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Abstract

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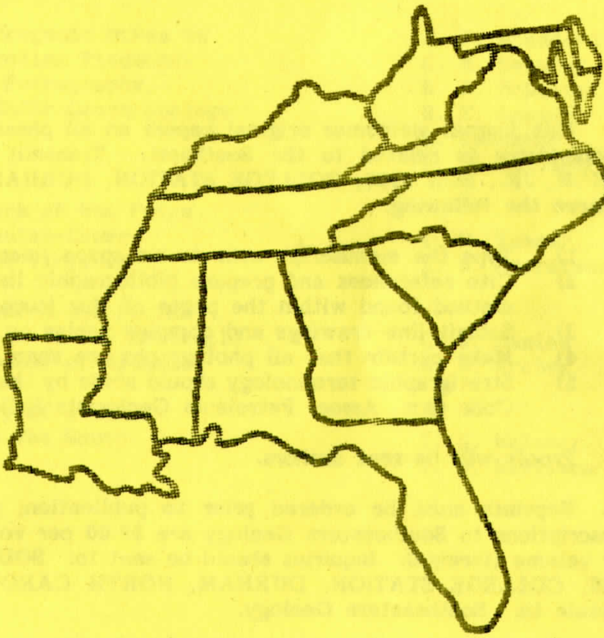

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SOUTHEASTERN GEOLOGY

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A NEW SUITE OF POST-OROGENIC DIKES IN THE EASTERN NORTH CAROLINA PIEDMONT: PART I. OCCURRENCE, PETROGRAPHY, PALEOMAGNETICS, AND RB/SR GEOCHRONOLOGY

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ABSTRACT

A new suite of hypabyssal dikes has been recently discovered and mapped in the northeastern North Carolina and adjacent Virginia Piedmont. The dikes have intruded late Precambrian (?) to late Paleozoic rocks of the Raleigh Belt and Eastern Slate Belt, and they trend between N10°W and N30°W, subparallel to the diabase dikes common in the Piedmont. Modeling of ground magnetic data indicates the dikes dip steeply, between 60°W amd 60°E. The dike rocks are bimodal in composition: the more felsic group consists of rhyolite porphyries and pitchstone or vitrophyre, and the more mafic are basalts or andesites. All rhyolite samples contain phenocrysts of alkali feldspar (sanidine-anorthoclase) and quartz (beta forms); many also contain phenocrysts of Fe-Ti oxide minerals, ferropigeonite, hastingsite, and apatite. The mafic rocks superficially resemble diabase, but they are quite different from nearby olivine diabase, in that they contain pigeonitic clinopyroxene, plagioclase, and Fe-Ti oxide minerals as phenocrysts, and they have alkali feldspar in the groundmass; none contain olivine. All samples (felsic and mafic) are amygdaloidal; amygdules in various samples are filled with a clay mineral, silica, or calcite. Field and petrographic characteristics suggest very shallow levels of emplacement; at one locality the rocks may have been extrusive. A nine-point sanidine-whole rock Rb/Sr isochron yields an age of 202 ± 5 Ma, with an initial $^{87}Sr/^{86}Sr$ of 0.7067 ± 0.0002. Paleomagnetic study of seven sites yields a virtual geomagnetic pole position of 67.6°N, 75.6°E (kappa=37, alpha-95=10, dp=6, dm=11), statistically equivalent to poles established for 200-Ma rocks in stable cratonic North America, as well as poles determined for diabase dikes of the southern Appalachian Piedmont. We conclude that these rock are late Triassic to early Jurassic in age, and roughly contemporaneous with the common diabase dikes of the Piedmont. Because of their trends and apparent age, we suggest that, like the diabases, the rocks of this suite are a result of processes leading up to and/or accompanying the initial opening of the Atlantic Ocean during the early Mesozoic.

INTRODUCTION

A suite of post-orogenic hypabyssal intrusive rocks and at least one occurrence of their possible extrusive equivalents occur in the northeastern Piedmont of North Carolina and adjacent Virginia. Although in several instances they are spatially associated with the familiar diabase dikes of Triassic-Jurassic age, they are not in all cases, and their petrography and geochemistry are strikingly distinct. No clear field evidence concerning the relative ages of these rocks with respect to the diabases or to sedimentary deposits of the Coastal Plain has been observed.

After the first discovery of an exposure of this suite by W. H. Spence in 1976, reconnaissance mapping by McDaniel (1980) for the North Carolina Geological Survey turned up several similar occurrences. Spence and McDaniel (1979) first reported the occurrence of felsic members of the suite; Delorey and others (1982) reported preliminary results of paleomagnetic and geochronologic studies. Since its discovery, the lithologies represented, geographic range, and mapping of dikes of the suite have been extended considerably (Kite, 1982; Delorey, 1983; Boltin, 1985; Stoddard, unpub. mapping). This paper aims to summarize the field relationships, petrographic characteristics, and age of these rocks. A companion paper (Part II; Stoddard, in preparation), deals with the geochemistry and petrology of the rocks of the suite.

GEOLOGIC SETTING

Few detailed geologic studies have been conducted in the area of the dikes. Parker (1968) did reconnaissance which included a portion of the area. McDaniel (1980) and Wilson (1981) have mapped portions of the area, in preparation for a new edition of the state map. Farrar (1985a,b) has completed a reconnaissance study of the entire North Carolina eastern Piedmont. Limited mapping and petrologic study of metamorphic rocks in

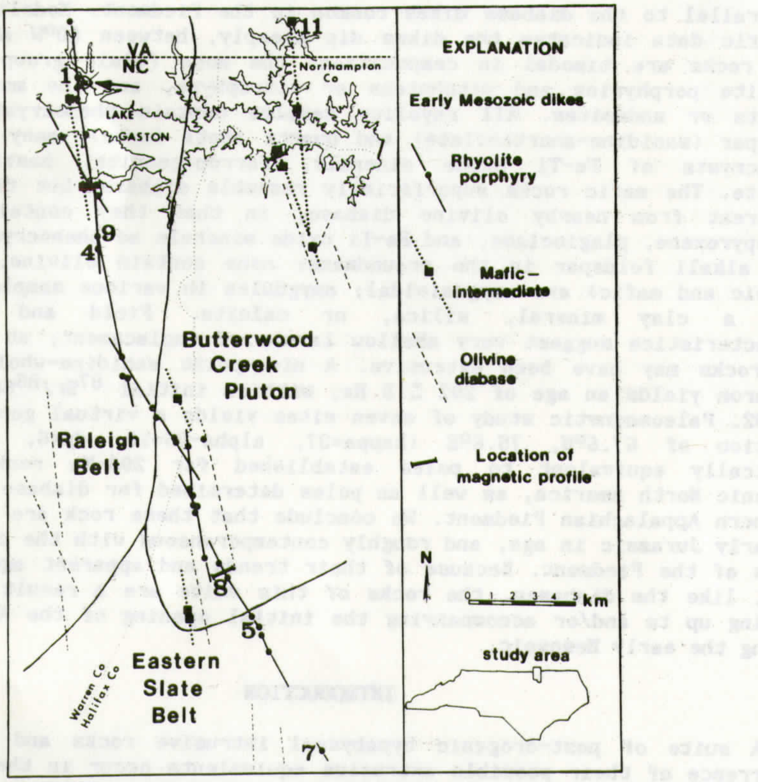


Figure 1. Generalized geologic map of the northeastern Piedmont of North Carolina and adjacent Virginia, indicating locations of dikes. Numbered points are localities referred to in text; exposures of silicic dikes are indicated by dots, mafic and intermediate ones by squares. The star locates the strongly flow-banded occurrence.

Franklin and Warren Counties has been undertaken (Stoddard and McDaniel, 1979), and a study of the Halifax County mafic-ultramafic complex has been completed (Kite and Stoddard, 1984). Kite (1982) and Boltin (1985) mapped several of the dikes in the Ringwood and Hollister quadrangles, respectively.

The dikes intrude a terrane of deformed metasedimentary and metavolcanic rocks which varies in regional metamorphic grade from greenschist facies in the southeast to amphibolite facies in the northwest (Figure 1). The low grade portion is part of what has been traditionally referred to as the Eastern Slate Belt; the higher grade rocks belong to the Raleigh Belt. In the area of the dikes, the boundary between the two belts is a steep metamorphic gradient (Farrar, 1985a; Boltin and Stoddard, 1983). Two late Paleozoic granitoid plutons have intruded the metamorphic rocks. These are the 292 Ma Butterwood Creek pluton (Russell and others, 1985) and the the 301 Ma Medoc Mountain pluton (Fullagar and Butler, 1979). Dikes of the new suite clearly intrude the Butterwood Creek pluton. Late Paleozoic deformation (Russell and others, 1985) associated with the Hollister mylonite zone has affected rocks of the Eastern Slate Belt, the Raleigh Belt, and the Butterwood Creek pluton (Farrar, 1985b; Kite and Stoddard, 1984; Boltin and Stoddard, 1983), but not the dikes.

OCCURRENCE AND FIELD RELATIONS

Ten separate dikes have been mapped in an area encompassed by seven 7.5-minute quadrangles in Halifax, Warren, and Northampton Counties, North Carolina, and Brunswick County, Virginia. The dikes strike in the range N10°W to N30°W, roughly parallel to the trends of olivine diabase dikes from the same region (e.g. Burt and others, 1978; Ragland and others, 1983) and most of the mapped dikes comprise a vaguely *en echelon* pattern (Figure 1). Undoubtedly additional dikes will be discovered as detailed field studies in the area progress. The thickness of the dikes, were measureable, ranges from less than one meter to more than 30 meters; outcrop patterns suggest near-vertical dips. The dikes are relatively well-exposed. Most examples occur as spheroidal boulders, but creekbed and roadside outcrops are not uncommon. The dikes are expressed locally as hills or ridges; because the rocks of the suite are very resistant, fresh examples are more prevalent that are those of the country rocks. In terms of the number of exposures observed, and of the total dike length mapped, the felsic dikes seem to be considerably more abundant than the mafic varieties. Exposures of this suite can easily be mistaken for the familiar olivine diabase dikes, also prevalent in the area. Commonly, the simplest means to make the distinction is the ubiquitous occurrence, in both felsic and mafic dikes of the new suite, of spherical or ovoid amygdules ranging from 1 mm to 1.5 cm in diameter, which are generally accentuated in the weathering rind. Locally, elongate amygdules display a preferred orientation, presumably the result of magma flow.

Ground Magnetics

In order to model the structural attitude of the dikes, nine ground magnetic traverses were carried out perpendicular to the strike of known dikes using a proton precession total field magnetometer. Readings were taken at intervals ranging from 0.5 to 3.0 m; the magnetic anomaly profiles thus obtained were then used to model the dikes using a technique which applies Gauss' method (Won, 1981) in order to approximate the width and dip of the dike, among other parameters. Magnetic anomaly amplitudes measured on the silicic dikes ranged from 125 to 400 gammas; the two mafic dikes traversed yielded anomalies of 430 and 775 gammas. Results of the magnetic models suggest dike widths, where measured, from 3.2 to 12.2 m, and dips ranging from 58°E to 59°W. Representative magnetic profiles and their best-fit models are shown in Figure 2.

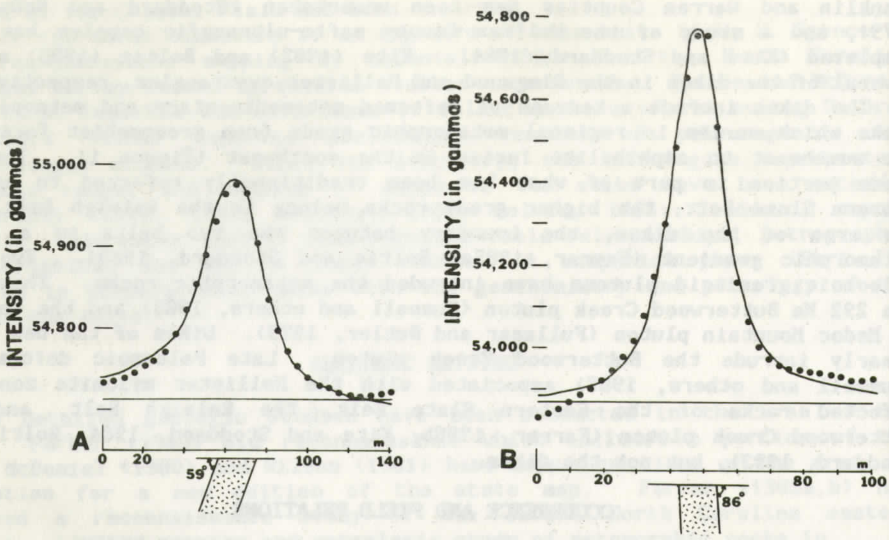


Figure 2. Representative ground magnetic profiles and their best-fit model for a silicic dike (A) and a mafic dike (B). The dots are measured points the curves are computer-generated models. Locations of traverses ar indicated on Figure 1; country rock in both cases is granitic.

Contact Effects

Although dike contacts with the country rocks are not well exposed, the can commonly be located to within considerably less than one meter. Effect of interaction between dikes and country rocks are not common, but in on place a very thin zone (about two cm) of microbreccia was observed along th contact, and in another case pelitic country rocks contain very coars recrystallized muscovite plates. The contacts are apparently exceedingl sharp in most cases. In a single, poorly exposed locality, a silicic dik appears to contain abundant xenoliths of the granitic country rock. In thi sections of these xenoliths, quartz-feldspar grain boundaries are occupied b a brownish altered but nearly isotropic material, suggesting local partia fusion of the country rocks.

PETROGRAPHY

On the basis of shared textural and mineralogical properties, all but tw of the exposures that have been examined petrographically fall readily int either the felsic group or the mafic group. One of the two exceptiona exposures is of a strongly flow-banded rock; the other is a dike thought t be intermediate in composition. These will be described separately; averag modal analyses are shown in Table 1. Figure 3 illustrates some of th petrographic features.

Silicic Dike Rocks

When fresh, these rocks are porphyritic with a dark gray to blac microcrystalline to glassy groundmass in which sit colorless or whit (commonly glomeroporphyritic) phenocrysts of sanidine-anorthoclase and quart (beta forms.). In thin section, partial resorption of early-formed quart phenocrysts by the magma is suggested by locally embayed crystal outlines Other phenocryst phases, which may or may not be present in a given sample include ferropigeonite, hastingsitic amphibole, plagioclase, ilmenite, Ti magnetite, apatite, and pyrite. Typically, the phenocrysts constitute five to 25 percent of the rock's volume. Amygdules in the silicic dike rocks may be filled with secondary silica, calcite, or more commonly a green or brown, nearly or completely isotropic clay mineral. Zeolites have not been found. Amygdules range from two to six volume percent.

Table 1. Average estimated modal analyses and petrographic features of Piedmont dike suite.

Group	No. Sections	Phenocrysts san	qtz	apa	opq	pla	pyx	olv	Groundmass		Amygdules
Silicic	54	9	5	1	1	tr	tr		80	(Glassy or felsitic; some with micropheno- crysts of oxides, hastingsite, biotite)	4
Flow-banded	4	11	1	tr	1	tr	2	tr	83	(flow-banded, spheru- litic, or glassy)	2
Mafic	12			1	9	30	10		45	(brownish; alkali feldspar-rich)	5
Intermediate	2			tr	1	20			75	(microphenocrysts of alkali feldspar, quartz, hastingsite, oxides)	5

san = sanidine-anorthoclase; qtz = quartz; apa = apatite; opq = Fe-Ti oxide minerals; pla = plagioclase; pyx = pigeonite-ferropigeonite; olv = olivine.

The groundmass of these rocks may be vitreous or pitchy in hand specimen, and gray and isotropic, with a few sparse perlitic cracks but no discernible crystalline phases under the microscope. More commonly, however, it is dark gray and aphanitic in hand specimen but in thin section a felsitic texture, comprising numerous tiny crystals and crystallites can be seen. Incipient spherulitic crystallization centers are present in a few sections, and most commonly the groundmass contains abundant (up to ten percent) tiny opaque crystals, and hairlike, locally slightly curved, skeletal brown crystallites of oxide minerals. The coarsest of the groundmasses contain discernible biotite, alkali feldspar, and brown (hastingsitic) amphibole, but no other groundmass phases are identifiable optically.

Mafic Dike Rocks

Four of the mafic samples examined belong to a dike which has been traced for about ten km; a similar dike has been mapped for at least 15 km. Samples from these dikes plus similar occurrences from the southern part of the area superficially resemble fine-grained varieties of local olivine diabase in hand specimen, but there are several important distinctions: the tiny (0.1-0.5 mm) plagioclase laths are usually not randomly oriented, as in nearby diabase, but lie in a weakly pilotaxitic arrangement; and nearly spherical clay-, silica-, or calcite-filled amygdules are common. In thin section, pigeonitic clinopyroxene is generally not interstitial to plagioclase, but occurs in prismatic crystals of about the same or slightly smaller size. Olivine is not present, opaque minerals are extremely abundant, and the brownish interstitial material is dominated by alkali feldspar.

Intermediate Dike Rocks

An intermediate dike rock occurs in two localities. It is a striking porphyritic rock with preferentially oriented blocky plagioclase crystals (some in excess of two cm in length) and large ovoid clay-filled amygdules, both preserving the same lineation. The only phenocryst phase aside from plagioclase are the opaque minerals (both ilmenite and Ti-magnetite are present); quartz and apatite occur as microphenocrysts. The alkali-feldspar dominated groundmass is also charged with oriented brown crystals of amphibole.

Flow-Banded Rocks

These rocks, obtained at a single locality, bear some petrographic similarities to the felsic dike rocks, but are dominated by a flow fabric. In thin section, the flow bands are alternately nearly opaque with only a few scattered spherulitic devitrification centers, or light gray and microcrystalline. The flow bands are commonly folded in complex, disharmonic fashion. These rocks are glomeroporphyritic; in addition to sanidine, anorthoclase, quartz, apatite, plagioclase, and opaques, they contain a few large crystals of pyroxene (ferropigeonite) and olivine (in the same thin section but not adjacent to deeply embayed quartz). These rocks contain amygdules similar to those in the felsic dike rocks.

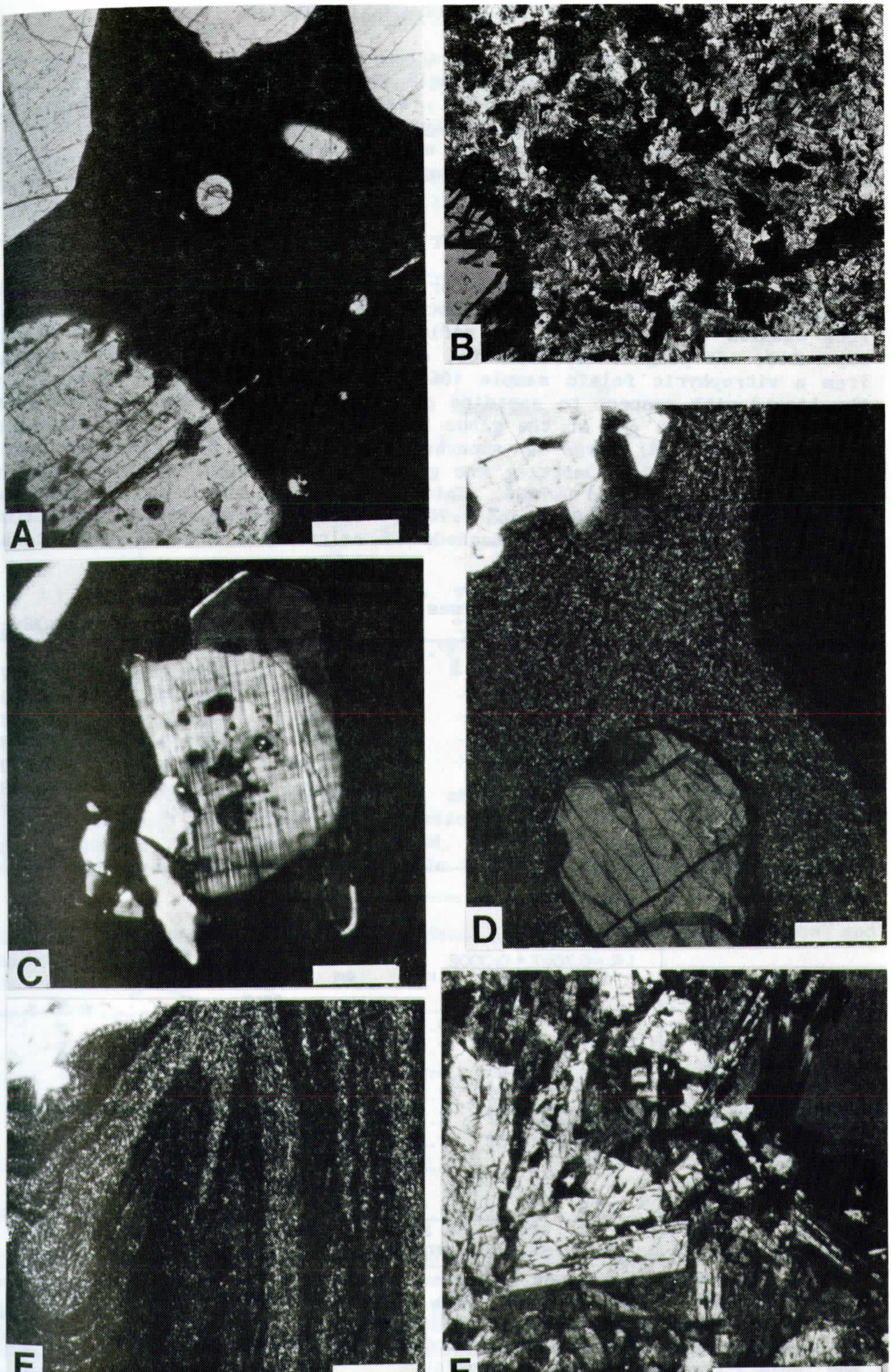
Cooling and Emplacement

The porphyritic and locally vitrophyric textures of the dike rocks, together with the common skeletal morphology of groundmass grains (especially titanomagnetite), suggest that these rocks were cooled exceedingly rapidly from liquidus temperatures. The ubiquitous and abundant amygdules require that vesiculation took place, and the relatively large size of these cavities in many samples (up to 1.5 cm) suggests shallow depths of emplacement. The single occurrence of flow banding similar in appearance to that common in volcanic rocks may have been formed in a subaerial flow, but there is no evidence of a former volcanic edifice in the area, and the nearest known stratified rocks of similar age are in the Durham basin, 60 km to the west. Perhaps it is more likely that the flow bands were produced in a plug or small volcanic dome.

Classification

Because of the predominantly aphanitic groundmasses of the rocks of the suite, volcanic rock names are thought to be more appropriate than plutonic ones. On the basis of the phenocryst assemblages, the felsic rocks would be classified as rhyolite, the flow-banded samples as quartz trachyte, the intermediate samples as andesite, and the mafic ones as basalt. Application of chemical criteria results in slightly different rock names (Stoddard, in prep.). No rocks of the suite appear to be trachytes, as previously reported by Spence and McDaniel (1979).

Figure 3. Selected photomicrographs, plane-polarized light. Scale bars are 0.5 mm in length. A. Rhyolite pitchstone, with glassy groundmass (black), and sanidine (lower left), and quartz phenocrysts. B. Rhyolite porphyry with relatively coarse-grained groundmass. Dark angular grains are hastingsitic amphibole; remainder of groundmass is almost entirely alkali feldspar. C. Anorthoclase phenocryst in porphyry. D. Ferropigeonite (lower center) and partially resorbed quartz (upper left) phenocrysts in flow-banded occurrence. E. Folded flow bands from same exposure as D. Sanidine glomerocryst at upper left. F. Sample of mafic dike of the suite. Large laths are plagioclase; smaller, high-relief prisms are pigeonite. Groundmass is alkali feldspar-rich. Edge of clay-filled amygdule at upper right.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RB/SR AND PALEOMAGNETIC STUDIES

Prior to this investigation, a late Cretaceous age for the felsic rocks was suggested on the basis of a single whole-rock conventional K/Ar age of 78.7 Ma (Spence and McDaniel, 1979). Because the suite is now known to be more widespread and compositionally variable than was previously believed, we have undertaken several independent methods of age determination. In this paper we report on Rb/Sr and paleomagnetic studies: K/Ar and $^{40}Ar/^{39}Ar$ are yet to be completed.

Rb/Sr Method

Nine specimens were analyzed for Rb and Sr isotopes (Table 2), using standard procedures (Fullagar and Butler, 1979). These include five whole-rock samples (three felsic, one mafic, and one intermediate), two sanidine separates, one plagioclase separate, and one sample of the glassy groundmass from a vitrophyric felsic sample (061781X). Rb fractionated strongly into the liquid with respect to sanidine phenocrysts, so the Rb/Sr ratios of the felsic whole rocks and of the glass range from 2.3 to 4.4. The nine-point isochron (Figure 4) gives an apparent age of 202 ± 5 Ma, and an initial $^{87}Sr/^{86}Sr$ of 0.7067. Omitting the glass does not significantly affect the results: 209 ± 7 Ma and 0.7066. Calculations using the felsic samples alone yields results of 196 ± 8 Ma and 0.7071. Within the analytical uncertainty, the results of these various methods of calculation are all statistically equivalent.

Table 2. Results of Rb and Sr analyses.

Sample No.	$(^{87}Sr/^{86}Sr)_N$*	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$
HFT-10	0.71465	126.4	137.2	2.667
HWR-Y	0.70808	57.83	363.9	0.460
RMW-D1	0.70770	69.57	421.0	0.478
CD-3	0.71697	143.0	122.9	3.369
061781X	0.71548	177.4	159.1	3.229
CD-3, sanidine	0.70998	68.42	225.4	0.878
061781X, sanidine	0.70829	47.51	248.9	0.552
RMW-D1, plagioclase	0.70618	7.00	695.7	0.029
061781X, glass	0.71896	193.6	126.2	4.442

*E+A 87/86 = 0.70800

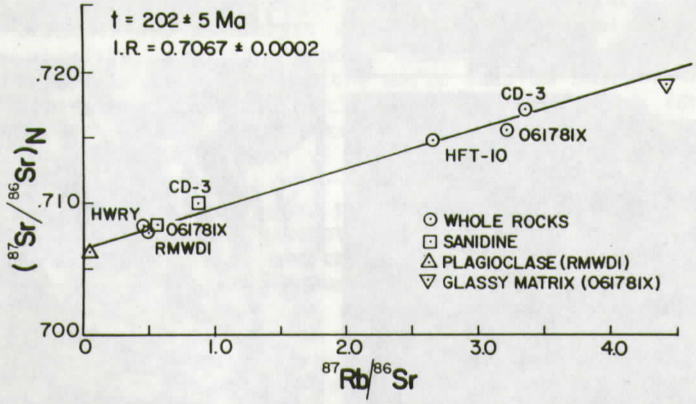

Figure 4. Rb/Sr isochron for five whole-rock samples (three silicic, one mafic, one intermediate), two sanidine separates, one plagioclase separate, and one concentrate of glassy groundmass of rhyolite vitrophyre. See text and Table 2 for details and discussion.

Paleomagnetic Method

A paleomagnetic study of the dikes has also been completed. Oriented cores were taken from six outcrops of felsic dikes and one of basalt belonging to the suite. An average of eight cores was obtained from each outcrop. The natural remanent magnetization (NRM) direction and intensity of each sample were measured before and after magnetic cleaning by partial demagnetization in an alternating field. The tighter clustering of the directions of magnetization after magnetic cleaning (compare Figures 5a and

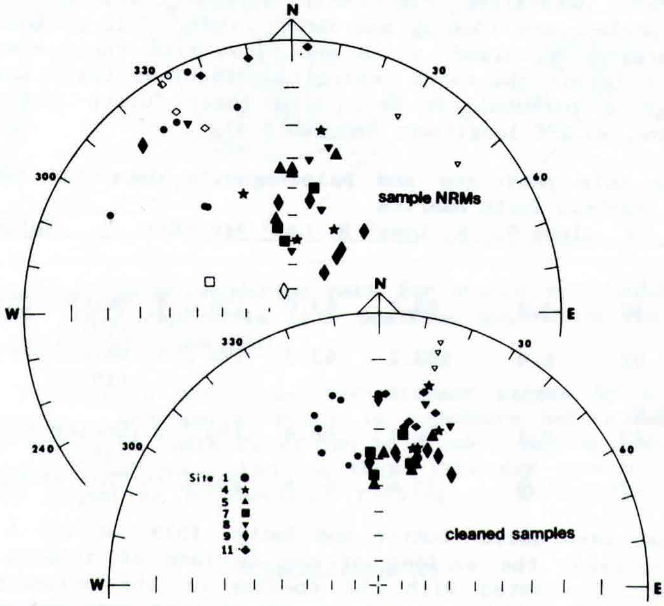

Figure 5. Stereographic projections showing directions of NRM for all samples included in the paleomagnetic study (top). After partial demagnetization in an alternating field, tighter grouping (bottom) suggests successful recovery of TRM. Open symbols indicate reversed polarity.

Table 3. Paleomagnetic results: Mean directions of magnetization and statistical parameters.

Site	Rock Type	N	Demag. (mT)	D°	I°	Alpha-95°	K	Inten. (amp/m)
1	R	10/12	20	348.9	27.0	7.7	40.0	0.712-1.680
4	R	4/5	40	4.1	38.9	11.0	71.1	0.013-0.483
5	R	6/7	15	17.6	39.9	8.1	70.2	0.006-0.316
7	R	4/5	25	16.1	27.5	11.2	68.4	0.115-4.844
8	R	7/11	25	18.7	12.2	15.2	16.7	0.166-0.870
9	R	8/12	30	14.3	34.3	12.6	20.4	0.006-0.539
11	B	6/6	15	10.7	24.8	6.0	124.4	6.669-16.80
Overall mean		7/9	--	10.2	29.6	10.02	37.2	

Virtual Geomagnetic Pole Position: 67.6°N, 75.6°E dp = 6.1, dm = 11.1

Notes: R = rhyolite; B = basalt; N = number of samples included in calculations / total number of samples measured; D = declination; I = inclination; K, alpha-95 = dispersion statistics; Inten. = range of NRM intensities; Demag. = conditions of magnetic cleaning, alternating field technique.

5b) suggests that the thermoremanent magnetization (TRM) directions were effectively recovered. Table 3 lists the NRM intensity, the recovered magnetic declination and inclination, and the corresponding pole position, together with standard paleomagnetic statistical parameters. The overall mean for all seven sites has a declination of 10° and an inclination of 30°, corresponding to a final virtual geomagnetic pole position of 67.6°N latitude and 75.6°E longitude, with a circle of confidence, alpha 95, of 10.02°. Further details concerning sample collection and analytical procedures are given by Delorey (1983).

This pole position agrees, within statistical limits, with pole positions which have been determined for Early Jurassic diabase dikes in the southeastern Appalachians (Dooley and Smith, 1982). It is also similar to positions determined on dikes, sills and flows from the Connecticut-Newark trend igneous rocks of the north central Appalachians (Smith and Noltimier, 1979), and agrees particularly well with their "Group 1" pole position (63.0°N latitude, 83.2°E longitude; see Table 4).

Table 4. Mean pole positions and paleomagnetic data for Early Mesozoic igneous rocks, eastern North America.

	N	K	alpha-95	E. Long°	N. Lat°	Age (Ma)	Reference
Northeastern U.S.							
Group 1	72	56	2.3	83.2	63.0	195 ± 4	Smith and Noltimier (1979)
Group 2	156	92	1.4	103.2	65.3	180 ± 3	Smith and Noltiemer (1979)
Southeastern U.S.							
	50	49	3.1	86.1	66.4	194 ± 4	Dooley and Smith (1982)
	7	37	10.0	75.6	67.6	200 ± 10	This study

Group 1 has been dated (Sutter and Smith, 1979) at 195 ± 4 Ma and is thought to represent the earlier of two periods of igneous activity of regional extent associated with the opening of the Atlantic (Smith and Noltimier, 1979). In addition to the agreement with ages and pole positions of igneous rocks of the eastern United States, the pole position determined in this study is also in agreement with Early Jurassic pole positions from stable cratonic North America (Smith and Noltimier, 1979). When plotted with Irving's (1979) apparent polar wandering envelope (Figure 6) determined for stable cratonic North America, the pole position obtained from the eastern Piedmont dikes is statistically consistent with those of comparable age (200 ± 10 Ma).

CONCLUSIONS

Dikes belonging to a distinctive igneous suite intrude late Paleozoic and older rocks of the northeastern North Carolina and adjacent Virginia Piedmont. The rocks are porphyritic and amygdaloidal; petrographically, most are either rhyolite or basalt. Textures and phenocryst mineralogy suggest very shallow levels of emplacement; well-developed flow banding at one locality suggests the faint possibility that the rocks are locally of extrusive origin. On the basis of Rb/Sr and paleomagnetic studies, we believe the suite is about 200 ± 10 Ma, and thus roughly contemporaneous with the familiar tholeiitic olivine diabase dikes of the Piedmont. Their trends are parallel to subparallel to those of the diabase dikes. Because of their similarity in age and orientation to the diabase, we suggest that dikes of the suite intruded fractures formed during crustal extension accompanying initial opening of the Atlantic Ocean. The petrographic distinctiveness of rocks of the suite suggests the possibility that they may have crystallized from magmas different from those which generated the diabases. Alternately,

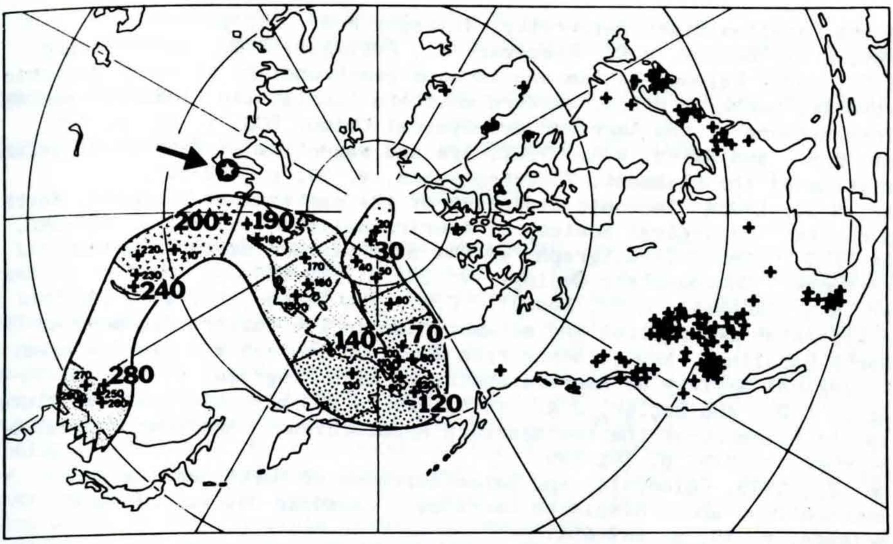

Figure 6. Apparent polar wandering path for stable cratonic North America (Irving, 1979). Star represents pole position determined for the Piedmont dike suite. Numbers are ages (Ma).

they may be related to the tholeiitic diabase magmas by any of various igneous processes. Geochemical study is necessary before any conclusions regarding the origin of these rocks can be drawn. However, at present, the possibility exists that more than one magma type may have played a role in early Mesozoic magmatism accompanying rifting in the southern Appalachian Piedmont.

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STRATIGRAPHIC FRAMEWORK OF THE PRICE FORMATION (UPPER DEVONIAN-LOWER MISSISSIPPIAN) IN WEST VIRGINIA

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ABSTRACT

Lithostratigraphic and chronostratigraphic subdivisions of the Price Formation in West Virginia are presented. On the basis of lithostratigraphic and biostratigraphic correlations the Oswayo Formation, Cussewago Sandstone, Riddlesburg Shale, and Rockwell Formation of western and central Pennsylvania are recognized as members of the Price in northern West Virginia. In southern West Virginia the Cloyd Coglomerate Member and Sunbury Shale Member of the Price Formation in Virginia are recognized in addition to the undivided upper portion of the Price. The rocks of the Price in West Virginia bear a greater lithologic similarity to the rocks of the Price Formation in Virginia than they do to the recently redefined Pocono Formation in northeastern Pennsylvania. For this reason, the use of the terms Pocono Formation and Pocono Group in West Virginia should be abandoned.

Rocks of the nearshore facies of the Sunbury transgression are recognized over much of the outcrop belt in West Virginia. These rocks comprise an important stratigraphic datum that when used in conjunction with biostratigraphic data permits chronostratigraphic subdivision of the marine facies of the Price in West Virginia. In northern West Virginia, marine rocks range from late Famennian to early Kinderhookian time, whereas those in southern West Virginia range from early Kinderhookian to early Osagean time.

INTRODUCTION

The Price Formation of West Virginia, formerly the Pocono Formation or Pocono Group, has never been comprehensively studied throughout its outcrop belt in West Virginia, except for an unpublished dissertation by Dally (1956). The present paper attempts to address this lack of knowledge by presenting a stratigraphic framework for the Price Formation in West Virginia. As part of a combined project on the paleoecology (Kammer) and sedimentology (Bjerstedt) of the Price, we found it necessary to revise the existing stratigraphic nomenclature for this interval in West Virginia. The proposed stratigraphic framework does not invoke any new rock-stratigraphic names. We found it was possible, and desirable, to extend stratigraphic nomenclature already present in surrounding areas into West Virginia. The revised stratigraphic nomenclature presented in this paper permits a more precise understanding of the depositional history of the Price because the subdivisions (members) represent genetically distinct sedimentary units. For ease of mapping in West Virginia, we have chosen to unite these subdivisions under the name Price Formation.

Detailed discussions of the depositional environments, paleoecology, and paleontology of the Price are beyond the scope of this paper. The measured sections that form the basis of this study will be included in Bjerstedt's (1986) dessertation.

Location

The Price Formation in West Virginia crops out along the eastern edge of the Appalachian Plateau from southeastern to northeastern West Virginia and in the western portion of the Valley and Ridge province (Figure 1). Twenty-one measured and supplementary sections in West Virginia form the basis of this study. In addition, ten outcrops of the Price in Virginia, and eleven outcrops of the Price, or equivalents, in Maryland and Pennsylvania were investigated in order to make a detailed comparison with these adjacent areas.

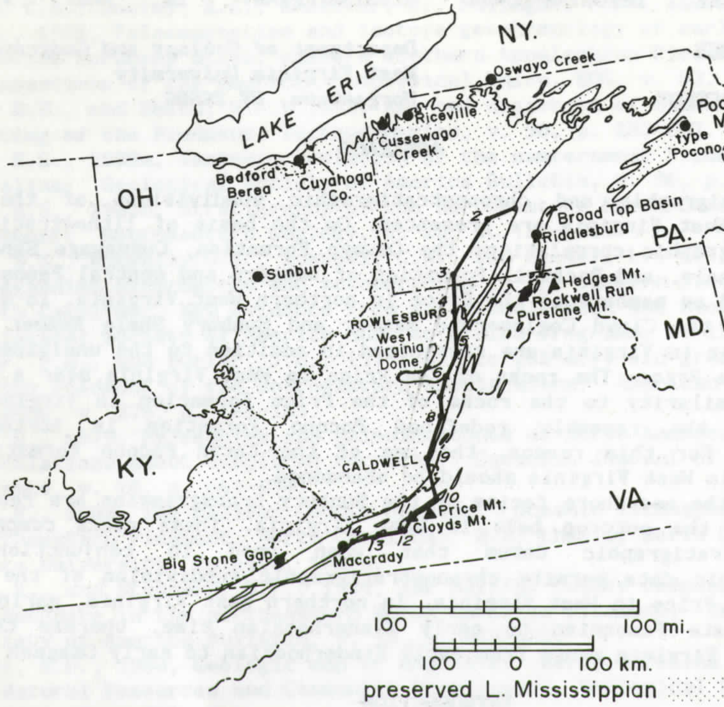

Figure 1. Index map showing preserved Lower Mississippian deposits in the Appalachian Basin. Type sections for rock-stratigraphic units discussed in text are shown as large dots if a place name and as triangles for mountains. Numbers indicate locations for sections used in the lithostratigraphic cross section in Figure 3.

HISTORY OF STRATIGRAPHIC NOMENCLATURE

The rocks of the Price Formation in West Virginia have had a variety of names applied to them. A review of these names is essentially a review of the name "Pocono". The nomenclatorial history of the Pocono is reviewed extensively by Read (1955), Sevon (1969), and Berg and Edmunds (1979) so only a brief summary will be given below.

H. D. Rodgers of the First Pennsylvania Geological Survey, in 1836, referred to the buff-colored sandstones between red beds below (Catskill) and red beds above (Mauch Chunk) as Formation Number 10. In 1838 he changed all his formation numbers to Roman numerals, thus Formation X instead of 10. In 1838 his brother, W. B. Rodgers of the Virginia Geological Survey, referred to the Price Formation at Caldwell and Marlinton, West Virginia (then part of Virginia) as Formation Number 10. Thus, the similarity of the rocks in Pennsylvania and Virginia (later West Virginia) was recognized. Later in 1844, H. D. Rodgers converted his Roman-numeraled formations to the hours of the Roman day and Formation X became the Vespertine Formation.

In 1876 J. P. Lesley of the Second Pennsylvania Geological Survey found it appropriate to give geographic names to Rodger's formations. The Vespertine thereby became the Pocono Formation because Lesley had mapped the Pocono Plateau of northeastern Pennsylvania as Vespertine in 1858. This began the long and controversial history of the rock-stratigraphic name "Pocono". I. C. White pointed out that there was no Vespertine in the Pocono Mountains, but Lesley was the Survey Director and his opinion prevailed.

This gave rise to the issue of the "false" Pocono (see Willard, 1939, p. 304). The Upper Devonian Catskill Formation, or its equivalents, crop out in the Pocono Mountains, whereas the true Pocono crops out in the Lehigh River Valley west of the Pocono Mountains (Sevon, 1969; Berg and others, 1980). Partially as a result of Lesley's mistake there has been a great deal of discussion in the literature as to the true age of the Pocono (for example: White, 1934; Chadwick, 1935). Although Lesley misapplied the name Pocono, it was used for rocks of the true Vespertine by other geologists.

Darton (1892, 1894) was the first to apply the name Pocono in West Virginia. He used the term for Vespertine rocks in Pendleton County, West Virginia as well as adjacent Rockingham and Augusta counties, Virginia. At approximately the same time, Campbell (1894) named the Price Formation for outcrops on Price Mountain in Montgomery County, Virginia (Figure 1). Strictly speaking, Darton's use of the name Pocono has priority over Campbell's use of Price. The name Pocono has been frequently used in a time-stratigraphic sense for all Lower Mississippian sandstones in Pennsylvania and it was thus logical to extend the name into the Virginias. The West Virginia Geological Survey has also used the name Pocono in a time-stratigraphic sense as the Pocono Series (Reger and others, 1923). The present Pennsylvania Geological Survey restricts the rock-stratographic name Pocono to nonmarine, coarse-grain sandstones in northeastern Pennyslvania (Berg and others, 1980). Thus rocks presently referred to as Pocono in West Virginia are not laterally contiguous with the rock-stratigraphic Pocono of Pennsylvania. For this reason we feel that the name Pocono must be abandoned in West Virginia.

Stose and Swartz (1912) divided what they called the Pocono Group near Hancock, Maryland into (ascending order) the Rockwell Formation, Purslane Sandstone, Hedges Shale, Meyers Shale, and Pinkerton Sandstone. The Myers Shale and Pinkerton Sandstone have been reassigned to the Mauch Chunk and Pottsville intervals, respectively, on the basis of their lithologies and nondiagnostic plant fossils (Read, 1955; Craig and Connor, 1979). The Rockwell, Purslane, and Hedges contain distinctive enough lithologies to be recognized as separate formations. The principal reference section for the Rockwell and Purslane formations is exposed in a new roadcut through Sideling Hill along U.S. Route 40, 10.4 km west of Hancock, Maryland (Bjerstedt, in press). The Hedges Shale is exposed only in the Meadow Branch syncline of Morgan and Berkeley counties, West Virginia (Stose and Swartz, 1912) (Figure 1).

The West Virginia Geological Survey county reports have commonly used informal driller's names such as Big Injun, Squaw, and Weir for sandstones on outcrop. Dally (1956), Pls. 2 & 3) in an unpublished dissertation proposed the Matoaka, Marlinton, and Manheim formations for his Pocono Group. Dennison and Wheeler (1975) listed Dally's names with a brief description for each. Neither driller's terms or Dally's units have formal status.

In southeastern West Virginia, the rock-stratigraphic units erected by Reger and Price (1926), e.g. Lindside Sandstone and Broad Ford (sic) Sandstone, should also be abandonoed. The name Lindside Sandstone has never been used on the outcrop by workers outside the West Virginia Geologic Survey since its initial definition in 1926. We also believe that the Broad Ford Sandstone cannot be reliably correlated outside its type area of southwestern Virginia, let alone into West Virginia and Pennsylvania as Reger (1927, p. 406) attempted to do. In addition, the Broad Ford, clearly meant by Reger and Price (1926) to be a Mississippian unit, has been so beset with differing age designations (Cooper, 1948, p. 258) and by the miscorrelations pointed out by Bartlett (1974, p. 21) that its usefulness as a rock-stratigraphic unit has ended.

ABANDONMENT OF "POCONO" IN WEST VIRGINIA

In West Virginia, we believe that substitution of Price for Pocono and subdivision of the Price into members meets the requirements of the North American Stratigraphic Code (1983, p. 855). To begin with, Formation X and Vespertine were never properly defined with a type section. Lesley compounded the problem by identifying Catskill sandstones as Vespertine and then designating the Pocono Mountains as the type area of the Pocono Formation. The original *concept* of the Pocono Formation was that it was a nonmarine unit that marked the base of the Carboniferous. This is essentially the use of the term today by the Pennsylvania Geological Survey (Berg and others, 1980). In northeastern Pennsylvania, the Pocono Formation as now recognized consists of Lower Mississippian fluvial sandstones that are equivalent to the fluvial Burgoon Sandstone of western Pennsylvania (Sevon, 1969; Berg and Edmunds, 1979; Berg and others, 1980). In the Lehigh River Valley type area, the Devonian-Mississippian Spechty Kopf Formation, previously considered part of the Vespertine and Pocono, lies below the Pocono Formation and above the Catskill Formation. In Pennsylvania rocks of the Pocono Formation are equivalent only to the upper part of the original Vespertine Formation and have a limited geographic extent. Rocks referable to the Pocono Formation do not extend into West Virginia. Rocks that have been called Pocono in West Virginia comprise a wide spectrum of lithologies and depositional environments unlike the Pocono Formation of northeastern Pennsylvania. Lithologies range from basinal black shales to continental conglomeratic sandstones. Major depositional environments include basin floor, submarine fan, shelf, marine deltaic, nonmarine deltaic, and fluvial depositional environments.

The above reasons suggest that stratigraphic nomenclature would be much improved by replacing Pocono with Price in West Virginia. Such a substitution would alleviate the present state of confusion by recognizing that rocks of the Price Formation in West Virginia are distinctly different from the Pocono sandstones of northeastern Pennsylvania. This change would also demonstrate the genetic similarity to the Price of southwestern Virginia, which contains a similar diverse facies assemblage (Kriesa and Bambach, 1973; Bartlett, 1974). The only argument against such a name change is that the name Pocono is entrenched in the West Virginia literature. This is not a significant problem, however, because many authors have referred to this interval as Price-Pocono (Campbell, 1894; Butts, 1940; Walker, 1964). The formations proposed by Stose and Swartz (1912) in eastern West Virginia and western Maryland (Figure 2) are distinct enough to stand alone and do not need to be combined as part of the Price Formation. In northern West Virginia and western Maryland the Price Formation should be recognized only where the Oswayo Member occurs on outcrop. Where this member pinches out eastward, in Allegany County, Maryland and Mineral County, West Virginia, the entire interval is referrable to the Rockwell Formation, except where the purslane Sandstone and Hedges Shale are also present.

In compliance with the Code of Stratigraphic Nomenclature, we feel there is sufficient justification for abondoning the name Pocono in West Virginia. The present use of this name in West Virginia implies rock-stratigraphic equivalence with the Pocono Formation of northeastern Pennsylvania, but the rocks of these two regions are lithologically and genetically very different. We have demonstrated a concern for nomenclatural stability by adopting the name Price. The rocks of the Price Formation in Virginia are laterally continuous with those in West Virginia and contain a similar suite of genetically related lithologies.

STRATIGRAPHIC FRAMEWORK

The Price Formation in West Virginia is comprised of distinctive lithologies that make the Price a readily mappable unit. The brown to gray sandstones, siltstones, and shales of the Price are easily distinguished from underlying and overlying lithologies. Over most of the state the Price is underlain by the red beds of the Hampshire Formation. Where the Price is

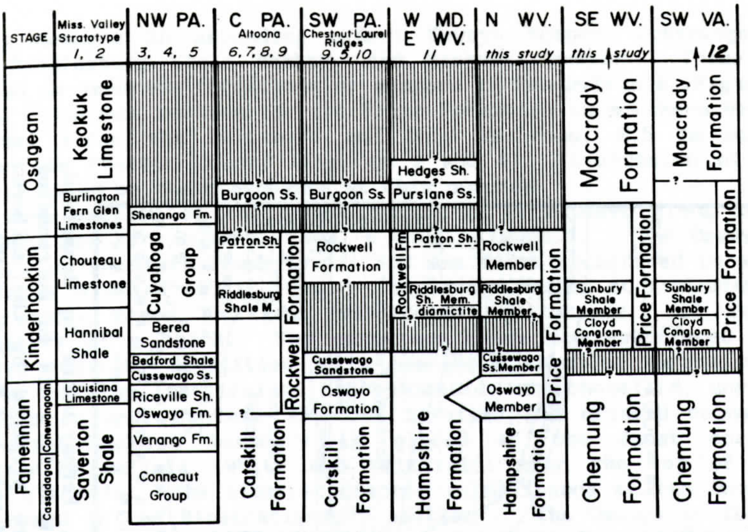

Figure 2. Correlation chart for the Price Formation of West Virginia and regions in adjacent Pennsylvania, Maryland, and Virginia. Numbers at top of columns refer to the following references: 1) Gutschick and Moreman (1967), 2) Dutro and others (1979), 3) Szmuc (1957), 4) Schiner and Kimmel (1972), 5) Berg and others (1980), 6) Berg and Edmunds (1979), 7) Streel and Traverse (1978), 8) Bayles (1949), 9) Laird (1941), 10) Laird (1942), 11) Bjerstedt (in press) 12) Bartlett (1974). Data contained in Laird (1941; 1942) has been reinterpreted.

underlain by the Chemung Formation in the southernmost counties, the base of the Price can be recognized by the presence of the Cloyd Conglomerate Member or the Sunbury Shale Member. The red beds of the Maccrady Formation overly the Price in southern West Virginia whereas the Greenbrier Limestone overlies the Price in central and northern West Virginia. In easternmost West Viginia (the panhandle) the red beds of the Mauch Chunk overlie the Rockwell, Purslane, and Hedges formations (Figure 2).

The Price is subdivided into members to better show its stratigraphic relationships with equivalent units in surrounding states (Figure 2). The Price has formation status rather that group status because the members are not easily mappable and have limited geographic extent. In addition, many outcrops of the Price are partial exposures where it is difficult to recognize those members that are present.

Deposition of Price sediments occurred in two large embayments or depocenters separated by a syndepositionally positive tectonic feature (Bjerstedt and Kammer, 1985) (Figure 3). This basement block has been called the Pocono Dome by Donaldson and Shumaker (1981). In view of the stratigraphic nomenclature proposed herein, we now prefer to call this feature the West Virginia Dome, or positive area, in accord with Craig and Connor (1979, Pl. 10). The dome experienced negligible subsidence in relation to the flanking depocenters during Price deposition and markedly influenced the pattern of facies distribution. The Price Formation north of the dome is older and is generally nonmarine. The Price south of the dome is generally younger and is dominantly marine representing the entire facies spectrum of a prograding, regressive sedimentary wedge, from basinal to upper delta plain.

Northern Depositional Basin

The Price Formation in northern West Virginia is divided into the

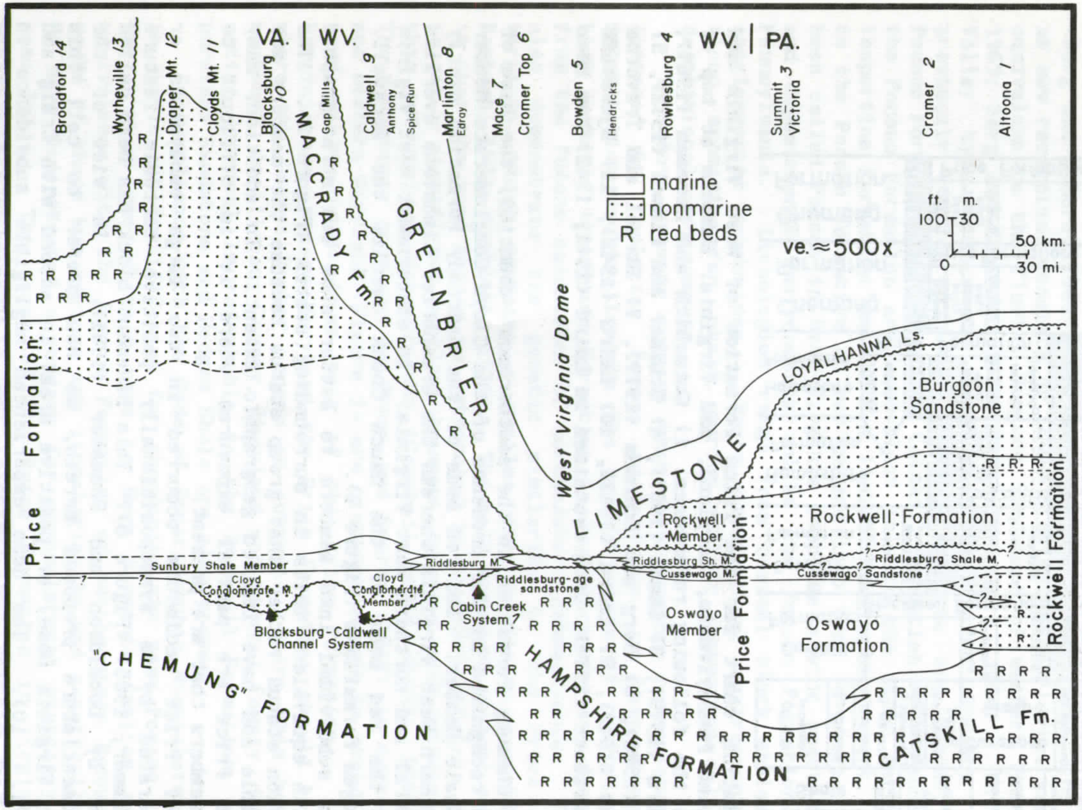

Figure 3. Lithostratigraphic cross section from Altoona, Pennsylvania to Broadford, Virginia showing the relationship of the price formation in West Virginia to surrounding areas. Measured and described sections in West Virginia were prepared by the authors. Pennsylvania sections from: Altoona - Swartz (1965); Cramer - Fettke and Bayles (1945); and Summit - Victoria - Laird (1941). Measured sections in Virginia from Bartlett (1974). Pennsylvania and Virginia sections have been modified by the authors based on field observations.

following members in ascending order: Oswayo Member, Cussewago Sandstone Member, Riddlesburg Shale Member, and Rockwell Member. These units are recognized as separate formations or members in Pennsylvania (Figure 2). The principal reference section for the Price Formation in northern West Virginia is exposed along the Baltimore and Ohio Railroad, 2.5 km northwest of Rowlesburg in Preston County (Figures 1 and 4). Discussion of individual members is based on their exposure at this outcrop.

The type section of the Oswayo Formation is exposed along Oswayo Creek near Olean, New York (Glenn, 1903, p 978) (Figure 1). The Oswayo is well-exposed in northwestern Pennsylvania and was first recognized in southwestern Pennsylvania by Laird (1941, 1942). The Oswayo Member at Rowlesburg consists of interbedded green and gray sandstones, siltstones, and silty shales approximately 65 m thick. The contained fauna and associated sedimentary structures indicate deposition in a nearshore, shallow marine environment. The fauna contains inarticulate, strophomenid, rhynchonellid, and spiriferid brachiopods as well as less abundant bivalves and crinoid columnals. The Devonian-Mississippian boundary is placed at the first occurrence of *Schellwienella inflata* (White and Whitfield) near the top of the Oswayo (Figures 4 and 7). The biostratigraphic significance of the Oswayo fossils are discussed in the Biostratigraphy section . The Oswayo at Rowlesburg is correlated with the Oswayo exposed in southwestern Pennsylvania near Summit and Victoria (Laird, 1941, 1942; Berg and others, 1980) on the basis of its faunal content, which is chiefly Devonian. The Oswayo represents nearshore environments that transgressed the alluvial plain of the Catskill delta.

The type section of the Cussewago Sandstone is exposed along Cussewago Creek in northwestern Pennsylvania (White, 1881) (Figure 1). The Cussewago Sandstone Member at Rowlesburg is apparently a marine deposit consisting of sandstones that are part of the "area F delta fan", or Gay-Fink Delta, of Pepper and others (1954, p. 36 Fig. 11, Pl. 13). The Cussewago is earliest Mississippian in age based on its fossil content. Pepper and others (1954) recognized this Cussewago delta as covering much of northern West Virginia in the subsurface with thicknesses approaching 30 m. At Rowlesburg the Cussewago is only 15 m thick. The Cussewago represents a minor regressive phase prior to the extensive basin-wide regression marked by the Berea Sandstone of Ohio (Pepper and others, 1954). Sedimentation was apparently continuous from Oswayo through Cussewago time. No sandstones correlative with the Berea Sandstone of Ohio have been recognized by us on the outcrop in northern West Virginia, although the Berea Sandstone is present in the subsurface of northern West Virginia (Pepper and others, 1954). The contact between the Cussewago Sandstone Member and Riddlesburg Shale Member at Rowlesburg is apparently disconformable as the result of Berea-age erosion.

The type section of the Riddlesburg Shale (Reger, 1927) is at Riddlesburg, Pennsylvania in the Broad Top Basin (Figure 1). The Riddlesburg Shale Member at Rowlesburg consists of 18 m of dark gray silty shales and siltstones. This unit records a marine transgression over the exposed Cussewago coastal plain and Berea-age erosional surface. Based on its position in vertical sequence, and faunal content of Kinderhookian brachiopods, we have correlated this unit with Reger's (1927) Riddlesburg Shale, a unit now recognized as a member of the Rockwell Formation in Pennsylvania (Edmunds and others, 1979). We have been able to trace the Riddlesburg Shale from Rowlesburg south to Marlinton in Pocahontas County. South of Marlinton the Riddlesburg grades into the Sunbury Shale at Caldwell (Figures 3 and 5). Partial exposures of the Riddlesburg can be seen at Hendricks (Tucker County), Harman (Randolph County), Wamsley Run (Pendleton County), and Mace (Pocahontas County) in addition to Rowlesburg and Marlinton. The Riddlesburg is the nearshore equivalent of the basinal Sunbury Shale of Kentucky, Ohio, southwestern Virginia, and southern West Virginia. The Sunbury is an oxygen-deficient, black shale deposited during a basin- wide transgression (Ettensohn and Elam, 1985).

The Rockwell Formation was named for exposures near Rockwell Run in

Morgan County, West Virginia (Stose and Swartz, 1912) (Figure 1). The type Rockwell is nonmarine and contains sandstones, coaly shales, and red mudstones. At Rowlesburg the Rockwell Member consists of 40 m of nonmarine sandstones, with minor siltstones and shales. The base of the Rockwell is marked by a prominent 4 m-thick conglomeratic, coarse-grain sandstone. At Rowlesburg there is a major unconformity between the Rockwell and the overlying Greenbrier Limestone. In southern Pennsylvania the Burgoon Sandstone lies between the Rockwell and Greenbrier, but there is no Burgoon on outcrop in northern West Virginia. The Purslane Sandstone, a Burgoon equivalent, crops out in the panhandle regions of western Maryland and eastern West Virginia. The absence of the Burgoon in northern West Virginia may be due to either non-deposition or pre-Greenbrier erosion. Dally (1956) incorrectly included Burgoon Sandstone at all of his measured sections north of Elkins in northern West Virginia.

Southern Depositional Basin

The Price Formation in southern West Virginia is divided into three parts with the Cloyd Conglomerate Member and Sunbury Shale Member near the base and an upper, unnamed part comprising the majority of the Price (Figures 2 and 6). The principal reference section for the Price Formation in southern West

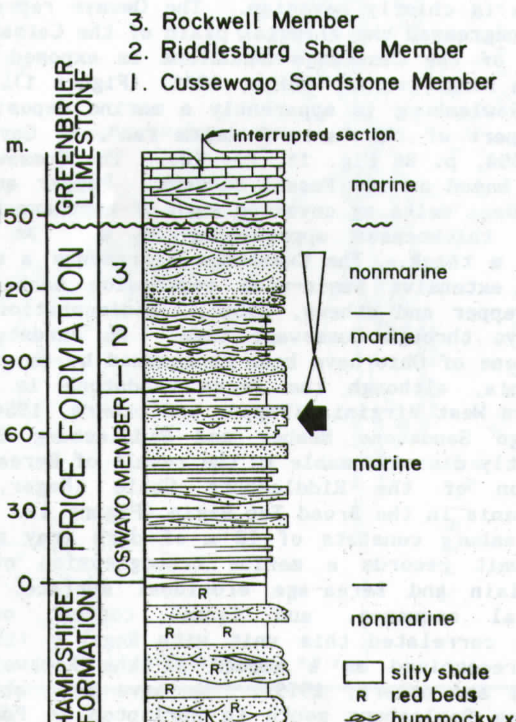

Figure 4. Principal reference section for the Price Formation in northern West Virginia at Rowlesburg in Preston County. Members are as labled with accompanying gross paleoenvironments and large-scale grain size trends. Arrow indicates approximate position of Devonian - Mississippian boundary based on the first occurance of the *Schellwienella inflata* (White and Whitfield).

Virginia is exposed along Interstate-64, 1 km southeast of Caldwell in Greenbrier County (Figure 6).

The Price Formation overlies the Devonian Chemung Formation in southern West Virginia and southwestern Virginia (Figure. 3). In an unpublished masters thesis, Glover (1953) proposed the name Parrott Formation for rocks of Mississippian age above the Chemung and below the Price. The "Parrott Formation" is lithologically identical to the Chemung Formation and was defined on the basis of what Glover believed to be the Mississippian-age fossils *Allorhynchus* and *Pseudosyrinx*. Neither of these genera were illustrated in his thesis. Fossils collected by us from the type section of Glover's "Parrott Formation" at Parrott, Virginia consist of long-ranging, eurytopic rhynchonellids and bivalves and the Devonian-age *Camarotoechia sappho* (Hall). None of the fossils indicate a definitive Mississippian age for the "Parrott Formation". Bartlett (1974, p. 311) reported *Cyrtospirifer disjunctus* (Sowerby) 49 m below the Cloyd Conglomerate, well within the

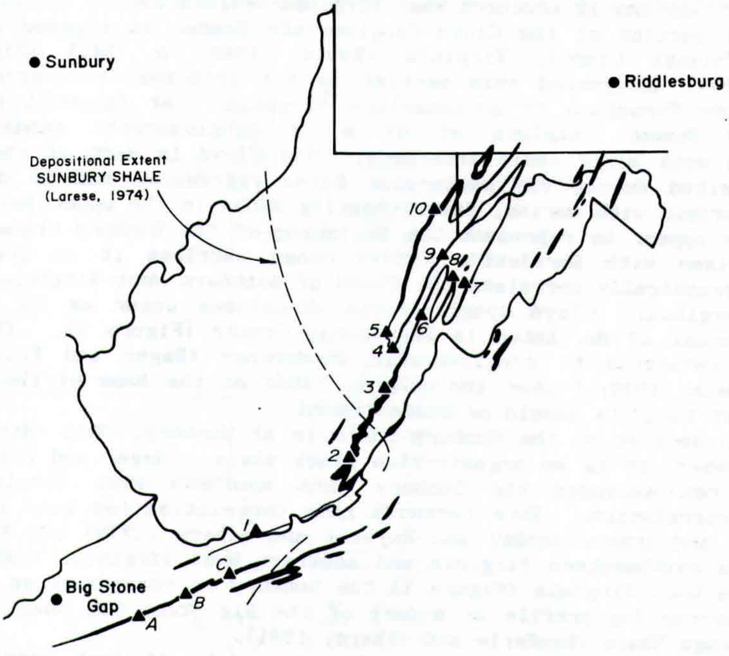

Figure 5. Outcrop belt of Lower Mississippian clastics in West Virginia showing depositional extent of the Sunbury Shale on outcrop and in the subsurface. Subsurface data based on gamma ray logs (Larese, 1974). Southwest of the dashed line, the Sunbury Shale Member of the Price Formation occurs as a basinal, grayish black to dark gray laminated shale and silty shale with interbedded siltstone. Northeastward the Riddlesburg Shale Member occurs as interbedded gray silty shales, silstones and sandstones. Near the axial region of the West Virginia Dome, Riddlesburg-age sandstones bearing Kinderhookian brachiopods were deposited in shallow-water, nearshore facies. Virginia locations, A, Hayters Gap; B, Broadford; and C, Ceres, are sections bearing typical dark grey, fissile lithologies of the Sunbury Shale (Big Stone Gap Shale) based on measured sections in Bartlett (1974, p. 239, 248, 258). West Virginia sections: 1, Bluefield; 2, Caldwell; 3, Marlinton; 4, Mace; 5, Monterville; 6, Cromer Top; 7, Wamsley Run; 8, Bowden; 9, Hendricks; 10, Rowlesburg. Sections 3, 4, 7, 9, and 10 contain Riddlesburg Shale whereas sections 5, 6, and 8 contain Riddlesburg-equivalent sandstones with Kinderhookian brachiopods deposited on the flanks of the West Virginia Dome.

"Parrott". Glover's "Parrott Formation" is actually part of the Chemung Formation and should not be recognized as a Mississippian-age unit as some authors have done (de Witt and McGrew, 1979; Craig and Connor, 1979, Pl. 15A). In as much as this quasi-formal unit (Cooper, 1961, 1971) has been established on paleontological grounds, it violates Article 22e of the North American Stratigraphic Code (1983) and should be abandoned as was done by Bartlett (1974, p. 21).

We believe there is an unconformity at the base of the Cloyd in the Virginias (Figure 2) because 1) there was an undetermined amount of erosion during the basin-wide "Berea" regression when the Cloyd Conglomerate Member was deposited, and 2) there are no Mississippian-age fossils at the top of the Chemung at Caldwell or Parrott, two places where both the Chemung an Cloyd are well exposed. There is a significant amount of relief on the tops of the Hampshire and Chemung formations caused by scouring in the Blacksburg-Caldwell (Donaldson and others, 1985) and Cabin Creek(?) (Pepper and others, 1954) channel systems in southern West Virginia (Figure 3).

The type section of the Cloyd Conglomerate Member is exposed on Cloyds Mountain, Pulaski County, Virginia (Butts, 1940, p. 343) (Figure 1). Bartlett (1974) designated this section as the principal reference section for the Price Formation in southwestern Virginia. At Caldwell the Cloyd Conglomerate Member consists of 47 m of conglomeratic sandstone and conglomerate with minor shale interbeds. The Cloyd is part of the fluvial system deposited during the basin-wide Berea regression and is dominantly fluvial in origin with marine, fossil-bearing zones in the upper half. These marine zones appear to represent the beginning of the Sunbury transgression. From comparison with Bartlett's (1974) cross sections it is possible to lithostratigraphically correlate the Cloyd of southern West Virginia with the Cloyd of Virginia. Cloyd conglomeratic sandstones occur as far north as Edray, northeast of Marlinton in Pocahontas County (Figure 3). The use of "Berea" in reference to conglomeratic sandstones (Reger and Price, 1926; Price and Heck, 1939; Potter and others, 1983) at the base of the Price in southern West Virginia should be discontinued.

The type section of the Sunbury Shale is at Sunbury, Ohio (Hicks, 1878) (Figure 1) where it is an organic-rich black shale. Reger and Price (1926, p. 525) first extended the Sunbury into southern West Virginia using subsurface correlation. More recently this correlation has been reaffirmed by Kepferle and others (1981) and Englund and others (1979) who traced the Sunbury into southwestern Virginia and southern West Virginia, respectively. At Big Stone Gap, Virginia (Figure 1) the Sunbury is recognized on the basis of its gamma-ray log profile as a part of the Big Stone Gap Shale Member of the Chattanooga Shale (Kepferle and others, 1981).

In southern West Virginia the Sunbury consists of dark gray to gray-black basinal shale with interbedded siltstones. At Bluefield the Sunbury is a laminated black shale similar in lithology to the Sunbury on outcrop in eastern Kentucky. The Sunbury at Caldwell is a medium-gray silty shale with a few interbedded fine-grain sandstone turbidites. The silty shales lack well-developed laminations. The Caldwell outcrop is the northernmost outcrop where the Sunbury Shale can be easily recognized because the basinal, black shale facies grades north into coeval shallow-water shales, siltstones, and sandstones, which are referable to the Riddlesburg Shale.

The upper part of the Price consists of fine to medium-grain sandstones, siltstones, and silty shales. This part of the Price is left unnamed because its heterolithic character does not allow subdivision into members that can be consistently recognized on outcrop. At Caldwell the lower portion of the upper Price consists of submarine fan deposits of the prograding Price delta (Figure 6). The submarine fan deposits consist of a series of graded rhythmites with thin, dark silty shale caps. Near the middle of the upper Price is a 14 m thick, dark gray silty shale sequence containing phosphate pebble lag concentrations. This shale sequence represents a major transgression younger than the Sunbury transgression. Above these basinal shales the Price consists of a coarsening-upward deltaic sequence. The top of the sequence contains distributary sandstones that grade into the alluvial plain red beds of the Maccrady Formation (Fig. 6).

North of Caldwell, towards the West Virginia Dome, the Price records a variety of facies changes that reflect the decrease in paleobathymmetry towards the dome. The dome was a positive feature during Price deposition (Bjerstedt and Kammer, 1985) and this is reflected by a halo of shallow-water sediments around the dome. The Sunbury Shale Member cannot be recognized north of Caldwell, but the Sunbury transgression can be traced through shallow-water clastics by the presence of Kinderhookian brachiopod faunas in the Riddlesburg Shale and in Riddlesburg-age shoreface sandstones deposited on the flanks of the dome.

THE SUNBURY SHALE AND EQUIVALENTS - A UNIFYING TRANSGRESSIVE DATUM

The Sunbury Shale is a basinal deposit formed during a basin-wide

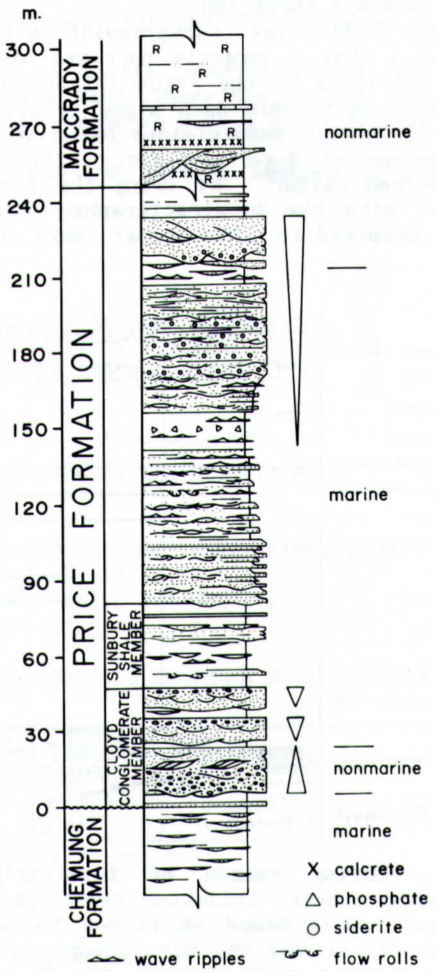

Figure 6. Principal reference section of the Price Formation in southern West Virginia at Caldwell in Greenbrier County. Symbols are as labeled and also according to Figure 4. Gross paleoenvironments and large-scale grain size trends are also shown.

transgression in the Appalachian Basin (Pepper and others, 1954; de Witt, 1970; Kepferle and others, 1981; Ettensohn and Elam, 1985). The black, organic-rich sediments of the Sunbury formed in an anaerobic environment produced by deepening of the Appalachian Basin. The deepening was apparently the result of lithospheric flexure caused by the final phase of mountain building during the Acadian Orogeny (Quinlan and Beaumont, 1984; Ettensohn, 1985a,b). The Sunbury Shale represents a nearly synchronous unit, making it a good chronostratigraphic marker. Recognition of the shallow-water equivalents of the Sunbury Shale allows the Sunbury-time horizon to be traced into the thick, nonmarine clastic facies of the Price (Figure 3). This widespread marine transgression is easily recognizable on outcrop because it often punctuates an otherwise nonmarine or marginal marine sequence and contains marine trace fossils and distinctive Kinderhookian brachiopods. Transgression during Sunbury time is represented by nearshore sandstones and silty shales (Riddlesburg Shale) in Pocahontas, Randolph, Pendleton, Tucker, and Preston counties. In Pennsylvania the transgression is also represented as far east as Blair, Huntingdon, and Bedford counties by the Riddlesburg Shale Member of the Rockwell Formation.

Recognition of the Sunbury-age transgression is the key to constructing a stratigraphic framework that accurately portrays the lithostratigraphic and chronostratigraphic relations of the Price (Figure 3). As discussed in the next section, the biostratigraphic data alone is not sufficient to subdivide the Price. Lithostratigraphic subdivisions based on gross lithology, such as the Broad Ford Sandstone of Reger and Price (1926) or Bartlett's informal members, have not worked either. By using the Sunbury transgression as a datum in conjunction with the biostratigraphic data, we believe that the Price subdivisions proposed in this paper more accurately reflect the

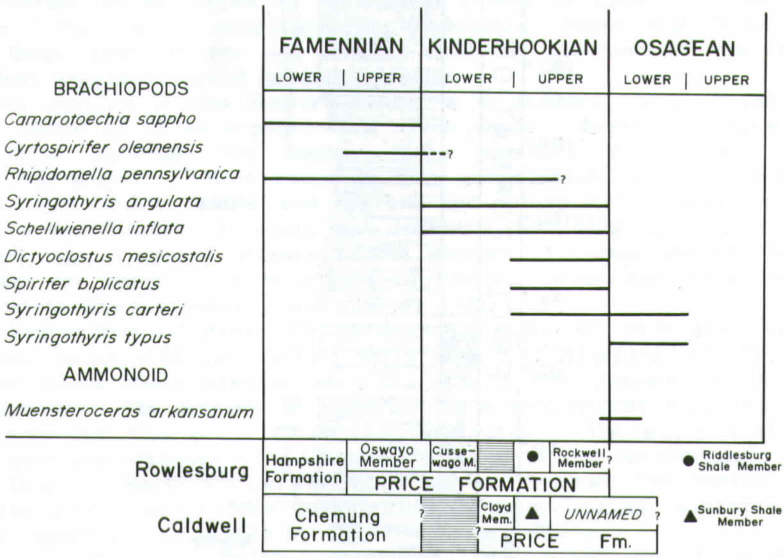

Figure 7. Chart showing ranges of biostratigraphically significant brachiopod and ammonoid species collected from the Price Formation in West Virginia. Brachiopod ranges based on ranges in northwestern Pennsylvania (Holland, 1958; Sass, 1960) and the Mississippi Valley (Carter and Carter, 1970). These marine fossils were found in the Oswayo, Cussewago Sandstone, and Riddlesburg Shale members, and the unnamed portion of the Price in southern West Virginia (Table 1). The time transgressive nature of the Price is demonstrated by a relatively older basin in the north and a younger basin in the south.

chronostratigraphy of the Price in West Virginia.

BIOSTRATIGRAPHY

Marine fossils from the Price Formation in West Virginia range from late Famennian to early Osagean in age (Figure 7). These fossils allow correlation of the members of the Price with equivalent-age units in Pennsylvania and Virginia. The fossils were not used to define the rock-stratigraphic subdivisions of the Price described in this paper. One important result of the biostratigraphic zonation of the Price is the recognition of the diachronous nature of the Price from northern to southern West Virginia (Figures 2, 3, & 7).

Past workers have assigned a variety of ages to the Price Formation in West Virginia and Virginia based primarily on its plant fossils and spores. Paleobotanical studies (White, 1913, 1934; Read, 1955) indicated a Mississippian age for the megascopic plant fossils found in the nonmarine portions of the Pocono of Pennsylvania and the Price of the Virginias. On the basis of spores, Streel and Traverse (1978) reported that the lower part of the Rockwell Formation near Altoona, Pennsylvania was latest Devonian in age.

The only description of marine invertebrates from the Price interval is Girty's (1928) study of the Riddlesburg Shale fauna from the type section in Pennsylvania. This fauna represents only a small fraction of the total Price

Table 1 - Brachiopods from the various members of the Price Formation in West Virginia.[1]

OSWAYO MEMBER
Orbiculoidea sp.
Lingula sp.
Schellwienella inflata (White and Whitfield)
Camarotoechia sappho (Hall) - *allegania* (Williams) complex
Cyrtospirifer oleanensis Greiner

CUSSEWAGO SANDSTONE MEMBER
Schuchertella sp.
Schellwienella inflata (White and Whitfield)
Syringothyris sp.

RIDDLESBURG SHALE MEMBER AND AGE-EQUIVALENT SANDSTONES
Orbiculoidea newberryi (Hall)
Schellwienella inflata (White and Whitfield)
Syringothyris angulata Simpson

UPPER PART OF THE PRICE FORMATION, SOUTHERN WEST VIRGINIA
Lingula sp.
Orbiculoidea newberryi (Hall)
Schellwienella inflata (White and Whitfield)
Rhipidomella pennsylvanica (Simpson)
Tornquistia sp.
Quadratia sp.
Dictyoclostus mesicostalis (Weller)
Camarotoechia sp.
Spirifer biplicatus Hall
Spirifer sp.
Syringothyris typus Winchell
Syringothyris carteri (Hall)
Syringothyris sp.

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[1] See Fig. 7 for stratigraphic ranges.

fauna. The many county reports of the West Virginia Geological Survey mention the presence of invertebrates in the Price, but failed to describe or adequately list them (for example, Reger and Price, 1926; Reger, 1931). Usually the county reports cited the paleobotanical work of White (1913) in stating the age of the Price. Butts (1940) correlated the Price of Virginia with the Burlington Limestone of the Mississippi River Valley stratotype. Although Butts was largely correct, he had the right answer for the wrong reason. He correlated the Price with the New Providence Shale near Louisville, Kentucky, a unit once thought to be age-equivalent with the Burlington. The New Providence Shale near Louisville has been shown to be age-equivalent to the Keokuk Limestone (Rexroad and Scott, 1964); Kammer 1984). Based on Butts' (1941) illustrations, Kammer has reason to believe that Butts misidentified some of the Price brachiopods (study of the Virginia Price brachiopods by Kammer is in progress). Cooper (1944) reported many of the same taxa as Butts and makes the same correlation. In addition, Cooper (1944) suggested that there were Keokuk age-equivalent fossils in the Price of Virginia. Based on the presently available evidence the Price in Virginia is probably Kinderhookian to early Osagean in age (Figure 2).

The only extensive study of Price fossils from West Virginia was Dally's (1956) unpublished dissertation. Dally's collections are housed at West Virginia University and are being incorporated into our ongoing work. Restudy of his collections has shown that much of the material is incorrectly identified. For example, the spiriferid *Syringothyris angulata* Simpson, which is quite abundant in a 50 cm zone just below the Riddlesburg Shale at Wamsley run, was identified as six species of *Syringothyris* and two species of *Spirifer* from this one population (Dally, 1956, p. 204). The combined ranges of these species would be late Famennian to late Osagean, which is much longer than the Kinderhookian range of *S. angulata*.

In spite of his misidentifications, precentage comparisons of his faunal lists with the Mississippi Valley stratotype "suggest the unlikely conclusion that all of the marine fossiliferous members of the Pocono should be equivalent to the Chouteau Limestone (upper Kinderhookian) in the Mississippi Valley" (Dally, 1956, p. 89). This conclusion, which he rejected, is generally correct (Figure 2). Dally believed that the Price in southern West Virginia ranged through the entire Kinderhookian and Osagean because "sedimentation in West Virginia was uninterrupted from the Devonian through Meramecian" (Dally, 1956, p. 92), an argument which presently has no basis. He also believed that the Price in northern West Virginia ranged from the upper Osagean through the Meramecian (Dally, 1956, p. 93). This latter age assignment was based on his belief that the upper half of the Hampshire Formation in northern West Virginia was Mississippian in age (Dally, 1956, p. 88). This conclusion was based on his correlation of the coaly Hedges Shale from the eastern panhandle region with the thin coals near the base of the Price in Pendleton, Randolph, and Grant counties, West Virginia (Dally, 1956, p. 87). The Hedges Shale is at the top of Stose and Swartz's (1912) Pocono Group, so he correlated the Purslane Sandstone and Rockwell Formation with the upper part of the Hampshire Formation in northern West Virginia (Dally, 1956, Pl. 3). The Hedges Shale is Osagean in age (Read, 1955), whereas the coaly zone at the base of the Price in Pendleton County is no younger than Kinderhookian in age because it is overlain by rocks with Kinderhookian brachiopods deposited during the Sunbury transgression. Therefore, Dally's correlation of these separate coals has no basis. In general, we have not found Dally's correlations to be valid.

The correlations presented in this paper are based on a restudy of the marine faunas in the Price of West Virginia. Upper Devonian and Lower Mississippian marine rocks of North America have been biostratigraphically zoned by a number of organisms. The most useful groups are the ammonoids, brachiopods, and conodonts (Dutro and others, 1979). Conodonts were not used in this study because of their great rarity in coarse-grain clastics. Ammonoids are also rare, except for two very notable occurrences. Their rarity is probably a reflection of the euryhaline, nearshore environments of much of the Price. Articulate brachiopods, along with bivalves and gastropods, are often the most abundant body fossils in the Price. Although brachiopod distribution within the Price was often controlled by the depositional environment, many of the brachiopods have well-established time ranges that make them useful biostratigraphic markers (Carter and Carter, 1970; Dutro and others, 1979).

Ammonoids

Only two ammonoid species have been found in the Price Formation. Two specimens of *Muensteroceras arkansanum* Gordon were found by us in the upper part of the Price at Marlinton, West Virginia. One specimen of *Protocanites lyoni* (Meek and Worthen) has been reported from the lower part of the Price at Richlands, Tazewell County, Virginia (Miller, 1936), which is about 52 km (33 miles) southwest of Bluefield, West Virginia.

Muensteroceras arkansanum is restricted to a very short time interval from latest Kinderhookian to earliest Osagean time (Gordon, 1964; Manger, 1979; Ramsbottom and Saunders, 1985) (Figure 7). This species essentially marks the Kinderhookian-Osagean boundary. Thus, the upper half of the upper part of the Price in southern West Virginia is Osagean in age (Figures 2 & 3).

Protocanites lyoni ranges throughout the upper Kinderhookian and into the lower Osagean (Dutro and others, 1979; Manger, 1979). The occurrence of *P. lyoni* in the Price indicates that the lower part of the Price in southwestern Virginia is late Kinderhookian to early Osagean in age. Brachiopods collected by Kammer from the upper part of the Price at Cowen Gap in Scott County, Virginia include the spiriferids *Spirifer gregeri* Weller, *Syringothyris typus* Winchell, and *Cleiothyridina incrassata* (Hall). These brachiopods are restricted to the Burlington-Fern Glen interval in the Mississippi Valley. This means that the upper part of the Price in southwestern Virginia is probably no younger than early Osagean.

Brachiopods

Sixteen taxa of brachiopods have been collected from the Price Formation of West Virginia (Table 1). Nine species are biostratigraphically useful (Figure 7). Nearly all previous workers have only presented faunal lists of the brachiopods from the Price rather than illustrating the specimens. The lack of illustrated specimens makes it nearly impossible to confirm the identifications. Kammer is presently preparing a systematic paper on the Price brachiopods. Only a brief discussion of the biostratigraphic significance of the Price brachiopods will be given in the present paper.

Correlation of the Oswayo Member in northern West Virginia with the Oswayo Formation of Pennsylvania is based on the presence of *Camarotoechia sappho* (Hall) - *allegania* (Williams) species complex and *Cyrtospirifer oleanensis* Greiner. These species apparently do not range beyond the late Devonian (Caster, 1930; Greiner, 1957; Holland, 1958). Greiner (1957) reported *C. oleanensis* from the basal Mississippian Knapp Formation, whereas Holland (1958) did not find this species in the Knapp and stated that it was limited to the Upper Devonian. The Uppermost Oswayo in West Virginia contains *Schellwienella inflata* (White and Whitfield), which is thought to be Kinderhookian in age (Rodriguez and Gutschick, 1967).

The Cussewago Sandstone Member at Rowlesburg also contains *S. inflata*, which is indicative of its Kinderhookian age. The only other brachiopod collected from the Cussewago is *Schuchertella* sp., which is not age definitive.

The Riddlesburg Shale Member at Rowlesburg also contains *S. inflata* along with *Orbiculoidea* sp. and poorly preserved chonetids. As stated previously, the Riddlesburg was deposited during the Sunbury transgression. The age of the Riddlesburg Shale at Riddlesburg, Pennsylvania is not clearly stated in the literature. Girty (1928) believed the Riddlesburg to be Mississippian in age, although he could not rule out a Devonian age. Laird (1942, p. 167) reported *Syringothyris anqulata*, a species limited to the Kinderhookian (Holland, 1958; Sass, 1960), from the Riddlesburg Shale of southwest Pennsylvania. Streel and Traverse (1978) reported the Famennian-Kinderhookian boundary below the level of the Riddlesburg at Altoona, Pennsylvania, on the basis of spores. The nonmarine facies from which they collected the Devonian spores are terrestrial equivalents of the marine Oswayo referable to the Rockwell Formation of Pennsylvania. Thus, we believe that there is no significant doubt of the Mississippian age of the Riddlesburg at its type locality. Its position in sequence above the Cussewago Sandstone (Bayles, 1949) indicates that it was deposited during the Sunbury transgression.

In southern West Virginia, immediately south of the West Virginia Dome, there is usually only one marine horizon in the Price, which is the Riddlesburg Shale Member, or age-equivalent sandstones. This is the case at Bowden, Wamsley Run, Monterville, and Mace. These sections all contain the Kinderhookian species *Syringothyris angulata* and *Schellwienella inflata*. The rocks which contain this fauna represent the nearshore facies of the Sunbury transgression. At all of these localities the fossils are found in well-sorted, nearshore sandstones. This horizon is also present at Marlinton 38 m below the second prominent transgression near the Kinderhookian-Osagean boundary (level of *Muensteroceras arkansanum*). South of Marlinton the Sunbury transgression is expressed as the Sunbury Shale.

Between Marlinton and the dome there is a major regional unconformity where late Kinderhookian-early Osagean rocks are absent (Figure 3). From Marlinton southward, most of the upper part of the Price is still preserved and contains scattered marine fossils of late Kinderhookian to early Osagean age. The brachiopods include *Dictyoclostus mesicostalis* (Weller), *Spirifer biplicatus* Hall, *Syringothyris carteri* (Hall), and *Syringothyris typus* Winchell. *Syringothyris typus* is found at Hardy, West Virginia, 10 km east of Bluefield, approximately 25 m from the top of the Price. In the Mississippi Valley this species is restricted to the Burlington Limestone. Thus the youngest rocks of the Price in West Virginia are early Osagean in age.

CONCLUSIONS

The Price Formation in West Virginia can be divided into the Oswayo, Cussewago Sandstone, Riddlesburg Shale, and Rockwell members in the northern part of the state and the Cloyd Conglomerate and Sunbury Shale members plus an unnamed member in the southern part of the state. All of these members have previously been recognized either as formations or members in Pennsylvania or Virginia. Price Formation is substituted for Pocono Formation, or Pocono Group, in West Virginia because the rocks formerly referred to as Pocono are not lithostratigraphically equivalent to the Pocono Formation in its type area of northeastern Pennsylvania, whereas they are lithologically similar, and generally lithostratigraphically equivalent, to the Price rocks of Virginia.

Recognition of the Sunbury Shale and its equivalents on outcrop in West Virginia allows the recognition of a nearly synchronous datum for time correlation. Use of this datum, in conjunction with the biostratigraphic data, permits chronostratigraphic subdivision of the Price Formation. Marine rocks in northern West Virginia range from late Famennian to early Kinderhookian in age, whereas those in southern West Virginia range from early Kinderhookian to early Osagean in age.

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SHOALING-UPWARD SEQUENCES AND FACIES-DEPENDENT TRACE FOSSILS IN THE MONTEAGLE LIMESTONE (MISSISSIPPIAN) OF ALABAMA

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ABSTRACT

Within the Monteagle Limestone (Mississippian: Meramecian/Chesterian) near Hunstville, Alabama, two types of small-scale carbonate depositional sequences occur and are differentiated on the basis of carbonate lithologies and trace-fossil expression. An oolitic-grainstone sequence consists of an upward succession of: 1) mudstone or wackestone, 2) skeletal and oolitic grainstones, 3) wackestone with grainstone laminae, 4) calcareous shale, and 5) dolomudstone. An echinoderm/bryozoan grainstone sequence consists of an upward succession of : 1) skeletal grainstone with thin wackestone beds and laminae, 2) wackestone and 3) geodiferous dolomudstone. The former sequence was deposited during bar migration and within shoaling to supratidal conditions whereas the latter sequence probably formed during tidal-channel development, also within areas of shoaling to supratidal deposition. Expression of the ichnogenera *Chondrites*, *Palaeophycus*, *Thalassinoides*, and *Rhizocorallium* within these depositional sequences can be used to delineate subtle changes in depositional regime and processes that operated during and after burrowing activity. Because of the greater effect of diagenesis in carbonate rocks as opposed to clastic rocks, only those trace fossils situated between contrasting lithologies commonly are preserved. In addition, coarse grain sizes of many units can hinder trace-fossil development owing to inadequate resolution of the host sediment to detail fine structure. Nonetheless, within rocks consisting of contrasting lithologies, differentiation of forms such as *Palaeophycus* and *Planolites* can be difficult. Open tubes can be filled with a lithology different from that of the host sediment in carbonate sequences, which originated from migration of differing lithologies and storm deposits, resulting in a trace fossil that resembles *Planolites*, but should ethologically be referred to in ichnogenus *Palaeophycus*. Thus care must be exercised in application ichnofossil taxonomy in order to avoid erroneous interpretations of depositional processes.

INTRODUCTION

Upper Carboniferous (Pennsylvanian) cyclicity has been a subject of long-term debate at least in part because sequences of this age are easily discernible owing to abrupt lithologic changes within a complex terrigenous detrital and carbonate depositional systems. In contrast, Lower Carboniferous (Mississippian) cyclicity is expressed as less obvious changes largely within a carbonate depositional system and can result from both global sealevel changes (large scale) or from the spatial and temporal migration of carbonate-platform subenvironments (small scale). Changes in trace-fossil expression and association can help define many of these less conspicuous, small-scale facies changes and furnish important information concerning carbonate platform subenvironments developed during the Mississippian (see Wu, 1982; Archer, 1984). The purpose of this study is to describe depositional sequences and trace-fossil associations within these sequences as seen in surface exposures of the Monteagle Limestone in northeastern Alabama (Figure 1).

Within the Alabama section (Figure 2), the Monteagle Limestone consists of approximately 200 ft of predominantly oolitic and fossiliferous grainstone. The name "Monteagle" was proposed by Vail (1959) in a dissertation and first used in print by Peterson (1962). Recognition of the Monteagle Limestone was extended into northern Alabama by Thomas (1967; 1972). The Monteagle Limestone is underlain by the Tuscumbia Limestone which consists primarily of carbonate mudstones, dolostones, and grainstone with common chert stringers and concretions. The Tuscumbia-Monteagle contact is gradational and arbitrarily defined as stratigraphically below massive oolitic limestone or stratigraphically above abundant chert, abundant dolostone, or abundant carbonate mudstone (Thomas, 1972, p. 23).

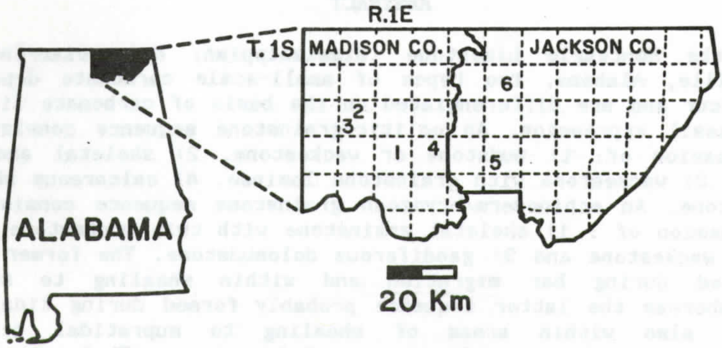

Figure 1. Locality map of study area. Numbered sections correspond with those listed in Appendix.

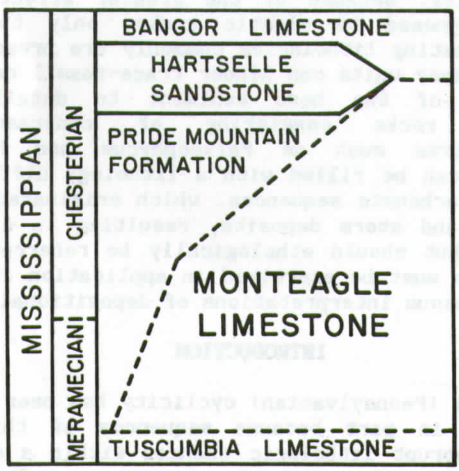

Figure 2. Middle Mississippian stratigraphy of Alabama (modified from Drahovzal, 1967; Thomas, 1972; Rich, 1980).

SEDIMENTOLOGY

Two small-scale (3-10 meters thick) depositional sequences are repeated throughout the stratigraphic thickness of the Monteagle Limestone. Recognition of these sequences is based on compilation of stratigraphic sections measured during the present study and from sections measured by authors as cited in the text. Units within the depositional sequences are numbered generally from offshore to more onshore depositional environments. However, this does not imply progressive shallowing in all cases, especially in depositional sequences with prominently developed skeletal-grainstone and oolitic units. Furthermore, where offshore/onshore relations are less clearly defined, the numbering scheme begins with the coarser-grained units, which commonly exhibit erosional lower contacts that truncate the underlying unit. Types of trace fossils that occur within the sequences can yield information concerning sedimentological processes occurring during and shortly after deposition of the sediments.

Oolitic-grainstone Sequence

A series of diverse lithologies, many of which are noted for their lateral discontinuity, constitute the oolitic-grainstone (OG) sequence. Carbonate lithotypes include skeletal and pelloidal wackestones, carbonate mudstones, dolomudstones, oolitic grainstones, skeletal and coated-skeletal grainstones, and chert- and quartzose-sand-bearing grainstones. Lesser amounts of clay shale are also present.

The idealized depositional sequence (Figure 3) begins with mudstone or wackestone (Unit OG-1) that contains increasing numbers of grainstone lenses and laminae toward the top. Burrows, including *Chondrites*, *Palaeophycus*, and *Thalassinoides* are common within this unit but are most easily discerned only within grainstone-bearing zones. The uppermost part of this unit commonly contains burrows that were filled with skeletal carbonate sands or ooids piped downward from the overlying units.

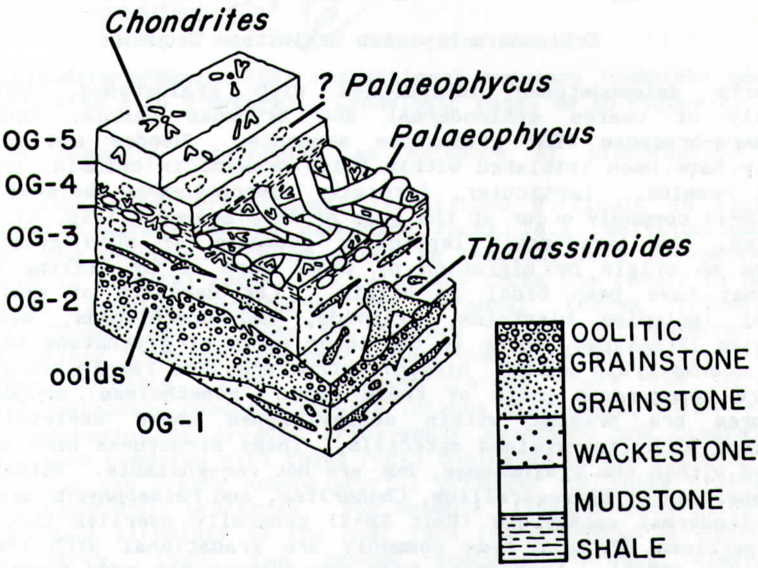

Figure 3. Oolitic-grainstone (OG) depositional sequence (complete sequence thickness ranges from 3 to 10 meters).

Unit OG-2 consists of crossbedded skeletal and oolitic grainstones. Coated skeletal grains are also common. These beds are commonly more oolitic at the top, usually are crosslaminated, and contain little detectable bioturbation. Such units were deposited as migrating shoals within a high-energy offshore environment (Hanford, 1978).

The overlying unit (Unit OG-3) is lithologically similar to Unit OG-1 except that grainstone laminae occur within the lower portions of the bed. The principal lithology is wackestone, which suggests lower-energy conditions when compared to deposition of the underlying Unit OG-2. Grainstone laminae are attributable to episodic overwash deposition from nearby, higher-energy shoals. Biogenic structures are also the same as those found in Unit OG-1 (*Chondrites*, *Palaeophycus*, and *Thalassinoides*).

Shale occurs commonly within the basal portion of Unit OG-4. Although these shales commonly are presistent laterally on outcrop, the explanation of their occurrence is somewhat problematic in this carbonate-dominated depositional environment. Some shale beds are laminated and unbioturbated whereas others are highly bioturbated. Undoubtedly some of the unbioturbated shale beds result from non-sutured seam solution of overlying and underlying limestone (Wanless, 1979.) *Paleophycus* is the most common burrow within bioturbated shale beds.

Thinly laminated or slightly bioturbated dolomudstones (Unit OG-5) occur commonly above wackestone beds. Body fossils are rare in Monteagle dolomudstones and consist principally of disarticulated echinoderm debris and *Lingula* associated with the trace fossil *Chondrites*. Laminations and dolomitization suggest deposition on shallow subtidal or supratidal flats within restricted environments. Presence of *Chondrites* and absence of other traces has been shown to indicate oxygen-poor sediment conditions in Mesozoic and Cenozoic rocks (Bromley and Ekdale, 1984). Similar interpretations have been reached for Pennsylvanian black shales in the Illinois Basin (Archer and Maples, 1984; Maples, 1985) and thus indicates that the occurrence of *Chondrites* and absence of other trace-fossil genera can be used as an indicator of oxygen-poor sediments into the Carboniferous. In this case, the presence of *Chondrites* would suggest a shallow subtidal environment with poor circulation as opposed to more oxygenated supratidal sedimentation.

Echinoderm-bryozoan Grainstone Sequence

Cherty dolomudstones interbedded with grainstones, which consist primarily of coarse echinodermal and bryozoan debris, constitute the echinoderm-bryozoan (EB) grainstone sequence. Geodes and chertification commonly have been initiated within voids present in crinoid, brachiopod, or mollusc remains. Lenticular, laterally discontinuous skeletal grainstones (Unit EB-1) commonly occur at the base of this sequence (Fig. 4). One larger exposures, the large-scale lenticular geometry of such grainstone units suggests an origin by migration of tidal bars or by filling of channels, which may have been tidal in origin. Lag deposits of coarse skeletal material including blastoids, crinoids, and brachiopods, and clasts of underlying lithotypes, occur in the lower parts of grainstone beds. Because of the coarse grain seized, biogenic structures are rarely recognized within the more homogeneous parts of these beds. Nonetheless, abundant biogenic structures are present within shaley zones where skeletal debris is intermixed with fine-grained materials. These structures were also probably produced within the grainstones, but are not recognizable. Within such zones high densities of *Rhizocorallium*, *Chondrites*, and *Palaeophycus* are recorded.

Echinodermal wackestone (Unit EB-2) generally overlies the grainstones. Lower portions of EB-2 beds commonly are gradational with the underlying grainstones (EB-1). Wackestone beds may contain few body fossils or may be relatively fossiliferous. Biogenic structures are rare except for simple, poorly preserved burrows.

The upper unit of this sequence consists of silty dolomudstone and contains abundant geodes (Unit EB3, Figure 4). Biogenic structures include *Chondrites* and *Palaeophycus*. Near the tops of these units, downwardly piped calcareous sand results in enhanced definition of biogenic structures, therefore *Rhizocorallium* is also present.

PROBLEMS

Recognition of trace fossils in the Monteagle Limestone proved challenging for a variety of reasons including generally poor preservation. Nonetheless, a number of forms can be referred to known trace-fossil genera. In this paper we use generic assignments described and illustrated in Archer (1984).

Because carbonate grainstones of the Monteagle Limestone have a comparatively coarse texture, the sediment lacked sufficient resolution to define most biogenic structures (see Archer, 1984). Although burrows are only rarely preserved, the lack of sedimentary structures in coarse

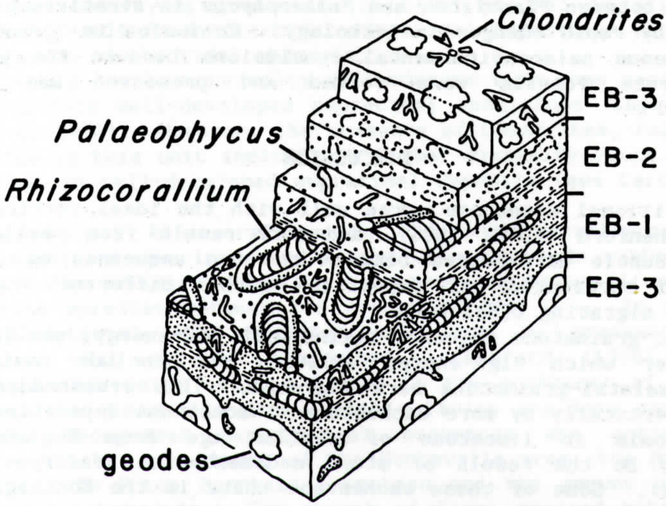

Figure 4. Echinoderm-bryozoan (EB) depositional sequence (complete sequence thickness ranges from 4 to 9 meters). Lithologic codes as in Figure 3.

grainstones is commonly interpreted as evidence of bioturbation (e.g. Hanford, 1978).

Diagenesis also makes trace-fossil recognition difficult in carbonate rocks. Diagenetic alteration in carbonate rocks (e.g. solution packing, dolomitization, and overgrowth cementation) is commonly more extensive than that encountered in detrital rocks. In carbonate rocks the result is poorly-preserved trace fossils dominated by infaunal traces (*Planolites*, *Thalassinoides*, *Chondrites*). Those few surface traces that survived storm reworking and current scouring have been almost completely obliterated during diagenesis (see Narbonne, 1984). Traces formed where two differing lithologies are juxtaposed commonly survive intense diagenesis, which tends to give a false impression of greater trace-maker abundance and diversity at these intervals when compared with those rocks dominated by one lithology.

Diagenesis also can create nomenclatorial problems for those traces that survive earlier taphonomic processes. For example, lined burrows filled with essentially the same lithology as the host rock (*Palaeophycus* as emended by Pemberton and Frey, 1982) can become obscured through diagenesis. Conversely, unlined burrows filled with a lithology essentially different from the host rock (*Planolites* as emended by Pemberton and Frey, 1982) can have the burrow boundary accentuated by differential diagenesis of the contrasting lithologies (e.g. difference in cementation or solution packing), which can produce the superficial appearance of a burrow lining. These problems can be overcome in part by careful petrographic study (Pemberton and Frey, 1982).

A more serious problem in application of the *Planolites/Palaeophycus* definitions is exemplified in the Monteagle Limestone. Because *Palaeophycus* can form by passive filling of an open tube, filling with the host-rock lithology is commonly assumed (see Pemberton and Frey, 1982). However, in rock sequences characterized by alternating lithologies representing episodic deposition, an open burrow may be filled with a lithology different from that of the host rock (Archer, 1983). The result is a lined burrow filled with a lithology different from that of the host rock. Ethologically and paleoenvironmentally this burrow would best be referred to as *Palaeophycus*, but it would have the appearance of *Planolites*. We follow the ethological definition of *Palaeophycus* because it is much more useful for paleoenvironmental interpretation. Extreme care must be used in distinguishing between *Planolites* and *Palaeophycus* in stratigraphic sequences characterized by rapid changes in lithology. Confusion in ichnotaxonomy can lead to erroneous paleoenvironmental conclusions because the processes by which the trace fossils were formed and preserved may be readily misinterpreted.

DISCUSSION

Both depositional sequences agree well with the ideal vertical sequences described by Hanford (1978; 1986), and both result from shallowing-upward deposition. Subtle differences between the two sequences may result from initiation and termination of deposition within different stages of the development of migrating tidal bars.

The oolitic-grainstone sequence begins with low-energy, shallow, subtidal wackestone over which high-energy oolitic- (to include coated skeletal grains) and skeletal-grainstone bars migrated. This crossbedded grainstone is succeeded vertically by more wackestone. Wackestone deposition in an area of oolite shoals in limestone of similar age from England has been interpreted to be the result of storm sedimentation (Jeffrey and Aigner, 1982; Wu, 1982). Some of these wackestone units in the Monteagle Limestone contain large numbers of articulated crinoid and blastoid calices with stems up to 3 feet in length and arms still attached (C. G. Maples and J. A. Waters, unpublished field notes) which lends further support to episodic or storm sedimentation. Wackestone in an oolitic-grainstone sequence is interpreted to indicate rapid burial whereas the presence of packstone in the sequence would have resulted from subsequent reworking and somewhat slower burial (Jeffrey and Aigner, 1982). Thus, the presence of grainstone laminae in wackestone below the oolitic- and skeletal-grainstone unit may indicate progressive shoaling and increased frequency of reworking as the tidal bar migrated across a lower energy environment.

Return to wackestone deposition with decreasing numbers of grainstone laminae could result from migration of the bar shoreward or seaward. Either situation results in quieter water with lower energy muddier sedimentation and presence of grainstone laminae proximal to the crossbedded oolitic and skeletal grainstone. In the first example, one should expect to see another crossbedded grainstone overlying wackestone as the sequence repeats. In the second example, skeletal wackestone is overlain by calcareous shale as marine regression continued and storm influence is lessened.

The wackestone overlying grainstone may have been deposited under intertidal or very shallow subtidal conditions in protected areas behind grainstone bars. Grainstone laminae in this lithology may also be small spillover lobes of grainstone from the more seaward bars. As regression continued, calcareous shale is overlain by intertidal to supratidal dolomudstone. The dolomudstone may have been deposited in restricted, oxygen-poor, shallow subtidal areas as indicated by *Chondrites* and few, if any, other traces (Bromley and Ekdale, 1984). However, in the absence of other indicators, we favor the intertidal to supratidal interpretation.

The echinoderm-bryozoan grainstone sequence is generally similar to the preceeding depositional sequence and was commonly initiated by large-scale, laterally-discontinuous skeletal grainstone with thin wackestone beds and laminae, which overlies dolomudstone. Ooids and coated grains are not developed in this facies. We interpret the grainstones to be the result of either tidal-channel or migrating-bar deposition. Although wackestone laminae are the principal evidence for storm events there is less evidence that these laminae have been reworked and buried rapidly (see Jeffrey and Aigner, 1982).

Skeletal grainstone is gradational with overlying wackestone that would have the same origin as unit OG-3 if the underlying grainstone were the result of migrating tidal bars. Alternatively, the wackestone units may have resulted from intertidal-supratidal deposition on the bar crests (Hanford, 1978). If the underlying grainstone is tidal channel in origin, overlying wackestone may result from intertidal-supratidal deposition in areas adjacent to and shorewards of the tidal channels.

Wackestone is overlain by silty dolomudstone with some geode development, which may indicate well-developed supretidal conditions (Chowns and Elkins, 1974; Hanford, 1978). However, the presence of *Chondrites*, *Palaeophycus*, and *Rhizocorallium* in this unit indicates a higher diversity fauna than one would expect to find in well-developed supratidal deposits (see Carter and others, 1984).

The presence of *Rhizocorallium* in the echinoderm-bryozoan grainstone sequence may reflect the increased amount of muddy beds within that package as opposed to the oolitic-grainstone sequence. *Rhizocorallium* is a U-shaped tube with fine spreiten between the prongs of the "U". In the absence of fine-grained material, the spreiten will not be preserved, therefore, *Rhizocorallium* will not be recognized. Hanford (1978) recognized a progression of increasing oolitic facies to the northeast of the Huntsville area. Within the Huntsville area, oolitic facies are less common, therefore most of the recognized depositional sequences are echinoderm-bryozoan grainstone sequences. Southwest of the Huntsville area, the Monteagle grades laterally into the Pride Mountain Formation and the amount of fine clastic material increases sharply. The amount of fine- grained material increases generally within the Huntsville area from northeast to southwest and the distribution of *Rhizocorallium* follows this trend.

CONCLUSIONS

Two depositional sequences are recognized in the Monteagle Limestone near Huntsville, Alabama. An oolitic-grainstone sequence records the progradation of oolitic, coated-grain, and skeletal grainstone bars over wackestone deposited below normal wave base. Back-bar wackestone overlies grainstone as marine regression continues. The sequence is capped by intertidal and supratidal calcareous shale and dolomudstone. An echinoderm-bryozoan grainstone sequence records deposition of tidal-channel skeletal grainstone over intertidal and shallow-subtidal wackestone. Intertidal wackestone overlies the grainstone of the echinoderm-bryozoan sequence and in turn is overlain by geodiferous dolomudstone probably of shallow subtidal origin.

Because trace fossils are formed by the arrangement of sedimentary particles, they are particularly subject to taphonomic effects in general and diagenesis in particular. Thus, diagenesis complicates recognition of many trace fossils, especially in carbonate sequences. Interlayering of differing lithologies facilitates trace-fossil recognition, therefore most of the trace fossils preserved in the Monteagle Limestone are situated at lithologic boundaries. The ichnogenera *Chondrites* and *Palaeophycus* occur both within the oolitic-grainstone sequence and within the echinoderm- bryozoan grainstone sequence. In contrast, *Thalassinoides* is confined to the oolitic-grainstone sequence and *Rhizocorallium* is restricted to the echinoderm-bryozoan grainstone sequence. The *Rhizocorallium*-producing animal may have been present in the oolitic-grainstone sequence, but the limited amount of fine-grained material in this sequence would not have allowed for preservation and recognition of the *Rhizocorallium* structure.

The most recent definitions of *Planolites* and *Palaeophycus* have some major drawbacks in carbonate rocks dominated by episodic sedimentation. Lined, open tubes may passively fill with a different lithology from that of the host rock producing a *Planolites*-looking trace that would ethologically be referred to *Palaeophycus*. Incorrect paleoenvironmental interpretations can result if care is not exercised in identification of these ichnotaxa.

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APPENDIX A

Locations of Studied Sections

Measured sections currently in print are indicated by an asterick with references given in brackets.

*1. Road-cut exposure along west side of U.S. Highway 431 (secs. 9, 10, and 15, T. 4 S., R. 1 E.; Huntsville, Alabama 7-1/2' Quadrangle). [Smith, 1967; Rich, 1980]

2. Active quarry on south side of Drake Mountain (S 1/2, SE 1/4, sec. 9, T. 3 S., R. 1 W.; Jeff, Alabama 7 1/2' Quadrangle.)

3. Abandoned quarry on east side of Oakwood Mountain (S 1/2, NW 1/4, sec. 20, T. 3 S., R. 1 W.; Jeff, Alabama 7-1/2' Quadrangle).

4. Abandoned quarry on southwest side of Gurley Mountain (NW 1/4, NW 1/4, sec. 11 and NE 1/4, NE 1/4, sec. 10, T 4 S., R. 2 E.; Moontown, Alabama 7 1/2' Quadrangle).

5. Abandoned quarry at Stephens Gap, southeast side of Nat Mountain (NE 1/4, sec. 29, T. 4 S., R. 4 E.; Lim Rock, Alabama 7 1/2' Quadrangle).

*6. Road-cut exposure along north side of Alabama Highway 146, northeast side of Fowler Cove (NE 1/4, sec. 22, T. 2 S., R. 4 E.; Princeton, Alabama 7 1/2' Quadrangle). [Smith, 1967; Rich, 1980]

STREAM WATER CHEMISTRY OF A SMALL FORESTED WATERSHED ON THE SOUTH CAROLINA COAST

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ABSTRACT

An intermittent blackwater stream in coastal South Carolina was sampled twice a week from January 1982 through December 1982 for pH, alkalinity, NH_4-N, PO_4-P, NO_3 + NO_2-N, dissolved organic nitrogen (DON), dissolved organic phosphorus (DOP), dissolved organic carbon, (DOC), Na^{+1}, Ca^{+2}, Cl^{-1}, K^{+1}, silicate, and SO_4-S. Based on correlation to discharge and ion ratios these dissolved constituents can be separated into distinct groups suggesting different biogeochemical processes.

Calcium, alkalinity, pH, and silicate all show strong negative correlations to the log of discharge. Solution of shell fragments and weathering of mica flakes from deep in the sandy parent material are the most likely sources of these materials. Na^{+1}, Mg^{+2} and Cl^{-1} all show weak negative correlations to log of discharge and have ion ratios similar to sea salt. Don, Doc, and SO_4-S all show positive correlations to log of discharge. Their source appears to be forest floor decomposition within the hardwood swamps. K^{+1}, DOP, PO_4-P, NH_4-N, and NO_3 + NO_2-N are all unrelated to discharge. K^{+1} shows a seasonal pattern suggesting leaching from live hardwood foliage. These results suggest that mineral dissolution, litter decomposition, and atmospheric input (sea salts) all influence intermittent stream water geochemistry in coastal South Carolina.

INTRODUCTION

Watershed research has been used to elucidate the hydrologic, chemical, and biologic factors controlling stream water geochemistry (Henderson and others 1978, Likens and others 1968, Johnson and Swank 1973, Webster and Patten 1979). Rainwater chemistry, alteration of this input by forest and soil components, and processes occurring within the stream systems all alter stream chemistry. Most of the watersheds analyzed to date are situated in mountainous terrain or on the Piedmont. There is a notable lack of information on Southeastern blackwater stream geochemistry.

The major objective of the study reported here was to evaluate the processes controlling water chemistry in a small blackwater stream along the South Carolina coast. The stream in this study was the major freshwater input in the Bly Creek ecosystem study, a study to determine nutrient movements and processing within a *Spartina alterniflora* marsh. The first step in this investigation was to evaluate the nutrient discharge relationships and generate hypotheses concerning controls on nutrients carried from the forest in the stream water.

METHODS

The small intermittent blackwater stream studied drains about 395 hectares of loblolly pine-oak forest. The entire system coupled with the Bly Creek Basin is situated on the western side of the North Inlet system, Georgetown County, South Carolina (Figure 1).

Water samples for nutrient analysis were taken twice a week from January 15, 1982 through December 20, 1982. The samples were returned immediately

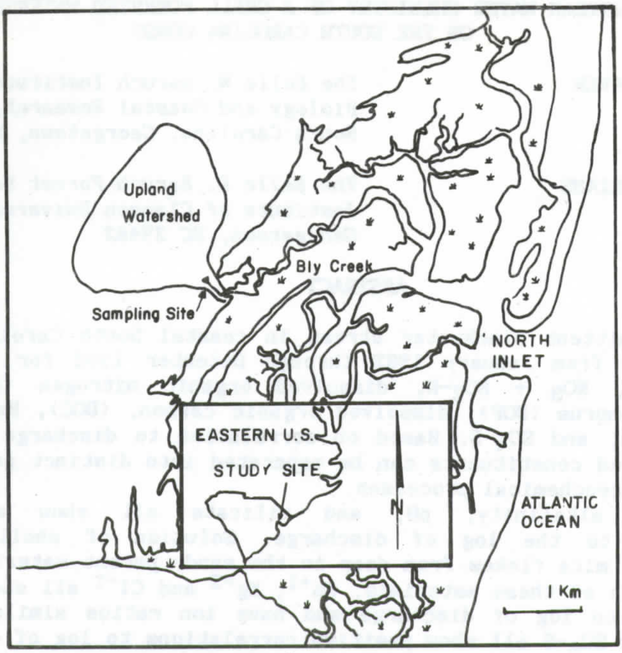

Figure 1. Location of study site.

Table 1. Analysis methods used.

Constituent	Method
NH_4^{+1}	Technicon autoanalyzer, Berthclot reaction. Industrial method #154-71W
$NO_3^{-1} + NO_2^{-1}$	Technicon autoanalyzer, cadmium reduction. Industrial method #158-71W
PO_4^{-3}	Technicon autoanalyzer, single reagent method. Industrial method #155-71W
Total Dissolved Nitrogen	Technicon autoanalyzer, alkaline persulfate digest (Gilbert and others 1977), digestate analyzed for NO_3+NO_2-N
Total Dissolved Phosphorus	Technicon autoanalyzer, alkaline persulfate digest (Gilbert and others 1977), digestate analyzed for PO_4-P
SO_4^{-2}	Technicon autoanalyzer, methylthymol blue method. Industrial method #116-DO96
Si^{+4}	Technicon autoanalyzer, molybdenum blue method. Industrial method #116-0291-01
Cl^{-1}	Technicon autoanalyzer, Thiocyanate method. Industrial method #116-0051-01
Dissolved Organic Nitrogen	Total Dissolved N-(NO_3+NO_2-N)-(NH_4-N)
Dissolved Organic Phosphorus	Total Dissolved P-(PO_4-P)
Dissolved Organic Carbon	Beckman carbon analyzer.
NA^+, Ca^{++}, K^+, Mg^{++}	Atomic absorption spectrophotometer

to the laboratory for chemical analysis. pH measurements were made using Corning pH probe while alkalinity titrations were performed using automated titrator and the single endpoint method. The rest of the sample was filtered through a Gelman GF/F filter with the filtrate preserved and stored. The following preservation techniques were used; NH_4-N (phenol); $NO_3 + NO_2$-N and PO_4-P (mercuric chloride); cations (1% HCl); total dissolved nitrogen and total dissolved phosphorus (frozen). Chemical analyses were performed by the methods outlined in Table 1.

Discharge of water in the stream was measured using a Parshall (1950) flume. The flume chosen had a throat width of 5 ft. (1.52 m) and discharge was calculated using the equation:

$$Q = 20\ h^{1.587}$$ (Parshall 1950)

Q - discharge ft^3/sec

h - depth at measurement point in ft.

The daily discharges (m^3/day) were plotted versus each chemical constituent for the dates when the latter were taken (Figure 2a). Various nonlinear transforms were applied to this data and it was found that the best fit was found with a linear (nutrient) - log (discharge) curve.

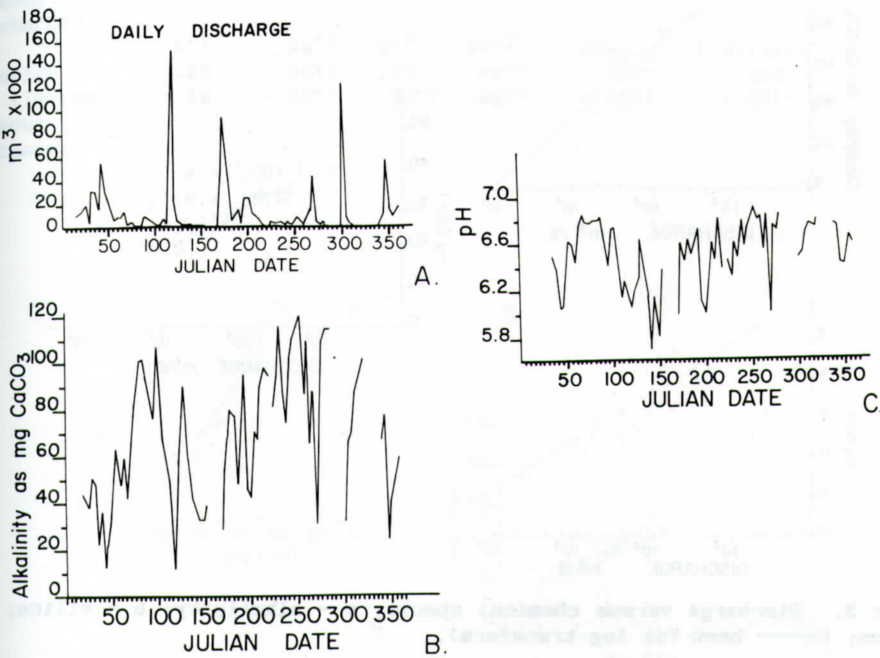

Figure 2. Time series of physical and chemical parameters versus time (julian date); a - discharge; b - alkalinity; c - pH.

RESULTS AND DISCUSSION

Johnson and others (1969) showed that streamwater chemistry of the Hubbard Brook system could be predicted by a simple mixing model of soil water enriched in ions and a relatively low concentration surface flow. Such a model predicts that element concentrations will vary as a function of discharge rate. Relationships of element concentrations to discharge were used in this study to generate hypothesis concerning the processes affecting streamwater geochemistry.

Alkalinity, pH, Calcium, Silica

Alkalinity, calcium and silica have a highly significant negative correlation with the logarithm of discharge (Figures 2b, 3a, 3b, 3c, Table 2), suggesting that these constituents are leached from a constant source within the system. It is hypothesized that calcite dissolution produces most of the observed calcium and alkalinty. This assertion is supported by 1) a significant correlation of alkalinity with calcium (r = .83 ; n + 74), the slope of the regression line near that expected for calcite dissolution, (Figure 4a) and 2) the presence of calcareous shells lying below the b horizon within the soil stratum. In addition, if calcite dissolution is present then pH and alkalinity in the groundwater and resultant stream water should be positively correlated as implied by the time series of these two variables (Figure 2b, 2c). The poor correlation (r = .53) between these constituents may be caused by pH being affected by processes other than calcite dissolution, such as microbial respiration and sorption reactions within the soil stratum.

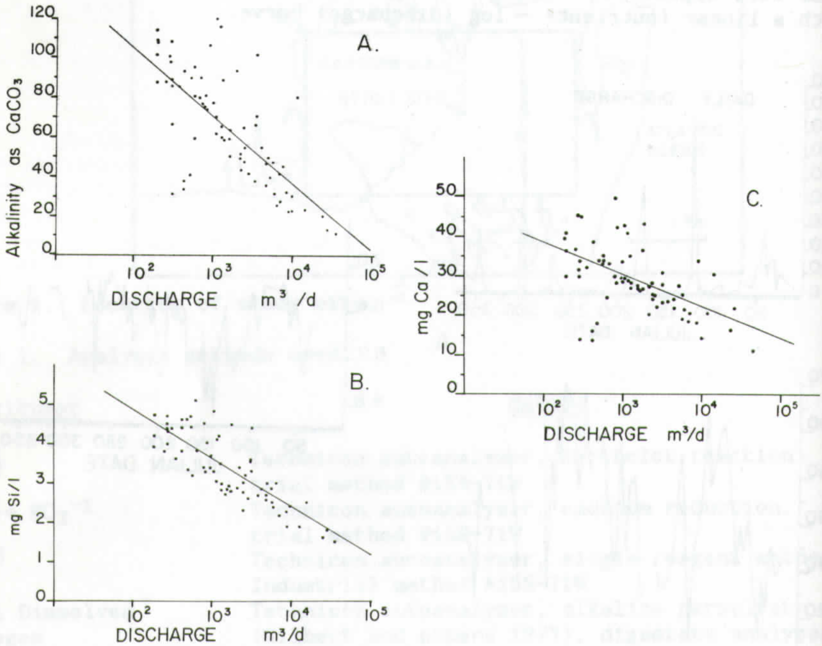

Figure 3. Discharge versus chemical specie; a - alkalinity; b - silica; c - calcium; (—— best fit log transform).

Silica as with calcium and alkalinity probably has its source in mineral dissolution within the soil stratum. The most probable source of silica is weathering of mica, since this mineral is found in association with shell fragments at depth in the soil profile. Another possible silica source could be weathering of quartz, since the surface soils are composed of mainly quartz sand grains (Stuckey, 1983). Streamwater silica concentrations are approximately double those at Hubbard Brook, (Likens and others 1977) and about 50% of those found in the Parana river (Bonnette 1975) and from 10 to 80% of those found in rivers of Uganda (Viner 1975). These values indicate a soil weathering climate intermediate between tropical and temperate conditions.

Chloride, Magnesium, Potassium, and Sodium

All these ions show negative relationships to the logarithm of discharge (Table 2), suggesting a proximate source within the system, as for Si^{+4} and

Ca^{+2}. However, salt spray aerosols are the most likely ultimate source of chloride, sodium and magnesium since all these species are directly related to chloride concentration (Figure 4b, 4c), and the Cl:Na and Cl:Mg ratios are similar to that of seawater. Potassium does not have a similar source since it shows no direct relationship to chloride, and K:Cl ratios much higher than expected if sea salt aerosols control rainwater chemistry. These trends can be explained by the presence of an internal source within the system such as leaching of K^{+1} from the forest canopy or litter layer (Wells and others 1972, Johnson and Risser 1974, Rolfe and others 1978).

Table 2. Regression coefficients (r)

Independent Variable	Dependent Variables							
	DON	DOP	DOC	NH_4-N	PO_4-P	NO_3-N	Si	Cl
Chloride	-.65††	.28††	-.59††	.34††	.18	-.02	.49††	1
log (instantaneous Discharge)	.37††	-.24†	.46††	-.20†	-.01	-.20†	-.79††	-.45

Independent Variable	K^{+1}	Na^{+1}	Ca^{+2}	MG^{+2}	SO_{4S}-S	Alkalinity
Chloride	.29	.94††	-.05	.86††	-.45††	-.004
Log (Instantaneous Discharge)	-.12	-.42††	-.53††	-.61††	+.40††	-.68††

α = .05†
α = .01††

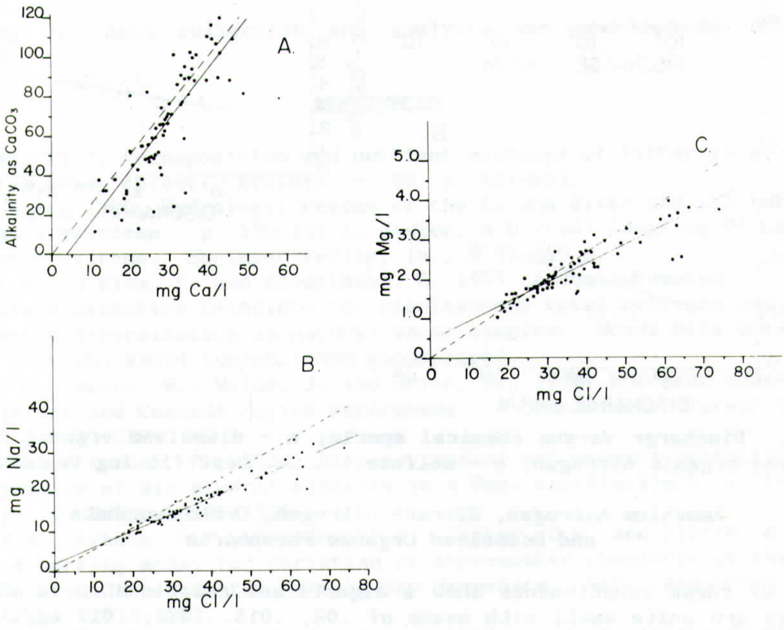

Figure 4. Graphs of: a - Calcium versus alkalinity (—— dissolution curve for calcite, —— linear regression); b - Chloride versus sodium (—— seawater ratio, —— linear regression); c - Chloride versus magnesium (---- seawater ratio; —— linear regression).

Dissolved Organic Carbon, Dissolved Organic Nitrogen and Sulfate

Each of these constituents show a weak positive relationship to the logarithm of discharge (Figures 5a, 5b, 5c). It is likely that large surface flows occurring during or after storm events leach DOC and DON from decomposing litter in areas of high water table. Brinson (1977) found that nearly all the DOC in *Nyssa acquatic* leaves was leached within 30 hours after placement in similar systems. This assertion is also supported by the work of Williams (1979) within this system which has shown that large surface flows are associated with both high water tables and movement of water out of low lying areas.

The same mechanism may be responsible for the sulfate found in this blackwater stream since this constituent shows the same general trends as with DOC (r = .51). Sulfate can also enter the system via rainwater since this constituent can account for a large percentage of total anions in rainwater (likens and others 1977, Shriner and Henderson 1978). Washing or leaching of sulfate from the forest canopy may also be an important source at this site (Swank, per comm.).

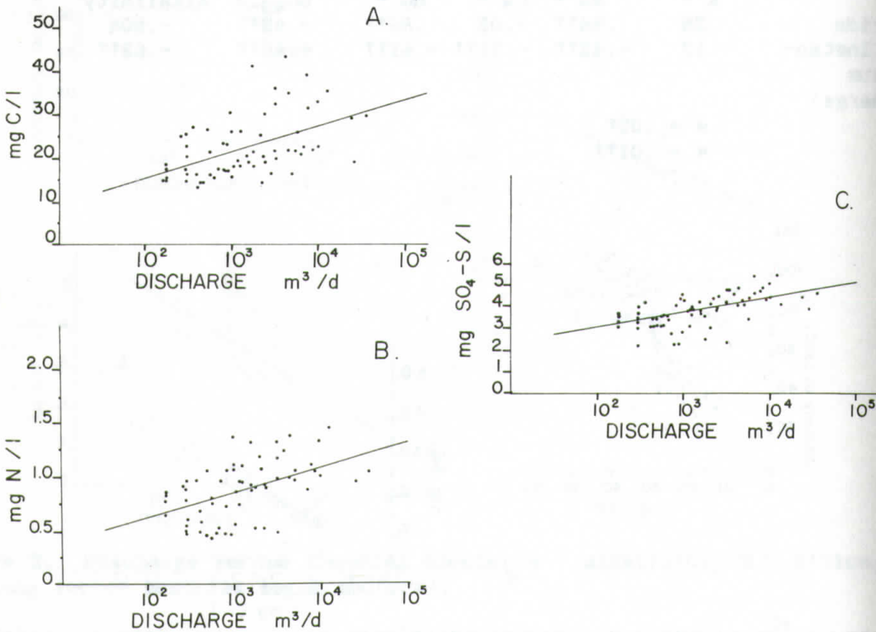

Figure 5. Discharge versus chemical specie; a - dissolved organic carbon; b - dissolved organic nitrogen; c - sulfate (——— best fit log transform).

Ammonium nitrogen, Nitrate nitrogen, Orthophosphate and Dissolved Organic Phosphorus

None of these constituents show a significant relationship to discharge. All values are quite small with means of .02, .015, .023, .012 mg/1 for DOP, PO_4-P, NH_4-N, NO_3 + NO_2-N, respectively. DOP and NO_3 + NO_2-N show slightly elevated values during the fall suggesting a seasonal trend. Ammonium nitrogen shows several peaks which often occur a few days after a storm peak, this possibly resulting from the decomposition of organic material. After very high flows there was often organic material deposited along the channel sides, this material subsequently decomposed.

SUMMARY

Chemical constituents of a small blackwater stream in coastal South Carolina can be grouped by their behavior with changes in discharge. These groupings coupled with graphs of the various constituents suggest that mineral dissolution, litter composition, and atmospheric input (sea salts) all influence intermittent stream water geochemistry in coastal South Carolina. We offer the following conclusions:

1) Silica and alkalinity show a strong negative correlation with the logarithm of discharge. Alkalinity appears to be due to dissolution of calcite in shells layers below the forest soil, while silica is most likely derived from soil weathering also from deeper in the profile.

2) Sodium, chloride and magnesium are all negatively associated with stream discharge. The Na:Cl and Mg:Cl ratios suggest that these constituents have their ultimate source in sea salt aerosols.

3) Dissolved organic nitrogen, dissolved organic carbon, and sulfate are positively correlated to the logarithm of discharge, and appear to have their source in the decompoition of litter. However, sulfate could enter the stream by washing or leaching the forest canopy with rainwater.

4) Potassium is not correlated to either discharge or chloride concentration. K:Cl ratios greater than that expected in seawater suggest a source of this constituent within the system, such as the leaching of potassium from live foliage.

5) Ammonium, nitrate, orthophosphate and dissolved organic phosphorus are all characterized by variability unrelated to discharge with only a slight indication of seasonality.

ACKNOWLEDGEMENT

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