers yellowish gray (5Y7/2). Samples A-33, A-34. | 3.0 | 94.0 |
| 28. Laminated sandstone. Dusky yellow (5Y6/4) laminated fine sandstone. Weathers yellowish gray (5Y7/2). Laminations are discontinuous and composed of v. fine grained material. Abundant mica and organic material. Samples A-35A, A-35B. | 4.0 | 98.0 |
| 29. Siltstone. Dusky yellow (5Y6/4) siltstone. Weathers yellowish gray. Sample A-36. | 2.5 | 100.5 |
| 30. Fine sandstone. Dusky yellow (5Y6/4) fine sandstone. Weathers yellowish gray Med. bedded. Burrowed at top. V. porous. Samples A-37A, A-37B. | 2.5 | 103.0 |
| 31. Covered | | |

Alta (HWY 60): Williamsburg-Blue Sulphur District, Greenbrier County, West Virginia. Measured along U.S. Hwy. 60 approximately 1.5 mi. west of Alta on the west limb of the Williamsburg Anticline. Starting at the limestone quarry continuing west for 0.4 mi. to the Union-Alderson contact and extending up the hill to the Alderson-Lillydale contact.

	Unit Thick Feet	Cum. Thick Feet
1. <u>Union Fm.</u> Oolitic grainstone.	Not measured	
2. <u>Alderson Fm.</u> Calcareous siltstone. Olive gray (5Y3/2) calcareous siltstone. Weathers dusky yellow. Sample ALT-1.	12.0	12.0
3. Skeletal wackestone. Olive gray (5Y3/2) skeletal wackestone. Weathers dusky yellow (5Y6/4). Fossils include bryozoans, echinoids, brachiopods, and corals. Sample ALT-2.	3.0	15.0
4. Oolitic grainstone. Medium dark gray (N4) oolitic grainstone. Weathers light gray (N7). Fossils include echinoids, bryozoans, brachiopods, and corals. Samples ALT-3 and ALT-4.	9.0	24.0
5. Skeletal wackestone. Light olive gray (5Y5/2) silty skeletal wackestone. Weathers medium light gray (N6). Fossils include bryozoans, brachiopods, and echinoids. Samples ALT-5 to ALT-7.	15.5	39.5
6. Skeletal grainstone. Dark gray (N3) silty skeletal grainstone. Weathers light gray (5Y6/1). Fossils mostly echinoids, others include brachiopods and bryozoans. Silty laminae and cross laminations. Sample ALT-8.	5.0	44.5
7. Silty mudstone. Light olive gray (5Y5/2) laminated silty mudstone. Weathers yellowish gray (5Y7/2). Wavy laminations and pods of sand. Less laminated at top. Abundant plant material in upper part. Possible channel plug. Samples ALT-9 and ALT-10.	20.0	64.5

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| 8. Skeletal packstone. Dark gray (N3) silty skeletal packstone. Weathers medium light gray (N6). Small, well rounded fossils including bryozoans, echinoids, and brachiopods. Sample ALT-11. | 6.0 | 70.5 |
| 9. Laminated mudstone. Grayish orange (10YR7/2) laminated mudstone. Weathers yellowish gray (5Y7/2). Laminations are medium dark gray (N4). Sample ALT-12. | 4.5 | 75.0 |
| 10. Silty skeletal wackestone. Olive black (5Y2/1) silty skeletal wackestone. Weathers olive gray (5Y5/2). Fossils are bryozoans. Samples ALT-13 and ALT-14. | 11.0 | 86.0 |
| 11. Calcareous sandstone. Light olive gray (5Y5/2) calcareous, fossiliferous, fine sandstone. Weathers light gray (N7). Fossils are brachiopods and unidentified fossil fragments. Also some organics. Sample ALT-15. | 4.0 | 90.0 |
| 12. Calcareous shale. Brownish black (5YR2/1) calcareous silty shale. Weathers same. Possible base of Lillydale Shale. Sample ALT-16. | 3.0 | 93.0 |

Alta (Interstate-64): Williamsburg District, Greenbrier County, West Virginia. Measured along Interstate-64 east of Alta on the east limb of the Williamsburg Anticline. Starting mi. west of Lewisburg at the Alderson-Lillydale contact and extending approximately 300 ft. eastward.

	Unit Thick <u>Feet</u>	Cum. Thick <u>Feet</u>
1. <u>Lillydale Shale Mbr., Bluefield Fm.</u>	Not measured	
2. <u>Alderson Fm.</u> Algal boundstone. Olive gray (5Y4/1) algal boundstone. Weathers light olive gray (5Y6/1). Shows some burrows. Top of algal mat has dessication cracks. This marks a very slight angular unconformity. Sample AA-2.	0.1	0.1
3. Oolitic packstone. Moderate red (5R4/6) skeletal oolitic packstone. Weathers grayish red (10R4/2). Fossils include rugose corals, brachiopods, bryozoans, echinoids, and trilobites. Eroional contact with unit 4. Sample AA-2.	0.1	0.2
4. Oolitic wackestone. Olive gray (5Y4/1) skeletal oolitic wackestone. Weathers light gray (N7) and moderate yellowish brown (10YR5/4). Replacement along fractures by ankerite. Fossils include brachiopods, echinoids, and bryozoans. Sample AA-2.	0.1	0.3
5. Intraclastic packstone. Olive gray (5Y4/1) skeletal intraclastic packstone. Weathers light olive gray (5Y6/1). Intraclasts are oolitic grainstone (possible Union Fm.) and range up to 3 ft. in diameter. Fossils include echinoids and brachiopods. Some oolites in matrix. Samples AA-3 and AA-4.	6.5	6.8

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| <p>6. Intraclastic packstone. Medium dark gray (N4) oolitic intraclastic packstone. Weathers light gray (N7) and grayish red (5R4/2). Abundant skeletal material including echinoids, brachiopods, bryozoans, and gastropods. Hematite zone of varying thickness (up to 1 in. thick). Intraclasts are of algal origin consisting of concentric laminae with some pyrite. Intraclasts vary in color (red, black, green, tan) and are aligned parallel to bedding. Sample AA-6.</p> | 1.0 | 7.8 |
| <p>7. Skeletal wackestone. Greenish black (N2) skeletal wackestone. Weathers light olive gray (5Y6/1). Fossils include echinoids, brachiopods, gastropods, bryozoans, and forams. Sample AA-7.</p> | 2.0 | 9.8 |
| <p>8. Bryozoan bafflestone. Olive gray (5Y4/1) bryozoan bafflestone. Weathers light olive gray (5Y6/1). Fossils include <u>Archimedes</u>, brachiopods, and echinoids. Samples AA-8 and AA-9.</p> | 4.0 | 13.8 |
| <p>9. Silty mudstone. Olive gray (5Y4/1) silty mudstone. Weathers light olive gray (5Y6/1). Contains plant fragments infilled with hematite.</p> | 1.5 | 15.3 |
| <p>10. Calcareous shale. Medium gray (N5) calcareous shale. Weathers light olive gray (5Y6/1). Sample AA-10.</p> | 5.0 | 20.3 |
| <p>11. Silty mudstone. Olive gray (5Y4/1) silty mudstone. Weathers light olive gray (5Y6/1). Horizontal burrows infilled with hematite. Sample AA-12.</p> | 2.0 | 22.3 |
| <p>12. Covered</p> | | |

APPENDIX B

APPENDIX C

APPENDIX C

AVERAGES FOR PERCENT CARBONATE AND INSOLUBLES

	% CARBONATE	% INSOLUBLE
FACIES I (undivided)	32.70	67.30
FACIES II		
IIA	47.91	52.09
IIB	61.60	38.40
IIC	56.26	43.74
OUTLIER 1	85.55	14.45
FACIES III		
INTRACLASTIC	85.62	14.38
OOLITIC	87.93	12.07
BIOCLASTIC	82.30	17.70
FACIES IV		
PELMICRITE	84.55	15.45
BIOMICRITE	77.45	22.55
MICRITE	64.77	35.23

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