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SOUTHEASTERN GEOLOGY

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IN SITU STRESS FIELD IN THE SOUTHEASTERN

UNITED STATES AND ITS IMPLICATION*

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ABSTRACT

Published and unpublished *in situ* stress measurements and studies of earthquake focal mechanisms in the southeastern United States provide useful information on the relative magnitude and orientation of existing stress fields in the region. These data provide general agreement with the complex geology and the present-day tectonic processes observed in many areas of the southeastern United States.

Stress measurements reveal the existence of high horizontal stresses in the Appalachian complex. The magnitude of the maximum horizontal stress ranged from 3.4 to 41.8 MPa. Different *in situ* stress states in the Appalachian complex, the Coastal Plain, and the stable interior region indicate the possibility for different faulting mechanisms. Data derived from the various techniques for determining *in situ* stress are consistent within the data scatter in each province.

INTRODUCTION

Knowledge of the natural stress field in rock is important for many problems in rock mechanics, earthquake geophysics, and geologic processes. Such knowledge is important for (1) construction of both surface and underground facilities, (2) evaluation of potential geological hazards and (3) implications of contemporary tectonics. Available information from *in situ* measurements regarding the regional stress in the southeastern United States was reviewed. Information developed during the past two decades on the state of stress in the earth's crust (Brown and Hoek, 1978; Bulin, 1971; Haimson, 1978; Hast, 1969; McGarr and Gay, 1978; Raleigh and others, 1976) indicates high horizontal compressive stresses at the surface of the earth's crust in many areas. Horizontal stresses much larger than those expected from gravitational loading alone have been measured in the United States, Europe, Africa, Iceland, and Australia.

In situ measurements of stress in the southeastern United States by either hydrofracturing or strain-relief techniques not only indicate the direction of the stress vector but also provide an estimate of the magnitude of the stress. Investigation of fault plane solutions for earthquakes that have occurred in the southeast can be used to infer the orientation of the stress field.

This study shows that the observed stress field in the southeastern United States is considerably different from that expected as a result of gravitational loading. Although the observed stress field is relatively continuous, it is heterogeneous from one area to another; locally anomalous stress conditions occur throughout the southeastern United States. In general, the stress field of a particular region appears to be related to its geology and tectonic history.

In recent years, a number of stress measurements have been made in the southeastern United States from the surface to depths of almost one kilometer. These measurements have revealed significant nonlithostatic stresses. In some instances, near-surface deviatoric[x] stress components of about ten MPa have been measured, and the stress gradients indicate even higher stresses at depth (McGarr and Gay, 1978).

Two methods have been used to measure stress *in situ*: the overcoring strain-relief technique by using deformation gauges like the USBM borehole deformation gauge and the direct measurement of stresses by hydraulic fracturing. The strain-relief method is limited to depths of up to one hundred meters from the surface but is very good for use in underground facilities. The hydraulic fracturing technique, developed from oilfield practices, has been used to depths of up to five kilometers.

The location and results of these tests and other relevant information are presented in Figure 1 and Table 1, respectively. These data represent measurements in crystalline rock, argillaceous rock, and semiconsolidated sediments at depths ranging from 0.5 to 840 meters below the surface. The magnitude of the maximum horizontal stress ranges from 3.5 to 41.8 MPa. The orientation of the maximum horizontal stress varies within the Appalachian area and is dependent on location within a tectonic province (Figure 1). A shift of greater than 90° occurs in Douglas County, Georgia, near the Brevard fault zone. This deviation may be due to the nearness to the fault zone, as erratic measurements at depths of up to about 60 meters have been observed in several other areas when made near fault zones. Therefore, this may account for the shift in direction.
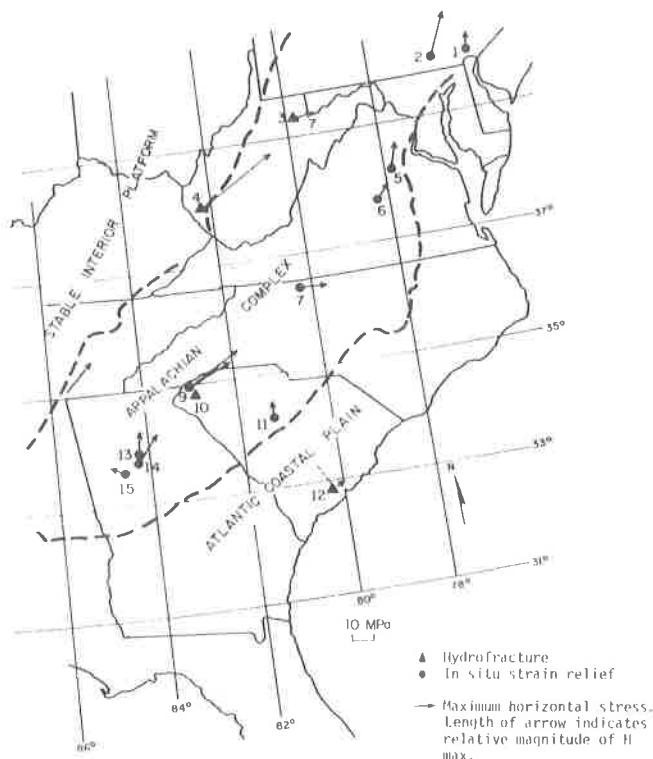

Figure 1. Direction of maximum horizontal principal *in situ* stresses in the Southeastern U. S. Length of arrow indicates magnitude of stress. For measurement 12, only the minimum stress (dashed line) was measured; therefore, direction of maximum stress is known but not the magnitude.

[x]Deviatoric stress component = (actual stress component)--(lithostatic component).

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Table 1. In Situ Stresses Determine in the Southeastern United States.

Location*	Method	Rock Type	Stress, MPa $\sigma_{H max}$	$\sigma_{H min}$	σ_{vert}	Depth of Measurement, meters	Reference
1	St. Peters, PA	strain-relief	norite	5.6	2.3	NA**	1.5	Hooker and Johnson, 1967 and 1969
2	Morgantown, PA	strain-relief	diabase	41.8	13.2	26.8	713	Agarwal and others, 1969
3	Morgantown, WV	hydrofracture	shale	10.4	5.5	(2.9)	30.5	Dahl and Parsons, 1972
4	Southwestern, WV	hydrofracture	shale	40.8	18.4	(21.0)	840	Haimson, 1977
5	Rapidan, VA	strain-relief	diabase	12.2	11.4	NA	1.5	Hooker and Johnson, 1967 and 1969
6	Mineral, VA	strain-relief	gneiss and schist	3.8	1.7	(0.1)	4.0	Lindner and Halpern, 1978
7	Mt. Airy, NC	strain-relief	granite	11.3	6.0	NA	0.7	Hooker and Johnson, 1967 and 1969
8	Raccoon Mt., TN			15.5	NA	7.4	274	Ingle and others, 1971
9	Bad Creek, SC	hydrofracture	gneiss	22.8	15.4	6.2	229	Hast, 1969
10	Bad Creek, SC	strain-relief	gneiss	29.3	18.4	10.2	~200	Schaeffer and others, 1979
11	Parr, SC	strain-relief	granodiorite	3.7	1.0	NA	5.6	Lindner and Halpern, 1978
12	Charleston, SC	hydrofricture	silty-clay	NA	4.2	7.3	344	Zoback and others, 1978
13	Stone Mt., GA	strain-relief	granite	10.3	6.9	NA	3.1	Hooker and Johnson, 1967 and 1969
14	Lithonia, GA	strain-relief	gneiss	15.2	7.7	(0.2)	8.7	Hooker and Johnson, 1967 and 1969
15	Douglasville, GA	strain-relief	gneiss	3.5	1.9	NA	0.5	Hooker and Johnson, 1969-1969

* Numbers are keyed to Figure 1.
** NA = not analyzed.
  ( ) indicates an uncertain value.
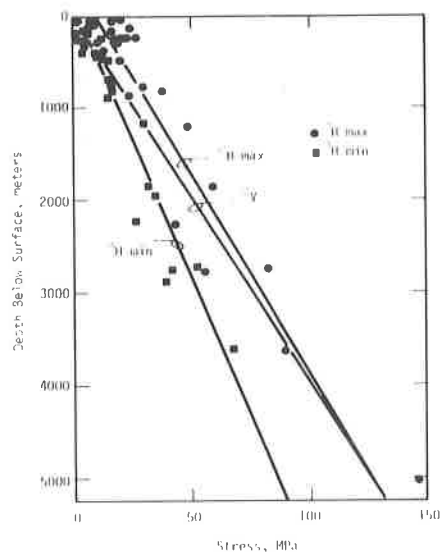
Figure 2. Variation in in situ stress with depth within the U. S. (after Haimson, 1978).

Several investigators have developed empirical relationships for in situ stresses on a regional or continental basis (Brown and Hoek, 1978; Haimson, 1978; Hast, 1973; Herget, 1974; Linder and Halpern, 1977). Haimson developed the following relationships (Figure 2) from hydrofracture data for the United States:

$$\sigma_{H max} = 2.0 \pm 0.16 \, d$$

$$\sigma_v = 0.025 \, d$$

where $\sigma_{H max}$ = maximum horizontal stress, MPa

σ_v = vertical stress, MPa

and d = depth, meters

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Using worldwide data from hydrofracturing and overcoring, McGarr and Gay (1978) found that $\sigma_v = 0.0265$ d. Using worldwide data from overcoring experience in mines, Brown and Hoek (1978) found that the average horizontal stresses were bounded by:

$$2.7 + 0.008 \; d < \sigma_{H \; avg} \leq 40.5 + 0.014 \; d$$

$$\sigma_v = 0.027 \; d$$

$$\text{where} \quad \sigma_{H \; avg} = \frac{\sigma_{H \; max} + \sigma_{H \; min}}{2}$$

Lindner and Halpern (1978) found that hydrofracture and strain-relief measurements in the United States are best represented by:

$$\sigma_{H \; avg} = 4.2 + 0.0038 \; d$$

$$\sigma_v = 0.023 \; d$$

Figure 3 shows nine focal mechanism solutions* for small, shallow earthquakes in the southeastern United States as developed by several seismologists. (Only a few of these solutions are well constrained.) (Bollinger and others, 1976; Tarr, 1977). An analysis of these and other focal mechanism solutions for the southeast has been reported by Guinn (1977) and is summarized in Figure 1.

DISCUSSION

Application of knowledge of the stress field to tectonic processes is required to understand regional deformation, regional seismicity, and plate movements. This review evaluates regional stress in the southeastern United States.
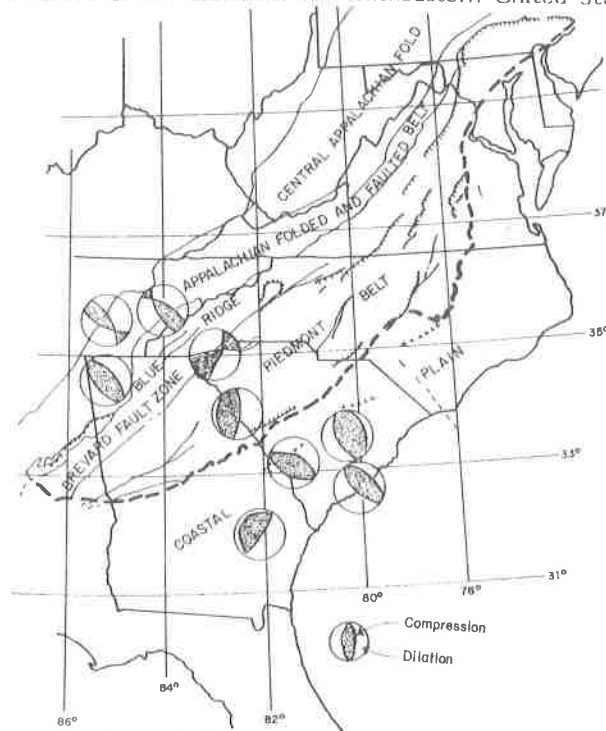

Figure 3.   Focal mechanism solutions for the southeastern U. S.

*In this figure, the circles represent the horizontal plane (top surface of a lower hemisphere). The shaded area within each circle represents the zone of compression. The unshaded area represents the zone of dilation.
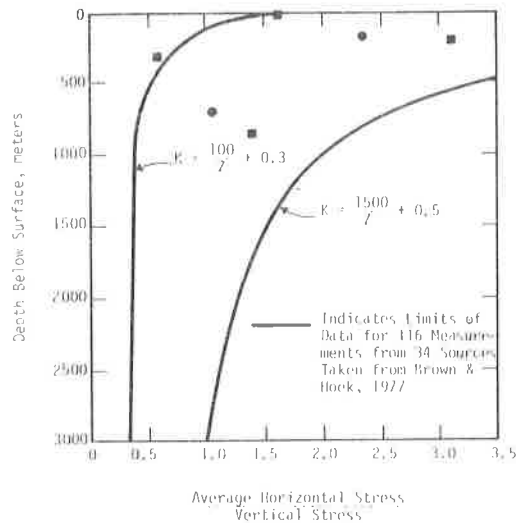
Figure 4. Ratio of average measured values of in situ horizontal stress to the vertical stress as a function of depth in the southeastern U. S. Square - hydrofracture; circle - overcoring.

Importance of Horizontal Stress

The increased number of *in situ* stress measurements throughout the world in the last two decades has shown that high horizontal stresses occur frequently at shallow depths (to several kilometers). Figure 2 (after Haimson, 1978) shows the variation of stress, with depth, within the continental United States; it is not until a depth of about 5 km is reached that the vertical stress is the principal stress. The data, especially those below 0.5 kilometer, are from measurements in sedimentary basins within the stable interior of the United States. Similar plots have been compiled by McGarr and Gay (1978) for South Africa and Canada. Plots of shear stress, $\sigma_1 - \sigma_3)/2$, as a function of depth indicate that higher shear stresses, as much as 20 MPa, are found at depths of less than two kilometers. In general, higher shear stresses are found in crystalline rocks.

Measurements at depths of more than ten meters in the rocks of the southeast are plotted in Figure 4 as the ratio of average horizontal stress to vertical stress. The lines are the general limits of worldwide data (Brown and Hoek, 1978). The ratio σ_H avg$/\sigma_v$ for measurements within ten meters of the surface are too high and variable to be plotted within the scale used for Figure 4. This ratio is greater than one for all measurements in the southeast except for those near Charleston, South Carolina. At Charleston, only the minimum horizontal stress was determined; however, it is doubtful that the maximum horizontal stress was large enough to make the ratio greater than about 0.8. The high values of σ_H avg$/\sigma_v$ in the southeast would indicate that for depths less than one kilometer, and especially for depths less than 0.5 kilometer, the existence of high horizontal stresses must be considered in the design of underground facilities by proper orientation with respect to the stress field.

Tectonic Framework for the Southeast

Anderson (1951) developed a classical relationship of faulting to principal stress; where when σ_1 is vertical, normal faulting occurs; when σ_2 is vertical, strike slip faulting occurs; and when σ_3 is vertical, thrust faulting occurs. A preliminary regional tectonic framework was developed by using this relationship to analyze the data from the *in situ* stress measurements and to compare the results with the fault plane solutions from earthquakes.

All measured *in situ* stress discussed in this paper is in the Appalachian complex

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except two: one in the Coastal Plain and one in the stable interior region. Principal stresses measured in rocks of the Appalachian complex, with the exception of those at Morgantown, Pennsylvania (which indicate the effect of the extensive mining activity on the stress distribution), show the minimum principal stress component (σ_3) to have a vertical or subvertical orientation which, according to Anderson's relationship, indicates thrust faulting. This requires more data at depth to verify; however, it appears to be the case. This interpretation is consistent with most of the fault plane solutions obtained in the Appalachian complex. The principal stress direction generally follows the structural trend of the region, parallel to the major thrusts of the Appalachian complex.

In the Coastal Plain of the southeast, in situ stress measurements show the major principal stress component (σ_1) to be in the vertical direction, which indicates normal faulting. Fault plane solutions for the Coastal Plain indicate both normal and reverse faulting. The solutions are not well constrained, and the exact mechanism is difficult to determine. Recent studies indicate normal faulting in Coastal Plain sediments near Charleston, South Carolina (Zoback and others, 1978); however, thrust faulting may be present in the crystalline basement. A better knowledge of the focal depth of the earthquakes and more definitive fault plane solutions are required.

The consistency of the above results for the Appalachian complex and the Coastal Plain compares well with the consistency of data for the intermountain seismic belt (Smith and Sbar, 1974) and, on a small scale, the consistency of data for the Rangely Anticline area, Colorado (Raleigh and others, 1976). At the Rangely Anticline, extensive in situ stress studies conducted by a variety of overcoring techniques, hydrofracturing, x-ray analysis, and fault plane solutions yielded consistent stress orientations. The measured stress magnitude from hydraulic fracturing and fault plane solutions indicates right lateral strike slip faulting. For the intermountain seismic belt, good correlation was obtained between the regional tectonic framework and the stresses and movements determined by fault plane solutions. For the eastern United States, measured in situ stresses, geological evidence, and fault plane solutions all indicated high horizontal stresses (Sbar and Sykes, 1973).

CONCLUSIONS

High horizontal stresses exist in the Appalachian complex with $\sigma_{H\,max}/\sigma_v$ ranging up to 3.7.

Based on the limited data base available, the three major physiographic and tectonic provinces--Coastal Plain, Appalachian complex, and the stable interior--have different in situ stress states, which may indicate different faulting mechanisms.

The various techniques used to determine in situ stress--hydrofracturing and overcoring yield relatively consistent values for both stress magnitude and orientation. Fault plane solutions give orientations generally consistent with the other two types of measurements.

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STRATIGRAPHIC DISCUSSION IN SUPPORT OF A MAJOR UNCONFORMITY SEPARATING THE COLUMBIA GROUP FROM THE UNDERLYING UPPER MIOCENE AQUIFER COMPLEX IN EASTERN MARYLAND

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ABSTRACT

Well log correlations across the lower Eastern Shore of Maryland strongly suggest that beds of the Upper Miocene Aquifer Complex ("Yorktown-Cohansey(?)" Formation) are truncated by an angular unconformity occurring at the base of the Columbia Group ("Pensauken Formation"). More detailed local studies have demonstrated that the base of the Columbia Group is defined by a network of complexly incised fluvial channels which locally cut out beds of the underlying Aquifer Complex.

At the Coast the Manokin Aquifer, basal member of the Complex, is separated from the Columbia Group by about 200 feet of post-Manokin sediments. Westward the upper beds of the Complex are truncated beneath a low-angle unconformity so that in western Wicomico County, a distance of about 30 miles, the Manokin Aquifer subcrops immediately beneath the Columbia Group. Juxtaposition of the fluvial, channel-fill sands of the Columbia Group with marginal marine sediments of the Upper Miocene Aquifer Complex has suggested to some workers (Owens and Denny, 1979a) that the units are lithofacies of the same depositional sequence. However, the cross-cutting of marker beds in the Aquifer Complex by the channel-fill sequence argues persuasively that the units cannot be coeval. For example, wells drilled across a paleochannel trend in north-central Wicomico County have shown channel-fill deposits cross-cutting, from youngest to oldest, a 60-foot thick aquitard assigned to the Aquifer Complex, the Manokin Aquifer and, in places along the thalweg, upper-most beds of the St. Marys(?) Formation.

Although clearly younger than the upper Miocene Aquifer Complex, the age of the overlying channel-fill sequence remains uncertain. Recently obtained paleobotanical evidence suggests that it may be Late Tertiary, rather than pre-Wisconsin Quaternary as formerly assumed.

INTRODUCTION

The lower Eastern Shore of Maryland, part of the Delmarva Peninsula, is a low coastal area mantled by a relatively thin, but stratigraphically complex, sheet of fluvial to marginal marine sediments. These sediments are usually assigned to the Columbia Group (Hansen, 1966; Jordan, 1974) and thought to be Pleistocene to perhaps Pliocene(?) in age (Rasmussen and Slaughter, 1955) (table 1). Until recently the channel-fill sediments occurring at the base of the Columbia Group in parts of Somerset, Wicomico, and Worcester Counties were believed to overlie and truncate older, southeasterly dipping Miocene units. Rasmussen and Slaughter (1955) assigned these beds to the upper part of the Chesapeake Group and subdivided them into the St. Marys(?) Formation and the Yorktown and Cohansey(?) Formations (undivided)*. The former is a fine-grained shelf deposit, which on geophysical logs grades upward into the Yorktown and Cohansey(?) Formation, a dominantly sandy, near shore complex consisting of several aquifers (e.g., the Manokin, Ocean City and Pocomoke Aquifers (Weigle, 1974). Owens and Denny (1979) have challenged this interpretation, however, by suggesting that the fluvial beds of the Columbia Group (their Pensauken Formation)
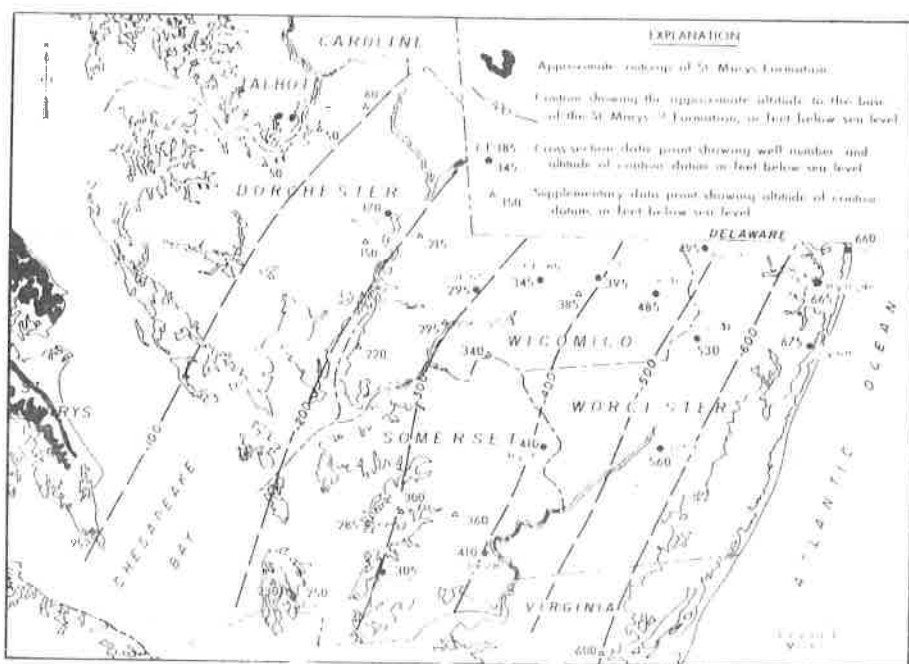
Figure 4. *Structure contour map showing depth to base of St. Marys(?) Formation lower Eastern Shore, Maryland.*

Hill), Som-Bg 3 (Whitesburg), and Som-De 28 (Rehobeth). This characteristic is suggestive of a thin phosphatic zone, perhaps indicative of an interval of nondeposition prior to St. Marys(?) sedimentaion. In the outcrop areas studied by Gernant (1970) the Choptank-St. Marys contact is also disconformable.

The upper contact of the St. Marys(?) Formation is not as sharply defined. In some places the gamma-ray logs show a progressive shift, suggesting that the St. Marys(?) Formation grades upward into the Manokin aquifer as part of a single depositional cycle (e.g., Wor-Bg 10, fig. 1). Shelfward, the St. Marys(?) Formation adds section at the top; a facies relationship with lower Manokin sands is implied (e.g., Wor-Cg 68, fig. 2). Elsewhere the contact may be marked by an abrupt trace shift suggestive of a local unconformity (e.g., Wor-Ae 19, fig. 1). In areas such as Janes Island Park, where the Manokin aquifer is poorly developed, the contact between the two units is difficult to pick on gamma logs.

To summarize, the St. Marys(?) Formation beneath the lower Eastern Shore of Maryland is considered an important marker bed because: (1) its basal contact is a disconformity of regional extent, easily recognized on gamma ray logs by an abrupt sand-clay shift that is sometimes associated with a high radiation "spike"; (2) the unit was deposited in a shelf environment that produced a relatively homogeneous lithology (and characteristic gamma ray signature) devoid of abrupt facies changes and unconformities; and (3) at its top the St. Marys(?) Formation grades into the overlying Manokin Aquifer as a coarsening-upward cycle that is generally recognizable in well logs.

Biostratigraphic Data: Traditionally the St. Marys Formation at its type locality was believed to include beds ranging in age from late middle to early late Miocene age (e.g. Gibson, 1971). Blackwelder and Ward (1976) have recently reevaluated the molluscan assemblages resulting in the type St. Marys Formation of Maryland being informally split into 3 units; the lower two, Little Cove Point and "St. Marys", were placed in the Late Middle Miocene and the upper, Eastover Formation, in the Late Miocene (Ward and Blackwelder, 1980).

At least as early as 1918, Clark, Mathews, and Berry (p. 219) studying the Eastern

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Shore subsurface correlated a fossiliferous deposit of clay, sand, and sandy clay with the St. Marys(?) Formation based on the occurrence of *Turritella variabilis* and *"Alectrion" peralta* (p. 317). The first detailed paleontologic studies were reported by Gardner (in Anderson and others, 1948) who investigated cuttings from a well (Ohio L. G. Hammond No. 1) near Parsonsburg. Between 330 and 510 feet Gardner logged an assemblage of molluscs that she could relate to the St. Marys Formation "without reservation" (p. 114): *Acteon pusillus* Forbes, *Bulliopsis quadrata* (Conrad), *Terebra curvilirata* Conrad, *Terebra simplex* Conrad, and *Uzita peralta* (Conrad). The Ohio L. G. Hammond No. 1 well is located about 3.5 miles from Wi-Cg 53 (fig. 1), but on-strike and at approximately the same elevation. In Wi-Cg 53 the St. Marys(?) Formation occurs between 345 and 460 feet and is broadly correlative to the St. Marys Formation of Gardner. Later Gardner (in Rasmussen and Slaughter, 1955, p. 60) studied an assemblage of molluscs from a well near Hebron located close to Wi-Cd 65 (fig. 1). In this well a St. Marys assemblage was encountered at 185 feet in sandy beds that are about 20 feet higher than the top of the St. Marys(?) marker bed correlated in figure 1. As previously discussed, the contact between the St. Marys(?) Formation and the Manokin aquifer is usually gradational, suggestive of an uninterrupted depositional sequence. It is plausible, therefore, that fossil assemblages associated with the St. Marys Formation at its type locality could extend up into the Manokin aquifer which is absent from the Calvert Cliffs section. Blackwelder and Ward (p. A9, in Owens and Denny, 1979a) have also commented on the likelihood of a St. Marys molluscan assemblage extending up into the Manokin sands.

Supporting Blackwelder and Ward's (1976) placement of the upper part of the St. Marys Formation in the Late Miocene is an investigation by Olsson (1976) of the planktic foraminiferal assemblages from several wells located near Wor-Ah 6 (fig. 1) and Wor-Cg 68 (fig. 2). A core taken from about the middle of the St. Marys(?) Formation (see Wor-Ah 6 at 590 feet) yielded an assemblage associated with the *Globorotalia plesiotumida* (N17) Zone of Late Miocene age (Berggren, 1972, p. 206). The assemblage suggested to Olsson that the sample was "deposited under shallow mid-shelf depths (65-265 feet)...indicated by the appearance of planktic foraminiferal species in association with characteristic mid-shelf benthic foraminifera. The planktic assemblage is subtropical to tropical in its specific composition...". A listing of the benthic and planktic foraminifers from the 590 foot interval follows:

Bolivina directa (2)	*Globigerinoides altiapertura (1)*
Bolivina cf. paula (1)	*Globigerinoides obliqua (1)*
Bolivina subaenariensis (1)	*Globigerinoides triloba (1)*
Buccella andersoni (3)	*Globoquadrina altispira (1)*
Buliminella curta (2)	*Globoquadrina dehiscens (1)*
Cassidulina carinata (3)	*Globorotalia continuosa (2)*
Chilostomella sp. (1)	*Globorotalia menardii (1)*
Fissurina lucida (2)	*Globorotalia plesiotumida (1)*
Florilus pizarrensis	*Globorotalia pseudopachyderma (2)*
Fursenkoina fusiformis (3)	*Hanzawaia concentrica (3)*
Globigerina angustiumbilicata (1)	*Legena dorseyae (2)*
Globigerina apertura (1)	*Lenticulina americana (1)*
Globigerina cf. conglomerata (1)	*Orbulina suturalis (1)*
Globigerina foliata (2)	*Quinqueloculina seminula (1)*
Globigerina decoraperta (1)	*Sphaeroidinellopsis subdehiscens (1)*
Globigerinita glutinata (1)	*Spiroplectammina sp. (1)*
Globigerinoides sp. (1)	*Textularia agglutinans (2)*
	Textularia deltoidea (1)

Number of specimens: 1 = 1-10   2 = 11-100   3 = 101-1000

Brush (1976) also studied core material from near the middle of the St. Marys(?) Formation (fig. 1) and reported an Upper Tertiary pollen assemblage dominated by *Juglandaceae*. The following microfloral list suggests a terrestrial source under warm temperate to perhaps subtropical conditions:

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TYPE	PERCENT
Ferns and fern allies	
Selaginella (spike moss)	2.8
Others	2.8
Gynosperms	
Pinus (pine)	5.6
Podocarpus	5.6
Angiosperms (trees)	
Alnus (alder)	2.8
Juglandaceae	
Carya (hickory)	41.5
Pterocarya	13.8
Quercus (oak)	11.1
Salix (willow)	5.6
Angiosperms (herbaceous)	
Ambrosia (ragweed)	5.6
"Cretaceous" types	
Monosulcates	2.8

Olsson (1976) noted a shallowing, and perhaps cooling, trend in a Late Miocene benthic assemblage obtained from a core 30 feet higher in the St. Marys(?) section (see 560 feet in Wor-Ah 6) (fig. 1). High numbers of the shallow water species *Elphidium clavatum* and *Buliminella elegantissima*, occurring in the absence of planktic foraminifers, suggested to Olsson deposition in shelf depths of less than 100 feet. *Elphidium clavatum's* living range is north of Cape Hatteras and contrasts with the subtropical planktic assemblage noted in the 590 foot core. A cooling trend is also suggested by a reduction in *Juglandaceae* (20.4%) dominance coupled with increased occurrences of spruce (6.8%) and pine (20.3%) in the shallower core (Brush, 1976).

A list of the benthic foraminifers from the 560 foot core follows:

Ammonia beccarii (1)	*Elphidium subarcticum (1)*
Bucella andersoni (1)	*Florilus pizarrensis (1)*
Buliminella curta (1)	*Hanzawaia concentrica (1)*
Buliminella elegantissima (3)	*Nonionella auris (2)*
Cassidulina carinata (1)	*Textularia agglutinans (1)*
Elphidium clavatum (2)	*Textularia deltoidea (1)*

Number of specimens: 1 = 1-10   2 = 11-100   3 = 101-1000

In summary, limited biostratigraphic data suggest that (1) the subsurface St. Marys(?) Formation is largely Late Miocene in age, perhaps coeval to the Eastover Formation (Claremont Manor Member) of Ward and Blackwelder (1980), and (2) the unit was deposited on a shoaling marine shelf (265 feet to < 100 feet) possibly during a climatic shift from a sub-tropical to a temperate environment.

"Yorktown and Cohansey(?)" Formations
(Upper Miocene Aquifer Complex)

At least as early as 1918 the dominantly sandy complex of marginal marine sediments that overlie the St. Marys(?) Formation in the lower Eastern Shore subsurface was considered of formational rank. Applying nomenclature extrapolated from New Jersey, Clark, Mathews, and Berry (1918, p. 324) tentatively referred these beds to the Cohansey Formation. Rasmussen and Slaughter (1955, p. 93) proposed that the Late Miocene complex in Maryland was stratigraphically equivalent to the outcropping Yorktown Formation in Virginia, but also accepted Richards' (1953) speculation that the Cohansey was a nonmarine facies equivalent of the Yorktown - hence the cumbersome Yorktown and Cohansey Formations(?) undifferentiated.

Later paleontologic work seriously questioned the age equivalency of the Yorktown Formation and the Cohansey Formation (Owens and Denny, 1979a, p. A7), rendering Rasmussen and Slaughter's nomenclature not only cumbersome, but probably misleading. For these reasons the "Yorktown and Cohansey(?)" Formations(?)

undifferentiated shall yield in this paper to the equally cumbersome, but strati-
graphically neutral designation of Upper Miocene (Manokin-Ocean City-Pocomoke)
Aquifer Complex (Weigle, 1974). Clearly, a new formation name needs to be erected,
but is not done here pending the availability of a more completely cored section.
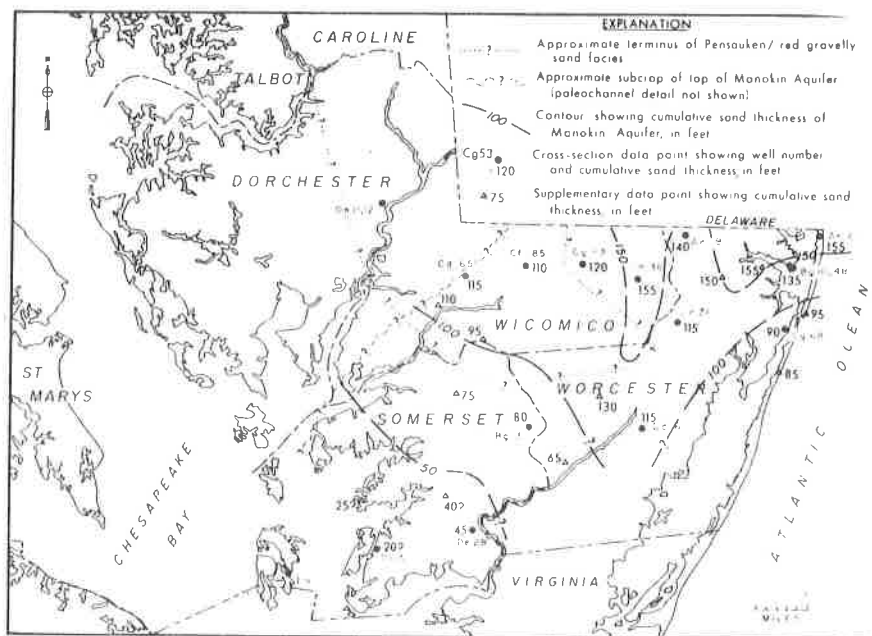

Figure 5. Sand thickness map of the Manokin Aquifer, lower Eastern Shore, Maryland.

Lithostratigraphic Data: The grayish Manokin sand is the basal unit of the Aquifer
Complex. It is widely used as a source of ground water and has been tapped by
hundreds of wells. A recent model simulation of the aquifer suggests strongly that, at
least in a hydrologic sense, it functions as a continuous, albeit heterogeneous, sand
sheet (Weigle and Achmad, in prep.). Typical of shallow shelf to marginal marine
deposition, cuttings from the Manokin exhibit a wide range of sand to fine gravel sizes
and include silty to clayey interbeds; lignitic or peaty material is commonly observed,
shelly cuttings less frequently. The Manokin is thickest in northwestern Worcester
County where it exceeds 150 feet (Wor-Ah 6, fig. 1). The aquifer ranges generally
between 100 and 150 feet in thickness (fig. 5), but thins west-southwestward and is
difficult to separate on gamma-ray logs from the coarsening upward sequence that
characterizes the upper part of the St. Marys(?) Formation (e.g. Som-Dc 3, fig. 2). In
coastal areas south of the Ocean City inlet the onset of Manokin deposition occurs
higher in the Upper Miocene section (e.g. Wor-Cg 68, fig. 2), suggesting a more
shelfward location.

Although the St. Marys(?) Formation coarsens upward and is transitional with the
Manokin, the latter marks more clearly the beginning of a major regressive cycle,
perhaps correlative with the global fall in late Miocene sea level noted by Vail,
Mitchum, and Thompson (1977, fig. 2). As a result of this shoaling condition, inner
shelf and marginal marine lithofacies begin to dominate the Upper Miocene section.
Complex depositional patterns caused by relatively minor transgressive and regressive
shifts in the shoreline are apparent. Because of rapid facies changes and local
unconformities the post-Manokin sediments are particularly difficult to correlate from
well-to-well. Rasmussen and Slaughter (1953) and Weigle (1974) recognized two sandy
members above the Manokin that, at least locally, were sufficiently thick and
permeable to function as significant aquifers. These sandy members were named the
Pocomoke Aquifer (younger) and Ocean City Aquifer (older) respectively after the two

communities where their occurrences are least questionable. Elsewhere the aquifers break-up into a lensing stack of interbedded silts/clays and sands of variable textures, making correlation tenuous at best.

For example, at North Ocean City (Wor-Ah6, fig. 1) the Ocean City Aquifer is about 50 feet thick and is clearly separated from the underlying Manokin Aquifer by a silt/clay confining bed. The separation is less clear, however, both west and south of Ocean City. In both the Isle of Wight well (Wor-Bg 48) and the Ocean City Airport well (Wor-Cg 68) the "confining bed" separating the two aquifers is much more sandy. The gamma-ray logs identify only about 10 feet of clay/silt separation. Updip the unit thins (fig. 1); for example, between Careytown (Wor-Ae 19) and Willards (Wi-Ch 36) the Ocean City Aquifer loses its gamma-ray signature by feathering out into a sequence of interbedded silt/clays and sands. Similarly, traversing cross-section B-B' (fig. 2) southwest of Ocean City the aquifer first begins to break up into a series of sandy and clayey beds (Wor-Ce 28 at Libertytown) and then at Snow Hill (Wor-Dd 60) becomes a dominantly fine-grained facies.

The distribution of the Pocomoke Aquifer is even more enigmatic and probably cannot be rationalized with the existing data. Som-De 28 (fig. 2) is near Rasmussen and Slaughter's typesection and there is little doubt that the dominantly sandy section between approximately 70 and 150 feet is their Pocomoke Aquifer. At this site the clayey confining bed separating the Manokin from the Pocomoke is only about 45 feet thick. Along strike the Pocomoke thins and is replaced by a thickening clayey section; for example, at Whitesburg (Som-Bg 5) and Snow Hill (Wor-Dd 60) the confining bed approaches 100 feet in thickness. Northeastward sands assigned to the Ocean City aquifer break into the section and result in a complex local stratigraphy that obscures the Pocomoke as a discrete unit. For example, at Libertytown (Wor-Ce 31) and Ocean City Airport (Wor-Cg 68) the uppermost sand in the Upper Miocene Aquifer Complex could be assigned to the Pocomoke, but that probably implies an areal continuity that does not exist. Further complicating the distribution of the Pocomoke Aquifer is its association with the basal sands of the Columbia Group. As shall be discussed subsequently, the Columbia Group overlies with channeled discordance truncated beds of the Pocomoke-Ocean City-Manokin Aquifer Complex. East and south of Salisbury the Columbia Group increasingly exhibits transitional marine lithologies broadly similar to the upper sandy beds of the Aquifer Complex. Sand-on-sand contacts are particularly difficult to establish using routine subsurface data such as drill cutting descriptions and geophysical logs. As a result, there has been a tendency to anticipate the occurrence of the Pocomoke based on extrapolated dip and strike relationships (Otton and others, 1969, map IX; Cushing, Kantrowitz, and Taylor, 1973, pl. 10). A hybrid unit has resulted. At best the "Pocomoke Aquifer" is the first significant sand to occur below the unconformity, although the lensing nature of the post-Manokin Aquifer Complex strongly implies that more than one sand bed is involved (Hansen, 1972, p. 92). In other instances the "Pocomoke Aquifer" has been confused with the basal sands of the Columbia Group, particularly in channel-fill areas such as Isle of Wight (Wor-Bg 48, fig. 1) where the latter occur at greater than normal depths.

In summary, the following characteristics of the Upper Miocene Aquifer Complex should be noted: (1) the Manokin Aquifer, occurring at the base of the Complex, is, like the underlying St. Marys(?) Formation, an areally mappable unit. Its upper contact is the only horizon within the Aquifer Complex sufficiently correlative for stratigraphic control, (2) the Ocean City and Pocomoke Aquifers are part of a stratigraphically complex, interbedded sequence of dominantly sandy and dominantly clayey/silty beds that overlie the Manokin Aquifer. The Ocean City and Pocomoke Aquifers are local lithofacies within this complex and are extrapolated with risk. The post-Manokin part of the Upper Miocene Aquifer Complex is best viewed as a single lithostratigraphic unit defined by its complex internal stratigraphy. Viewed in this way the unit becomes recognizable in the subsurface because it occurs between two dominantly sandy units, the underlying Manokin Aquifer and the overlying channeled sand sheet of the Columbia Group.

Biostratigraphic Data: The biostratigraphy of the Upper Miocene Aquifer complex remains to be studied systematically. At present only random core samples or cutting intervals from a few wells have been investigated in the lower Eastern Shore area. For

example, Olsson (1976) found the following Upper Miocene to Pliocene foraminiferal assemblage in a sample from near the Manokin Aquifer-Ocean City Aquifer contact (Wor-Cg 68, fig. 2):

Bolivina directa (1)	*Florilus pizarrensis (2)*
Buccella sp. (2)	*Globigerina sp. (10)*
Buliminella curta (1)	*Planorbulina mediterranensis (1)*
Buliminella elegantissima (3)	*Quinqueloculina seminula (1)*
Dyocibicides biseralis (3)	*Rosalina floridensis (1)*
Elphidium clavatum (2)	*Textularia floridana (2)*

Number of specimens: 1 = 1-10   2 = 11-100   3 = 101-1000

The sample is dominated by shallow water benthic types suggestive of an inner shelf (< 100 feet) depositional setting. A sample from near the top of the Ocean City Aquifer (Wor-Ah 6, fig. 1) exhibited a very low diversity of species and was probably deposited in coastal waters at a depth of less than 35 feet. *Elphidium clavatum* and *Buliminella elegantissima* dominate the assemblage which also includes lesser numbers of *Buccella frigida* and *Hanzawaia concentrica*. These species range from Miocene to Recent and are not useful for dating.

Owens and Denny (1979a, p. A9) collected fossils from an auger hole drilled through the Manokin Aquifer at its type locality (Manokin River, west-central Somerset County). The assemblage was studied by B. W. Blackwelder, C. W. Ward, and J. E. Hazel. Noting the occurrence of the mollusks *Mesodesma mariana, Bulliopsis integra,* and *Bulliopsis quadrata* and the brachiopod *Discinisca* sp., Blackwelder and Ward placed the Manokin beds near the middle Miocene-late Miocene boundary. Abundant occurrences of the mollusks *Gemma, Bulliopsis,* and *Nassarium* along with the brackish-water ostracode *Cyprideis* indicated "deposition of shallow water, probably with nearby tidal flats..." (Owens and Denny, 1979a, p. A9).

The same group of USGS workers reported on a Pocomoke assemblage from an auger hole located very close to Wor-Dd 60 near Snow Hill (fig. 2). These beds, broadly correlative to the 115 to 155 ft. interval in Wor-Dd 60, were dated late Miocene on the basis of the molluscs *Pecten eboreus, Astarte rappahannockensis,* and *Isognomen* sp., a date corroborated by a glauconite (K/Ar) age of 6.4 million + 5,000 years (Owens and Denny, 1979a, p. A10). The "Pocomoke fauna" from this boring is indicative of shelf deposition in significantly deeper water than the Manokin assemblage noted above (Owens and Denny, 1979a, p. A10). However, to the extent that both units exhibit lithofacies changes this generalization should be extrapolated with care. The post-Manokin sediments in particular exhibit a complex stratigraphy suggestive of a locally shifting shoreline.

Brush (1976) studied the pollen assemblages from several cores taken from the Upper Miocene Aquifer Complex (table 2). The samples typically contain exotic *Juglandacea* types, such as *Englehartia, Platycarya,* or *Pterocarya,* which Sirkin (in Owens and Denny, 1979a, p. A9) associates with a Tertiary age flora. Also present in low percentages are palynomorphs that are normally associated with the Cretaceous (e.g. Monosulcate and tricolporate grains). An extension of these forms into the Miocene is implied, but reworking cannot be ruled out. The dominant microflora *(Carya-Quercus)* is characteristic of a warm-temperate climate, although cooler intervals can be inferred by the *Picea-Pinus* dominance exhibited by core Wor-Ah 37 (196-198 ft.).

In summary, scant biostratigraphic data suggest the following: (1) The Manokin-Ocean City-Pocomoke Aquifer Complex is late Miocene in age. The Complex is older than the Yorktown Formation of Virginia (lower to middle Pliocene) and younger than the St. Mary's Formation at its type location. It may be equivalent in part to the Cobham Bay member of the Eastover Formation (Ward and Blackwelder, 1980). As discussed previously, the contact between the Aquifer Complex and the St. Marys(?) Formation is gradational and probably time transgressive; and (2) the Aquifer Complex was largely deposited in inner shelf and marginal marine environments. Onset of Manokin deposition marked a major phase of shoreline progradation, perhaps coincident with a late Miocene fall in global sea level. This major regressive cycle was punctuated by at least one transgressive phase, however, as evidenced by the return of a deeper shelf fauna in the Pocomoke (Owens and Denny, 1979a, p. A10).

Table 2. *Distribution of pollen and spore taxa in well samples from the Pocomoke-Ocean City-Manokin Aquifer Complex (from Brush, 1976).*

	Wor-Ae 23	Wor-Ah 37	Wor-Bg 48	Wor-De 36	Wor-De 36
Well No. Depth	251'-252'	196-198'	185'-186'	92'	206'-208'
Stratigraphic Interval	Near top of Manokin	Near top of Ocean City	Near top of Ocean City	Near top of Pocomoke	Near top of Manokin
Ferns and fern allies:	percent	%	%	%	%
Dryopteris (wood fern)			1.0		
Lycopodium (club moss)	2.3		2.1		
Monolete spores		2.4	3.1		
Polypodium		2.4	2.1		
Others (undivided)	4.5			1.4	3.4
Gymnosperms:					
Picea (spruce)		7.3	6.2	4.2	5.2
Pinus (pine)	6.8	36.6	5.2	21.1	36.2
Podocarpus			1.0		
Tsuga (hemlock)	4.5				
Angiosperms (tree):					
Acer (maple)	6.8		3.1	2.8	1.7
Alnus (alder)			1.0	1.4	3.4
Betula (birch)	4.5		6.2	2.8?	1.7
Castanea (chestnut)			2.1	4.2	1.7
Cornus (dogwood)			1.0?		
Corylus (hazelnut)	2.3				
Fagus (beech)	2.3?		4.2		
Fraxinus (ash)			1.0	2.8	5.2
Juglandaceae:					
Carya (hickory)	19.2	2.4	15.6	11.2	17.2
Engelhardtia type	2.3		1.0		1.7
Juglans (walnut) type	2.3	2.4	6.2	1.4	
Platycarya			4.1	1.4	
Pterocarya	6.8			1.4	5.2
Liquidambar (sweet gum)					
Quercus (oak)	15.9	4.9	10.4	16.9	1.7
Salix (willow)	11.4	2.4	12.5		5.2
Tilia (basswood)					1.7
Ulmus (elm)			1.0		
Angiosperms (herbaceous):					
Artemisia (sage)				2.8	
Ambrosia (ragweed)			2.1		
Caryophyllaceae (pink family)		2.4			
Ericaceae (blueberry)					1.7
Gramineae (grass)			1.0	2.8	
Liliaceae (lily) type		14.6			
Nymphea (water lily)	2.3	7.3	1.0	14.1	
Typha (cattail)				1.4	
"Cretaceous" types:					
Monosulcate type		2.4	4.2		3.4
Praebaesopollis			2.1		
Pseudoplicapollis		2.4			1.7
Tricolpate grains	2.3(16μ)			1.4(9μ)	
Tricolporate grains	2.3(12μ)	2.4(12μ)			
Unidentified	2.3	7.3		5.6	

COLUMBIA GROUP

McGee (1886) first applied the name Columbia Formation to the surficial deposits of the middle Atlantic region. The deposits were subsequently subdivided into several morphostratigraphic units and the term elevated to Group status in Maryland (e.g. Shattuck, 1906). By 1918 (Clark, Matthews, and Berry) the name was applied not only to the outcropping "terrace-formations", but also to the shallow, dominantly sandy subsurface unit that mantles much of the Eastern Shore of Maryland. Excellent reviews of the evolution of the Columbia Group nomenclature and associated stratigraphic problems are provided by Oaks and Coch (1973) and Jordan (1974).

Prior to the work of J. P. Owens, C. S. Denny, and colleagues (Sirkin and Owens, 1976; Owens and Denny, 1978, 1979a, 1979b) a concensus was emerging concerning the stratigraphic position and depositional history of the Columbia Group on the Delmarva Peninsula. Briefly stated: The Columbia Group was thought to be bounded by unconformities. It bevelled with angular discordance the truncated edges of older, off lapping Cretaceous and Tertiary sediments (including the Upper Miocene Aquifer Complex) and, in turn, was entrenched with cross-cutting Holocene-filled, late Wisconsin(?) channels that closely mimic the modern drainage. Internally the Columbia deposits were broadly subdivided into two genetically distinct units. The basal unit formed a pervasive, pebbly sand sheet, largely fluvial in origin (Jordan, 1964; Hansen, 1966). In the lower Eastern Shore of Maryland the sand sheet was overlain by a shoreline complex consisting of beach, lagoonal, and dune deposits. The shoreline complex was subdivided into a number of formal and informal units (e.g. Rasmussen and

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Figure 6. Cross-section showing cross-cutting relationship between channel-fill sediments of the Columbia Group and the Upper Miocene Aquifer Complex near Salisbury, Maryland.
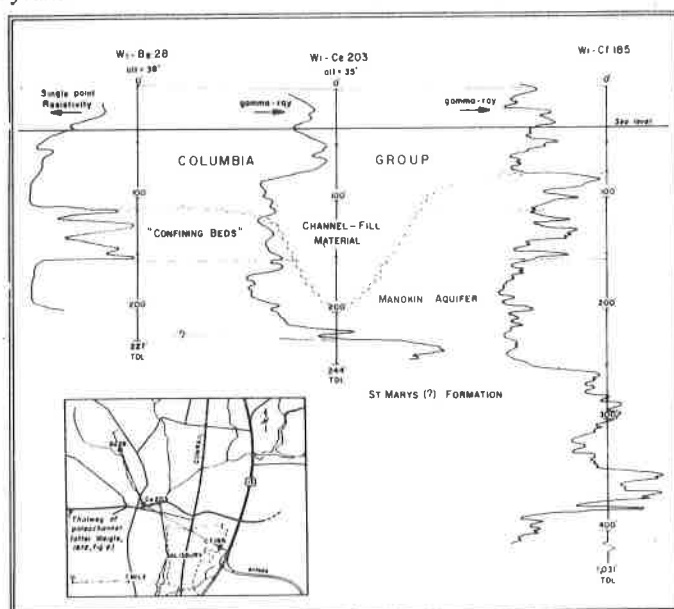
Slaughter, 1955; Jordan, 1974).

In areas north of the shoreline complex, which includes two-thirds of Delaware, Jordan (1976, p. 2) has suggested that the Columbia be reduced to formational rank because only an undivided fluvial sequence occurs. In adjacent Maryland the same unit is commonly referred to as the "red gravelly sand" facies of the Columbia Group. Owens and Denny (1979a) believe that these deposits correlate with the nonmarine Pensauken Formation of New Jersey and have extended that name into Delaware and Maryalnd.

Lithostratigraphic Data: Over much of the Delmarva Peninsula the basal sand sheet of the Columbia Group consists of interbedded orange to reddish brown sands, pebbly sands and gravels. Clayey beds are encountered very infrequently, but have been mapped locally (e.g. Weigle, 1972, pl. 13). The unit is generally cross-stratified and fairly well-sorted. The sedimentary structures, textural characteristics, and coloration (below the water table) are strongly indicative of fluvial deposition, a view subscribed to by all recent workers (e.g. Rasmussen and Slaughter, 1955; Jordan, 1964; Hansen, 1966; Owens and Denny, 1979a). Deposition was apparently initiated within discrete channels which later infilled to form a coalescing sand sheet. The unit is thickest along these paleochannel trends and in one area near Salisbury (fig. 6) has been found to be about 175 feet thick (Hansen, 1966). The contact between the channel-fill and the underlying upper Miocene Aquifer Complex occurs only in the subsurface and must be examined using borehole data. In some borings the contact appears sharp and erosive. In others the upper-most beds of the Aquifer Complex exhibit regolith-like profiles in which ocherous mottling of the dark clays and ferruginous staining of the gray sands occur. In addition the contact is occasionally defined by the presence of a thin iron oxide "hardpan." From these data it seems clear that the contact at the base of the fluvial facies of the Columbia Group marks at least a local hiatus during which both weathering and erosional processes occurred.

The oxidized "red gravelly sand" facies of the sand sheet becomes very patchy and is not evident in southeastern Delaware and neighboring parts of the lower Eastern Shore of Maryland. In Maryland the "red gravelly sand" facies occurs in a broadly defined lobate pattern that includes central Wicomico County, northwest Worcester

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County and northeast Somerset County (fig. 5). Jordan (1964, 1974) and Hansen (1966) considered termination of the "red gravelly sand" as evidence for a major facies change in the Columbia sand sheet. The distal facies of the sand sheet, generally called the Beaverdam Sand after Rasmussen and Slaughter (1955, p. 115), is unoxidized (gray, tan-gray, white) and lacks the distinct coloration of the "red gravelly sand" facies. The textural and bedding characteristics of the two facies are similar, although as a broad generalization the Beaverdam is slightly better sorted and finer grained than the "red gravelly" (Hansen, 1966, p. 15). Also, clayey interbeds are more frequently encountered in the Beaverdam, particularly eastward toward the coast (Weigle, 1974, p. 7). Like the "red gravelly sand" the base of the Beaverdam is channeled, deeply in some places (e.g. Wor-Bg 48, fig. 1), and probably of fluvial origin. Jordan (1974) has suggested that the Beaverdam channel-fill is of fluvial origin and represents an unweathered distal extension of the "red gravelly." Hansen (1966) attributed coloration of the two facies to depositional factors and suggested that the Beaverdam sands were of marginal marine or estuarine origin deposited during a marine transgression. Fossil evidence supporting this speculation is generally lacking, however, except for the widespread occurrence of ichnofossils (*Callianassa* borings) in the outcropping upper part of the formation (Owens and Denny, 1979a, p. A14).

Owens and Denny (1978; 1979a; 1979b) reject any temporal relationship between the Beaverdam and the fluvial facies of the Columbia Group. Instead they correlate the latter with the Pensauken of New Jersey and propose that it is a facies equivalent of the "Yorktown and Cohansey(?)" Formations (table 1). The Beaverdam is viewed as a younger unit channeled into both the Pensauken and the "Yorktown-Cohansey(?)."

To a large extent Owens and Denny have relied on biostratigraphic data to support their contention that the Pensauken Formation (i.e., "red gravelly sand" facies of the Columbia Group) is a temporal equivalent of the "Yorktown-Cohansey(?)." These aspects of the problem will be discussed in the next section, but it may be noted here that the only fossils found in the Pensauken are relatively long ranging palynomorphs.

Owens and Denny's (1979a, p. A12) contention that the Pensauken interfingers with the "Yorktown-Cohansey(?)" to form a large fluvio-deltaic complex is based chiefly on a hypothetical depositional model, offered because

> "it provides an explanation for the intro-
> duction of coarse clasts, including gravel, into
> a marine environment (represented by the "Yorktown
> and Cohansey(?)" beds) interpreted to be well out
> on the Continental Shelf. It also could explain
> the ample supply of immature sediments (moderately
> feldspathic beds containing a very immature heavy-
> mineral suite) and the widespread occurrence of
> woody fragments in these marine beds."

Owens and Denny provide little stratigraphic evidence in support of this conclusion, chiefly because their subsurface control was overwhelmingly based on shallow borings that bottomed-out within or just below the base of the Pensauken (Hess, 1977). As a result, the internal stratigraphy of the "Yorktown-Cohansey(?)" (i.e., the Upper Miocene Aquifer Complex) was not worked out in sufficient detail to map the structural relationship between the base of the Pensauken and the beds of the underlying unit. Owens and Denny (1979a, fig. 6; 1979b) obscured this vital relationship by treating the "Yorktown-Cohansey(?)" Formation as an undifferentiated, largely schematic, stratigraphic unit.

Biostratigraphic Data: After many years of investigation the sand sheet of the Columbia Group has failed to yield a time-specific fossil assemblage. Invertebrate fossils of any kind are extremely rare, being restricted to a reported occurrence of fresh-water diatoms (Flint, 1940, p. 778) in the Columbia deposits of Delaware and ichnofossils in the Beaverdam (Owens and Denny, 1978). Occasionally, unoxidized clay lenses within the sand sheet have yielded microfloral assemblages. Although a systematic pollen stratigraphy could not be worked out because of the sampling methods employed, the presence of boreal (pine-spruce) species were strongly suggestive of a Pleistocene climate (e.g., G. Brush in Weigle, 1974, p. 51-55). These

data appeared to reenforce the long standing assumption that the Columbia deposits were of Pleistocene age. Most workers familar with the sediments agreed, however, with Jordan's caveat that the Pleistocene age was not proven. Noting the paucity of fossil data, he warned that, although a Pleistocene age could be reasonably concluded, it was based "largely upon the less reliable criteria inferred from the requirements of geologic processes and from the more firmly founded history of the surrounding region" (Jordan, 1974, p. 35).

Citing Leopold (1969, p. 411) as an authority, Sirkin and Owens (1976) and Owens and Denny (1979a) challenged the age implications of cool temperature taxa, preferring to give greater importance to the minor occurrence of "Tertiary exotics", chiefly *Juglandaceae*. For example, Owens and Denny (1979b) note that *Pterocarya* and *Englehartia* are present in small amounts in Pensauken clay lenses. Also a peaty bed from the upper part of the Beaverdam has yielded a flora which included *Engelhartia, Cyrilla, Platanus, Ephedia,* and *Eucommites.* Even though these species are not extinct, their presence in eastern North America is believed to have ended prior to the onset of Pleistocene glaciation. However, in the absence of other independently dated fossils, the temporal significance of the "exotics" is somewhat speculative, although in accordance with current paleobotanical concepts. It should be noted that in northern Europe, for example, Tertiary relicts are believed to have persisted into at least the earlier Quaternary interglacials (Leopold, p. 420).

In summary it can be fairly concluded that presently available biostratigraphic data do not provide compelling evidence that the "Yorktown-Cohansey(?)" Formation (Upper Miocene Aquifer Complex) and the Pensauken (fluvial facies of the Columbia Group) are coeval. The former has been independently dated with molluscan and foraminiferal assemblages and a late Miocene age seems well demonstrated. On the other hand, the microfloras yielded by the Pensauken and Beaverdam cannot be precisely dated. Only a broadly bracketed age assignment of later Tertiary to perhaps early Quaternary seems defensible for these deposits, pending development of a more precise pollen stratigraphy.

STRUCTURAL CONSIDERATIONS

In the absence of time-specific biostratigraphic data the relationship (i.e., facies change or unconformity) between the Columbia sand sheet ("Pensauken") and the Upper Miocene Aquifer Complex must be reconciled using physical stratigraphy. A key factor in determining whether or not these units are part of the same depositional sequence is the structural relationship between the channeled base of the sand sheet and any mappable units occurring within the Aquifer Complex. Of particular importance is the Manokin aquifer which is a relatively thick, widely distributed, sandy unit. If the gravelly sands of the Pensauken are a fluvial facies of "all or part of the 'Yorktown and Cohansey(?)' Formations" (Owens and Denny, 1979a, p. A12), then the shallow shelf to marginal marine sands of the Manokin would seem to be a reasonable downdip equivalent.

Although plausible as a depositional model, serious problems are encountered when the subsurface relationships between the two units are worked out in greater detail. Cross-section A-A' (fig. 1), which subparallels the dip of the Coastal Plain units, provides a useful basis for discussion (B-B' is a strike section): Because the most persistent, correlative horizon in the Upper Miocene sequence occurs at the base of the St. Marys(?) Formation, wells penetrating this datum were chosen wherever possible. Preference was also given to wells having gamma-ray logs. By so doing a standardized method of correlation based on a widely recognized lithostratigraphic datum could be used in the well network. Other stratigraphic datums are not as well defined, although generally recognizable. For example, the Manokin-St. Marys(?) contact is gradational over a transition zone that can be as thick as 50 feet (Wor-Ah 6). A consistent mapping horizon can be achieved, however, by picking the "contact" at the base of the transition zone in each well correlated. The top of the Manokin is more difficult to establish, particularly in areas where the overlying Ocean City aquifer is present (Wor-Ae 19, Wor-Bg 48). Generally speaking the Manokin is a dominantly sandy unit punctuated by an occasional clay/silt bed. On the other hand, the part of the Aquifer

Complex overlying the Manokin is an irregular sequence of lensing sandy and clayey beds. Internal correlations within the upper part of the Aquifer Complex may not be possible, except locally. This very inhomogeneity, however, provides a basis for correlating the unit *in toto* and allows it to be differentiated from the more lithologically consistent formations bounding it. The superjacent beds are dominantly sands, a concensus opinion shared by all recent workers (Hansen, 1966; Jordan, 1964, 1974; Owens and Denny, 1978, 1979a, 1979b) without regard to the geologic reconstructions they have employed. Again most workers recognize that the "sand sheet" exhibits two distinctive lithotopes: (1) a pervasively iron-stained, pebbly sand (Pensauken Formation or "red gravelly sand facies" of the Columbia Group) and (2) a whitish to tanish gray sand with minor interbedded lenses of clay/silt (Beaverdam Formaton or Beaverdam facies of the Columbia Group). Both lithotopes fill local channels trenched into the Upper Miocene Aquifer Complex. The base of the sand sheet is more easily mapped where the "red gravelly facies" occurs because of its sharp color-break with the Aquifer Complex; some care in picking the contact must be exercised because iron stained beds may occur below it in a relatively thin regolith. The base of the Beaverdam is more difficult to define, particularly where it occurs as a sand-on-sand contact (Sundstrom and Pickett, 1969, p. 30). In cross-secton A-A' the contact was usually picked at the first occurrence of either a shelly sand or thick (5-10 ft.) clay bed. An unfossiliferous sand of the Aquifer Complex occurring above these marker beds could, therefore, have been placed within the Beaverdm and miscorrelated. Along the line of section displayed in figure 1 individual sands at the top of the Aquifer Complex probably do not exceed 15 feet in thickness An upward shift of the contact by this magnitude would not significantly change the structural relationships shown in cross-section A-A'.

In general the shallow Coastal Plain beds exhibit a homoclinal trend with the slope rate increasing with depth. Between Salisbury and the Coast the top of the St. Marys(?) Formation has an average dip of bout 10.5 feet per mile. The top of the Manokin Aquifer slopes at about 8 feet per mile, reflecting downdip thickening of that unit. The base of the Columbia Group is defined by a network of channels, complexly incised into a more gently dipping interfluvial surface. The interfluvial surface dips at about 2 to 6 feet per mile between Salisbury and the Coast. The paleoslopes of individual thalwegs slope more steeply, but only short reaches have been mapped in detail (e.g. Weigle, 1972, p. 82).

Near the Coast approximately 200 feet of Upper Miocene section separates the interfluvial surface at the base of the Columbia Group (Beaverdam Formation) from the top of the Manokin Aquifer. In well Wor-Ae 19 located in northwestern Worcester County near Careytown cross-roads the post-Manokin sediments of the Upper Miocene Aquifer Complex have thinned to about 135 feet. Further west at Parsonsburg the post-Manokin beds are 70 feet thick. In well Wi-Cg 53 this interval exhibits a characteristic "saw-tooth", gamma-ray signature representative of interbedded clay/silt and sand. The signature can be traced through Salisbury (Wi-Cf 185) to Hebron (Wi-Cd 65) where only 12 feet of section remain between the Columbia Group and the Manokin Aquifer. Although correlation within the post-Manokin sediments is difficult, the angular discordance between the Manokin marker beds and the base of the sand sheet is strongly suggestive of erosional truncation.

Evidence of truncation is provided by several detailed studies of a "Pensauken" channel-fill sequence near Salisbury (Hansen, 1966; Mack and Thomas, 1972; Weigle, 1972). Figure 6 is a cross-section that traverses the Salisbury paleochannel. The section is anchored by two wells (Wi-Be 28 and Wi-Cf 185) located in interfluvial areas bordering the paleochannel. Wi-Ce 203 is located very near the thalweg. In Wi-Ce 203 the "red gravelly sand" of the Columbia Group is unusually thick with the base of the channel-fill occurring at about 155 feet below sea level. Unlike adjacent interfluvial areas the channel-fill penetrated by Wi-Ce 203 has trenched through the top of the Manokin aquifer and rests within about 25 feet of the top of the St. Marys(?) Formation. In another paleochannel well (Wi-Be 41), located about 2 miles northeast of Hebron, channel-fill sediments rest directly on eroded St. Marys(?) Formation 165 feet below sea level (Weigle, 1972, fig. 11). Data from these wells provide direct evidence that a cross-cutting relationship exists between the channeled base of the Columbia Group (or Pensauken/Beaverdam) and the Upper Miocene Aquifer Complex (or "Yorktown and Cohansey"(?) Formation).

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CONCLUSIONS

Gamma-ray log correlations suggest that beneath the lower Eastern Shore of Maryland a channeled angular unconformity separates the sand sheet of the Columbia Group (Pensauken/Beaverdam of Owens and Denny (1979a) from underlying sediments assigned to the Upper Miocene Aquifer Complex ("Yorktown and Cohansey(?)" Formations). Post-Manokin beds of the Aquifer Complex, which may be as thick as 200 feet at the Coast, thin up-dip so that between Salisbury and Hebron (fig. 1) they are bevelled to a feather-edge. The relative parallelism of correlative marker horizons at the top and bottom of the Manokin strongly suggests that erosional truncation was the dominant mechanism, although some toplap (progradational) tapering cannot be entirely ruled out.

The suggestion of Owens and Denny (1979a) that the Pensauken channel-fill is the fluvial facies of the "Yorktown and Cohansey(?)" Formations is rejected because it violates the law of stratigraphic superposition. The thickest marginal marine sand of the late Miocene Aquifer Complex is the Manokin. If the Pensauken and the Aquifer Complex are part of the same depositional sequence, then the Manokin should, at least in part, be an age equivalent of the former. This cannot be demonstrated. As shown in figure 1, the Pensauken overlies the Manokin disconformably. In updip areas the Pensauken rests directly on the subcropping Manokin. Downdip, however, a thickening wedge of younger beds separate the two units. In these areas the Pensauken and the Manokin are only juxtaposed in deeply incised paleochannels where overlying beds of the Aquifer Complex have been cutout. For example, in a paleochannel near Salisbury the Pensauken channel-fill has cross-cut at least 60 feet of post-Manokin beds (fig. 6).

Finally, the stratigraphic arguments against making the sand sheet of the Columbia Group and the Upper Miocene Aquifer Complex facies of a single depositional sequence are independent of the absolute ages of the units. It remains possible that both units, although not coeval, may be of late Tertiary age, as claimed by Owens and Denny (1979a).

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STRUCTURAL RELATIONSHIPS AS A KEY TO STRATIGRAPHIC SEQUENCE IN THE CAROLINA SLATE BELT, LAKE MURRAY, SOUTH CAROLINA

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ABSTRACT

In most regions of the Carolina slate belt, contrasting lithologic sequences of epiclastic and metavolcanic rocks are present. In South Carolina, divergent interpretations of the relative ages of these sequences have been proposed by various workers. This controversy is probably the result of the following aspects: complex lateral facies variations, complex polyphase deformation, and ambiguous stratigraphic top criteria in epiclastic rocks apparently deposited in part in a tidal shelf environment. Near Lake Murray, South Carolina, we have identified a major F_1 synclinorium here referred to as the Delmar synclinorium, which contains epiclastic rocks of the Richtex Formation in its core and which has metavolcanic rocks of the Persimmon Fork Formation in its steep north limb. These relationships suggest that in this region the Richtex Formation overlies and is younger than the Persimmon Fork Formation.

INTRODUCTION

Two distinctive lithologic sequences are of widespread occurrence in the Carolina slate belt (Fig. 1). One of these, variously called the Uwharrie Formation in North Carolina (Conley and Bain, 1965; Seiders, 1978), the Persimmon Fork Formation in South Carolina (Secor and Wagener, 1968), and the Lincolnton metadacite and felsic pyroclastic sequence in Georgia (Carpenter, 1976; Whitney and others, 1978), is composed predominantly of intermediate to felsic metavolcanic rocks that have Rb/Sr whole-rock ages and U/Pb zircon ages in the range 520-580 m.y. (Hills and Butler, 1969; Fullagar, 1971, p. 2847; Butler and Fullagar, 1975; Seiders and Wright, 1977; Wright and Seiders, 1977; Carpenter and others, 1978). The other sequence, variously called the Albemarle Group (Conley and Bain, 1965; Stromquist and Sundelius, 1969), the Richtex Formation (Secor and Wagener, 1968), and the upper sedimentary sequence (Carpenter, 1976) is predominantly epiclastic, although metavolcanic rocks occur locally. A Rb/Sr whole rock age of 550 $\pm$ 7 m.y. has been obtained for the Badin Greenstone, which is interbedded with the rocks of the Albemarle Group (Stromquist and Sundelius, 1969; Black, 1978), and the overlying Morrow Mountain Rhyolite has a Rb/Sr whole rock age of 525 $\pm$ 15 m.y. (Hills and Butler, 1969; Stromquist and Sundelius, 1969; Fullagar, 1971). St. Jean (1973) has reported the occurrence of a Middle (?) Cambrian trilobite from the epiclastic sequence in North Carolina. The regional stratigraphic significance of the metavolcanic and epiclastic sequences is uncertain because very little detailed geologic mapping has been accomplished in the Carolina slate belt, and because there appears to be considerable overlap in the radiometric ages that have been reported for the two sequences. In most places the epiclastic sequence is interpreted to be younger than the volcanic sequence, although Daniels (1974) and Pirkle (1977, 1978) have argued
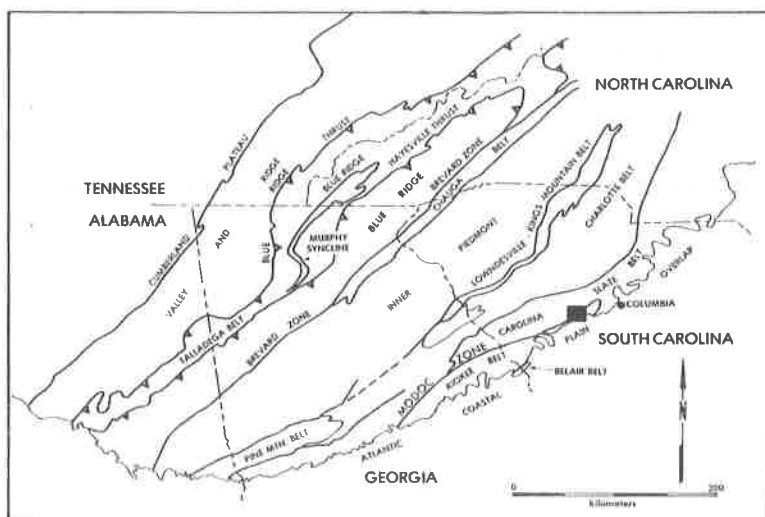
Figure 1. A regional geologic map of the southern Appalachian orogen showing the location of the study area (modified from Williams, 1978).
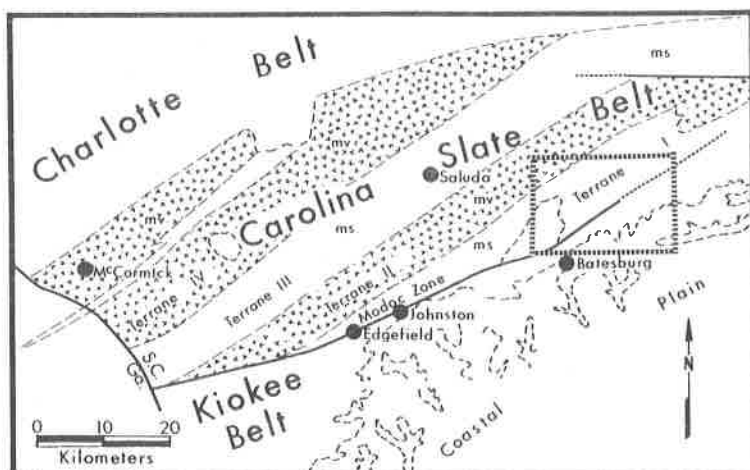

Figure 2. Map showing the distribution of metavolcanic (mv) and metasedimentary (ms) terranes in west-central South Carolina (modified from Overstreet and Bell, 1965; Secor and Wagener, 1968; Daniels, 1974; Pirkle, 1977, 1978; and Whitney and others, 1978).

that epiclastic sequences are older than volcanic sequences in west-central South Carolina.

The distribution of epiclastic and metavolcanic rocks in the central and western part of the Carolina slate belt in South Carolina is illustrated in Figure 2. The epiclastic rocks occur in two extensive terranes (I and III) that are flanked by terranes of metavolcanic rock (II and IV). Secor and Wagener (1968) interpreted portions of the epiclastic terranes (I and III) to overlie the metavolcanic rocks of terrane II. However, this interpretation was inferred from structural relationships and was made before recognition of the complex fold chronology (Secor and Snoke, 1978) characteristic of the slate belt in central South Carolina. In the central Savannah River area, Daniels (1974) interpreted the epiclastic rocks of terranes I and III to be of different ages and to respectively underlie and overlie the metavolcanic rocks of terrane II. These conclusions were mainly based on stratigraphic tops indications from graded beds in terranes I and III. Pirkle (1977, 1978) interpreted the epiclastic rocks of terrane III to
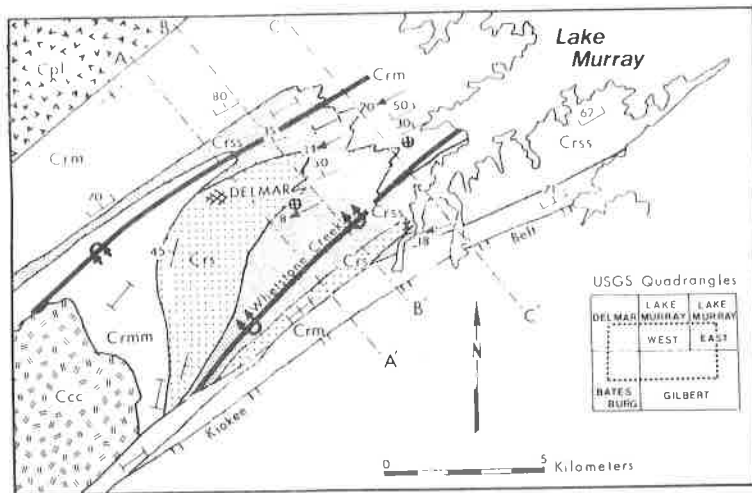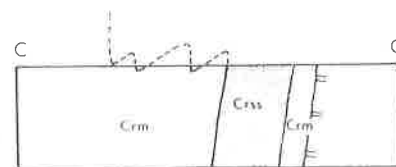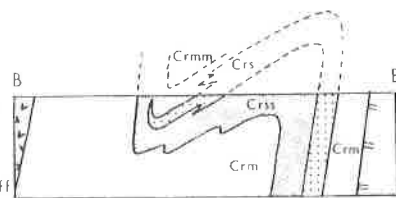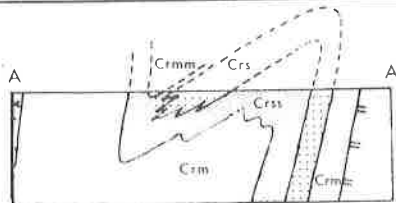
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Figure 3. Geologic map of the Delmar synclinorium and surrounding area. Geologic data from field studies by D.T. Secor, Jr., A.W. Snoke and O.P. Costello, Jr. (1976–1978).

be a homoclinal sequence beneath the metavolcanic rocks of terrane IV, based on structural attitudes and graded beds. Carpenter (1976) interpreted the metavolcanic rocks in terrane IV to underlie the epiclastic rocks in terrane III. In our opinion, the conflicting interpretations of the relative stratigraphic chronology in the South Carolina slate belt are the result of complex sedimentary facies changes and a complex deformational chronology coupled with ambiguous sedimentary tops indications in the epiclastic sequences.

In this article, we present the results of a detailed mapping program in the Lake Murray, South Carolina area (Fig. 2 and 3) where stratigraphic and structural relationships between the epiclastic sequence (Richtex Formation, terrane I) and the volcanic sequence (Persimmon Fork Formation, terrane II) have been studied. Using various mesoscopic fabrics associated with large F_1 structures, it has been possible to

infer the stratigraphic sequence from the geometry of F_1 folds.

STRATIGRAPHIC OVERVIEW

The Persimmon Fork Formation of terrane II forms a northeast-trending band along the western and northern shores of Lake Murray. It is characterized by intermediate to felsic lapilli tuff, crystal-lapilli tuff, vitric tuff, volcanic breccia, nonfragmental flows, and small amounts of intrusive hypabyssal rock. Sporadically interlayered with these volcanic lithologies are lenses and layers of volcanic wacke and ripple-laminated quartz siltstone. The Persimmon Fork Formation is over 2000 meters thick, and grades into the epiclastic rocks of the Richtex Formaton in terrane I through a interval of a hundred meters or more.

The Richtex Formation of terrane I is predominately a complex sequence of quartz-rich and pelitic metasedimentary rocks, but it also locally contains lenses of intermediate to felsic metavolcanic flows and lapilli tuff. For mapping purposes, the Richtex Formation has been subdivided into four informal members: 1) laminated mudstone, wacke and metavolcanic rock, 2) ripple laminated quartz siltstone, 3) quartz sandstone, and 4) evenly laminated to massive mudstone. The ripple laminated quartz siltstone characteristically contains bifurcated wavy flaser bedding (Reineck and Wunderlich, 1968) in which lenticular sets of crossbedded quartz-rich strata, 0.3-30 mm thick and 5-30 cm long, are separated by thin seams of pelitic material. Similar sedimentary structures, on a larger scale, are found in the quartz sandstone where lenticular sets of crossbedded quartz-rich strata, 10-200 cm thick, are draped by thin seams of pelitic material. The sedimentary structures in the ripple laminated quartz siltstone and quartz sandstone suggest that these units accumulated in a tidal shelf environment where the transportation and deposition of sediment was dominated by tidal currents (Reineck and Singh, 1975), although it is not known whether the deposits are intertidal or subtidal. These tidal shelf deposits grade laterally into both the evenly laminated to massive mudstone unit and into the laminated mudstone, wacke and metavolcanic unit, which are interpreted to have accumulated in adjacent depositional environments. The gradational nature of the contact between the metavolcanic rocks of the Persimmon Fork Formation (terrane II) and the epiclastic rocks of the Richtex Formation (terrane I), as well as the local occurrence of rocks interpreted to be tidal shelf deposits in the Persimmon Fork Formation and the local occurrence of metavolcanic rocks in the Richtex Formation suggest that the rocks in terranes I and II are a coherent stratigraphic sequence that accumulated in a group of closely related environments. The observation that the various facies present in the Richtex and Persimmon Fork Formations grade laterally into each other is also compatible with and supports the interpretation that terranes I and II are a coherent stratigraphic sequence.

STRUCTURAL ANALYSIS

Geologic studies along the Fall Line in South Carolina (Carr, 1978; Maher, 1978; Secor and Snoke, 1978) have indicated that the rocks have a complex deformational history and contain multiple fabrics. Two generations of macroscopic folds (F_1, F_2) have been identified in the Carolina slate belt. F_1 folds are typically tight to isoclinal passive folds which developed synchronously with regional greenschist facies metamorphism and which have a well developed slaty cleavage oriented approximately parallel to their axial surfaces. The time of D_1 is poorly constrained by available geochronological data but is probably pre-Carboniferous. The S_1 slaty cleavage has been folded by F_2 flexural folds which are typically coaxial with F_1 and which have axial surfaces commonly inclined at a high angle to S_1. Regional geochronological studies (Fullagar and Butler, 1979; Snoke and others, 1980) indicate that D_2 is Late Carboniferous to Permian (i.e. 300-260 m.y.). In the present study area (Fig. 3) clear evidence for major F_2 folding is absent, and the orientation of S_1 is relatively uniform. The apparent minor dispersion of poles to S_1 along a partial girdle perpendicular to the strike (Fig. 4) may be due to low-amplitude F_2 folding of S_1. The main conclusion of
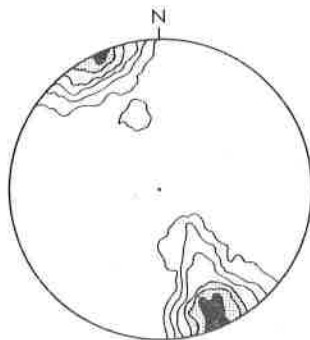
Figure 4. Lower hemisphere, equal-area projection of poles to 126 S_1 foliation planes from the Carolina slate belt in the area of the geologic map illustrated in Figure 3. Contours: 22-18-11-7-4-1%.
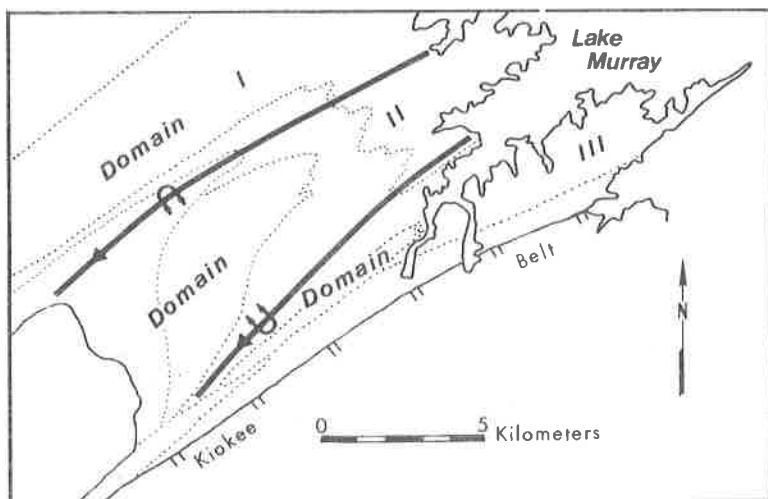

Figure 5. Illustration of the locations of domains used in the structural analysis of the study area.

this study, concerning the relative ages of stratigraphic units, is based on the inferred geometry of major F_1 folds, and is not affected by the uncertainty concerning the presence or absence of low amplitude F_2 folds.

The outcrop pattern of the informal lithologic members of the Richtex Formation (terrane I, Fig. 3) coupled with the relatively uniform orientation of S_1 indicates that major F_1 fold structures control the outcrop pattern of Carolina slate belt rocks in the Lake Murray area. A fold hinge, converging to the northeast in plan view, occurs in the region of Delmar, northeast of the Clouds Creek pluton in the northern part of the Batesburg 7 1/2 min. quadrangle and the southeastern part of the Delmar 7 1/2 min. quadrangle. The massive to laminated mudstone member of the Richtex Formation outcrops in the core of this structure. To the northeast, the quartz sandstone and quartz siltstone members, taken together, wrap around the axis of this fold. The outcrop pattern in this region is complex because of the apparent lenticular nature of the quartz sandstone member. A fold hinge, coverging to the southwest in plan view, is suggested by outcrop bands of the quartz sandstone member in the vicinity of Whetstone Creek, southeast of Delmar. For the purposes of the structural analysis which follows, the three limbs of these two adjacent folds are taken as domains I-III, as illustrated in Figure 5.

Study of the orientations of bedding (S_0), slaty cleavage (S_1), bedding-cleavage intersections ($L_{0 \times 1}$), and mesoscopic parasitic F_1 folds yield additional information on
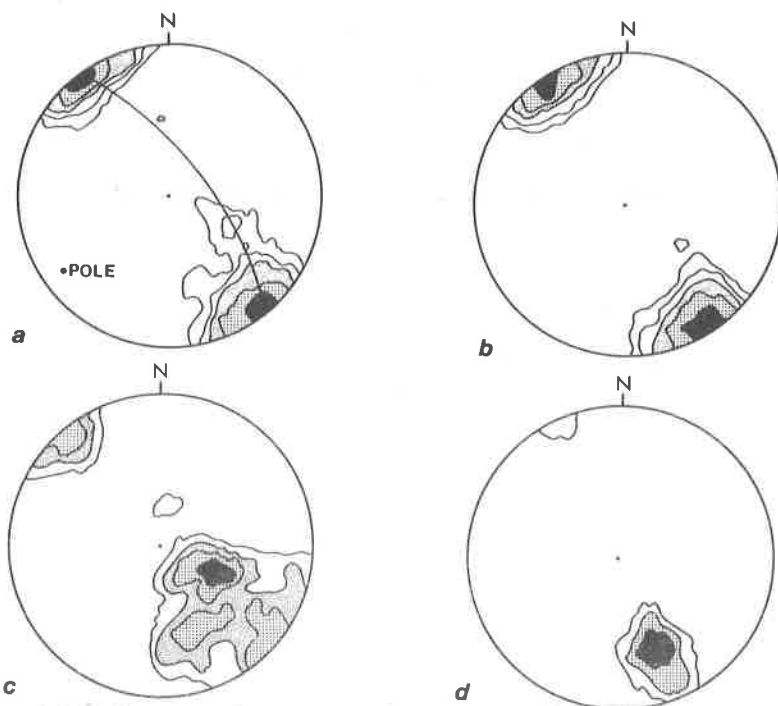
Figure 6a. A best fit great circle to a lower hemisphere, equal-area projection of poles to 198 S_0 bedding planes from domains I, II, and III of the study area. The orientation of the pole to this great circle indicates that F_1 fold axes plunge gently southwest. Contours: 20-11-6-4-1%.

Figure 6b. Lower hemisphere, equal-area projection of poles to 116 S_0 bedding planes, from the north limb of the Delmar synclinorium (domain I) in the Lake Murray West, Delmar and Batesburg quadrangles. Contours: 29-17-10-5-3%.

Figure 6c. Lower hemisphere, equal-area projection of poles to 61 S_0 bedding planes, from the shared limb of the Delmar and Whetstone Creek Structures (domain II) in the Lake Murray West, Delmar and Batesburg quadrangles. Contours: 10-5-3-1%.

Figure 6d. Lower hemisphere, equal-area projection of poles to 21 S_0 bedding planes, from the south limb of the Whetstone Creek anticlinorium (domain III) in the Lake Murray West, Lake Murray East, Delmar, Gilbert and Batesburg quadrangles. Contours: 34-14-5%.

the character of these two folds. Poles to 198 S_0 measurements from domains I, II, and III in the Delmar and Whetstone Creek areas are plotted in Figure 6a. The S_0 data have a great circle distribution and fall close to a girdle having a pole oriented $16°S51°W$. The S_0 data, therefore, indicates that the fold structures in this region plunge gently to the southwest. This plunge direction coupled with the directions of convergence of the two fold noses suggest that the structure in the vicinity of Delmar (converging to the northeast in plan view) is a synclinorium, and that the Whetstone Creek structure (converging to the southwest in plan view) is an anticlinorium. The average orientation of S_0 in the north limb of the Delmar synclinorium (domain I) is $N50°E$ vertical (Fig. 6b), the average orientation of S_0 in the shared limb between the Delmar synclinorium and the Whetstone Creek anticlinorium (domain II) is $N25E39°NW$ (Fig. 6c), and the average orientation of S_0 in the south limb of the Whetstone Creek anticlinorium (domain III) is $N63°E60°NW$ (Fig. 6d). The average orientation of S_1 in this region ($N66°E88°NW$, Fig. 4) is almost parallel to the steep northwest limb of the Delmar synclinorium, and clearly differs from the orientation of the symmetry plane of this structure ($N43°E63°NW$) which bisects the angle between the limbs of the folds (Fig. 7a).

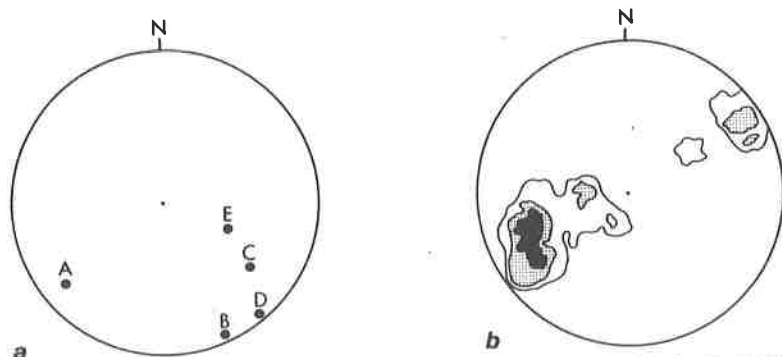If the fold structures in the vicinity of Delmar and Whetstone Creek are

Figure 7a. *Lower hemisphere, equal-area projection of structural elements of the Delmar synclinorium. A- fold axis derived from S_0 data: B- pole to average orientation of S_1; C- pole to the plane of symmetry of the Delmar synclinorium; D- pole to average orientation of S_0 in the north limb of the Delmar synclinorium (domain I); E- pole to the average orientation of S_0 from the shared limb of the Delmar and Whetstone Creek structures (domain II).*

Figure 7b. *Lower hemisphere, equal-area projection of 60 L_{0x1} lineations in the Delmar synclinorium area from domains I, II, and III in the Lake Murray West, Lake Murray East, Gilbert, Delmar and Batesburg quadrangles indicating that F_1 fold axes plunge gently southwest. Contours: 12-5-2%.*

genetically related to the same deformational processes that formed the S_1 slaty cleavage, the L_{0x1} intersection lineations should, on the average, be approximately parallel to the axes of the folds. Data on 60 L_{0x1} lineations from domains I, II, and III are plotted in Figure 7b. The close groupings of the data points about an average orientation of 22^oS62^oW which is similar to the fold axis orientation determined from S_0 data (16^oS51^oW) suggests that the folds and slaty cleavage formed together, and the southwestward plunge of L_{0x1} data reinforces the conclusion that the Delmar and Whetstone Creek structures are respectively a synclinorium and an anticlinorium.

A few observations of parasitic mesoscopic F_1 folds also indicate a regional plunge to the southwest, and support the above structural interpretations.

DISCUSSION AND CONCLUSIONS

A 4 km thick coherent section of strata from the Persimmon Fork Formation (terrane II) and Richtex Formation (terrane I) crops out in the core and in the north limb of the Delmar synclinorium. Analysis of the data on the orientation of bedding, slaty cleavage, bedding-cleavage intersections and parasitic fold axes lead to the conclusion that the Delmar synclinorium is a major D_1 fold. The position of the Richtex Formation in the core of the synclinorium clearly indicates that the Richtex overlay the Persimmon Fork at the time of D_1 folding, and more indirectly suggests that the Richtex is younger than the Persimmon Fork. This conclusion could be invalid if the deformation episode herein identified as D_1 was in fact not the earliest deformation. In particular, if the stratigraphy had been inverted by an earlier episode of pre-D_1 recumbent folding, or overthrust faulting, the Richtex could be older than the Persimmon Fork. An early episode of recumbent folding is evident in parts of the Inner Piedmont belt, and in the Blue Ridge province (Hatcher, 1977); however, no evidence for an episode of early recumbent folding has been identified in the Carolina slate belt. In the absence of such evidence, we interpret the Richtex Formation (terrane I) to be younger than the Persimmon Fork Formation (terrane II). This interpretation is in agreement with the stratigraphic models proposed by Secor and Wagener (1968) and Carpenter (1976), but conflicts to varying degrees with models proposed by Daniel (1974), Howell and Pirkle (1976), and Pirkle (1977, 1978).

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PALEOECOLOGICAL ASPECTS OF A FRESHWATER EPHEMERAL STREAM,

NEW HOPE CREEK VALLEY, ORANGE COUNTY, NORTH CAROLINA

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ABSTRACT

Depressions that dot the surfaces of upland river floodplains, such as ponds, back-bar sloughs, and temporary stream channels, represent one variety of depositional subenvironment in which the meager fossil record of the lotic biome is preserved. In New Hope Creek valley, mollusks from both riffle and pool communities were swept mainly alive into an ephemeral stream channel during spring floods, and subsequently produced a large number of burrows and overlapping furrow systems (comparable to the ichnogenera *Cylindricum, Scolicia,* and *Taphrhelminthopsis*) within a restricted area. As the water in the pools on the channel floor disappeared through seepage and evaporation, the trace-making activity of the marooned organisms increased, and after complete subaerial exposure there remained a shelly deposit composed predominantly of the fingernail clam, *Sphaerium simile.* Fossil deposits formed in this manner could be recognized by the stratigrapher by the following combination of characteristics: 1) discontinuous, shoestring geometry of channel sands, 2) stratigraphic position within a floodplain lithosome, 3) patchy distribution of traces (if preserved) indicative of temporary pools, and 4) occurrence of freshwater clams and snails that originally lived in a variety of stream communities and substrate-niche configurations.

INTRODUCTION

Organisms that can survive hydraulic transport in flooded streams are dislodged from a variety of upstream communities and sometimes deposited in small depressions that dot the surfaces of upland stream valleys. The relatively heavy, skeletonized benthic organisms, such as bivalves and gastropods, are also susceptible to dislodgement and relocation by seasonal floods, or what the ecologists term "catastrophic drift" (see Anderson and Lehmkuhl, 1968). The types of embayments in which large numbers of freshwater mollusks are concentrated during flood stages in stream valleys are: 1) sloughs or other depressions on bars (e.g., Pryor, 1967; Turner, 1978), 2) depressions (ponds) on the adjacent floodplain (e.g., Starrett, 1971, p. 270-271; Devore, 1975; Bickel, 1977), and 3) temporary stream channels marginal to trunk stream channels (this study). The living organisms marooned in these depressions by the waning of flood waters produce a large number of traces within a small area of substrate and, after the embayed waters evaporate or seep into the surrounding floodplain, leave a localized

shelly deposit composed of the mixed remains of bivalves and gastropods displaced from a variety of upstream ecosystems.

Although we recognize that fossil deposits formed in upland lotic depositional environments are rare, the recent literature of freshwater invertebrate paleontology and palichnology discloses that occurrences, albeit spotty, are not as infrequent as generally believed. Where present, these occurrences add greatly to the accuracy of paleoenvironmental reconstructions of fluvial deposits (e.g., Selley, 1970; Stanley and Fagerstrom, 1974; Devore, 1975; Eshelman, 1975; Miller, 1975, 1978; Hanley, 1976; Bickel, 1977; Kerney, 1977; Olsen, 1977; Turner, 1978). In order to add accuracy to environmental reconstructions, we believe it is important that the composition and structure of lotic fossil assemblages be understood in terms of the ecological properties of the organisms involved and the hydraulic conditions responsible for concentration and burial. Our purpose is to describe a shelly, lotic fossil deposit "in the making" within an ephemeral stream channel adjacent to New Hope Creek, a meandering Piedmont stream in Orange County, North Carolina (Figure 1), to demonstrate the types of mechanisms and the kinds of materials that interact to form fossil deposits occasionally included as part of the stratigraphic record of upland streams.

The sedimentology of ephemeral streams has been intensively investigated by Williams (1970) in Australia, and by Picard and High (1973) in the United States. Several ecological studies have centered on the biota of temporary streams (Stehr and Branson, 1938; Clifford, 1966; Harrison, 1966; Harrel and Dorris, 1968; Hynes, 1972, p. 403-406). This report focuses on: 1) paleoecological aspects of the mollusks that became trapped in the New Hope Creek valley ephemeral stream channel during periods of flooding, 2) the traces produced by some of these mollusks during the waning stages of the floods, and 3) the stratigraphic utility of the resultant assemblage of shells and traces in the reconstruction of ancient fluvial subenvironments.

METHODS

Between periods of high water during the spring of 1978, the ephemeral stream channel was mapped, the locations and types of bed forms and substrates were recorded, and a general survey collection of mollusks from throughout the channel was made. The channel was revisited and photographed during several episodes of flooding and subaerial exposure. After one period of intense flooding in March, 1978, seven 0.36 m^2 quadrats were mapped to record the spatial distributions, densities, and orientations of mollusks at locations within the channel that appeared to be undisturbed by hikers and scavenging animals. Four of the quadrats were excavated to a depth of 2 cm and all mollusk specimens larger than 1 mm in smallest diameter were separated out by wet-screening. Specimens were then identified using published keys and descriptions, as were the specimens collected in the general survey (Table 1). During several visits to the ephemeral stream before embayed water had evaporated or seeped out of the channel, photographs were made of mollusks generating traces and the types of traces made by each species were recorded. A reconnaissance of the surrounding valley was made to see if shells were accumulating in other areas, and several back-bar sloughs were located that contained empty shells.

In January, 1980, we revisited the channel and dug two 0.36 m^2 pits to a depth of 10 cm on the point bar and on the channel bar at the northern end of the channel (Figure 1). In each pit we removed 2 cm of sediment from the bottom, analogous to our excavations of the surface quadrats in 1978. The same methods of specimen separation and identification were used for the subfossil mollusks contained in the samples, and preservation potential of shells and traces was assessed by noting which of the features recorded in the surface quadrats actually survived shallow entombment.

PALEOECOLOGICAL ASPECTS OF THE EPHEMERAL STREAM CHANNEL

Channel Floor Depositional Environment

The ephemeral stream channel is a former section of a footpath that runs along
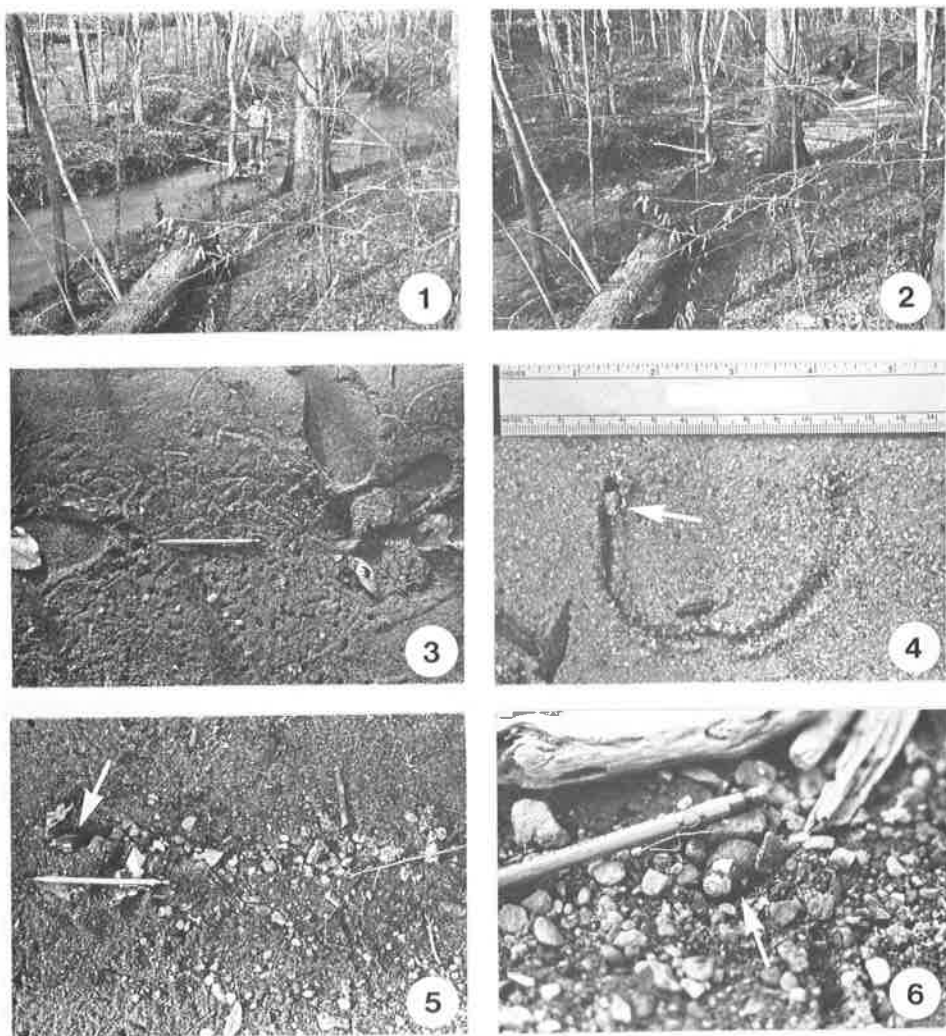
Plate 1. Figure 1. Ephemeral stream channel during a spring flood in New Hope Creek valley (looking north and upstream).

Figure 2. Channel during subaerial exposure between floods (looking north and upstream).

Figure 3. Furrows and burrows produced by *Sphaerium simile*. Area above pencil is lower flank of channel bar with abundant randomly-oriented and U-shaped furrows; below pencil is sand-veneered channel surface with clusters of small, vertical burrows. (Pencil is 18 cm long and 0.7 cm in diameter.)

Figure 4. Close-up of U-shaped furrow made by *S. simile*. (Arrow points to clam digging burrow to escape desiccation.)

Figure 5. Furrow produced by *Elliptio complanata* just prior to subaerial exposure. Note pebble entrainment. (Arrow points to clam and scale is same as in Figure 3.)

Figure 6. *Campeloma decisum* nestled beneath pebbles to escape desiccation in sand-veneered channel. (Arrow points to snail and scale is same as in Figure 3.)
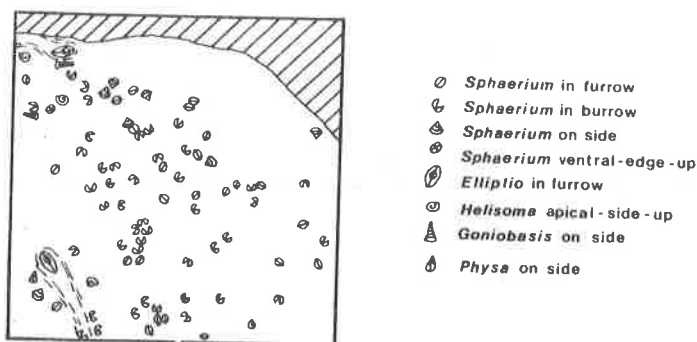
Figure 3. Mollusks concentrated within sand-veneered channel (quadrat F in Figure 1). Each side of quadrat is 0.6 m long; cross-ruled area indicates outcrop of firm floodplain mud.

Table 2. Mollusks from subsurface samples.

TAXA	CONDITION	RELATIVE ABUNDANC (N= 139)
BIVALVIA		
Sphaerium simile	3, 2, 1	7.8%
Pisidium casertanum	3	3.7
P. variabile	2	0.7
Elliptio complanata	3, 2, 1	1.9
GASTROPODA		
Ferrissia rivularis	3	5.9
Helisoma anceps	3, 1	12.6
Physa heterostropha	3	2.2
Goniobasis symmetrica	3, 1	46.7
Campeloma decisum	3, 1	18.8
		100.0%

*3= articulated or entire shells, 2= disarticulated valves,
1= indentifiable fragments.

The minor components of the surface collections and the distributions of all taxa found on the floor of the channel are listed in Table 1.

Two subsurface collections were made 10 cm below the locations of quadrats C and E (beneath the channel bar at the northern end of the channel and beneath the point bar). The sample from beneath the point bar contained the same sparse fauna noted in quadrats on the surface of the bar. However, the sample from beneath the channel bar apparently represents a buried sand-veneered channel with abundant G. symmetrica, C. decisum, and H. anceps. These snails were found nestled under and around decaying plant detritus. Table 2 contains a summary of the abundances and conditions of the subfossil mollusks recovered from the two samples.

The mollusks were swept mainly alive into the ephemeral stream by flood waters that temporarily disrupted the spatial distribution of organisms in upstream benthic communities. Lighter, unskeletonized taxa presumably were carried around or through the channel to points downstream because few soft-bodied taxa* were observed in the

*In addition to mollusk shells, a single fish vertebra was collected from the channel floor and a number of arthropod subfossils were recovered from subsurface samples, including several caddis-worm cases, a coleopteran carapace (?Elmis sp.), several indeterminate insect fragments, and one myriapod.

Table 3. Original mollusk-substrate associations and community types from which the ephemeral stream mollusks were displaced. (Note that substrate preferences are not strict and that freshwater mollusks are usually not restricted to one substrate type, as pointed out recently by Tevesz and McCall (1979); category assignments merely reflect original substrate predilections of taxa that typically range over a variety of bottom types. Likewise, taxa are not restricted to the community category to which they are assigned in the table, but attain their maximum abundances in these communities. These categories nonetheless emphasize the ecologically heterogeneous nature of lotic freshwater shell accumulations.)

Taxa	Original Mollusk-Substrate Association [1]	Original Stream Community [2]
BIVALVIA		
Sphaerium simile	SB	pool
Musculium transversum	SB?	pool
Pisidium casertanum	SB?	pool
P. variabile	SB?	pool
Elliptio complanata	CC	riffle
GASTROPODA		
Ferrissia rivularis	CC	riffle
Ferrissia sp.	CC?	riffle?
Helisoma anceps	SB	pool
Planorbula sp,	LL	pool
Gyraulus sp.	AP	pool
Physa heterostropha	SB?	pool
Lymnaea columella	AP?	pool
Goniobasis symmetrica	CC	riffle
Campeloma decisum	SB,LL	pool

[1]Mollusk-substrate categories based on those of Harman (1972), with modifications, and on our observations at New Hope Creek. SB= sand bottom in low energy areas; CC= clean cobbles in current-swept areas; LL= leaf litter and decaying stems; AP= aquatic plants.
[2]Division of the lotic biome into two basic ecological units, pool and riffle communities, based on McNaughton and Wolf (1979, p. 471-473). The pool community includes the biota of low-energy riffle margins; the biota of high-energy, upstream tributaries is lumped with riffle community.

ephemeral stream. The molluscan fauna, then, is an ecological mixture of taxonomic components from as many as four different mollusk-substrate associations and from at least two different kinds of upstream communities in New Hope Creek (Table 3). The fauna is ecologically mixed in the sense of being composed of mollusks from a variety of upstream communities, but is biostratonomically in-place because the clams and snails were found buried in "life positions" within burrows and nestled beneath stems (see Hanley, 1976, Table 1).


Traces and Trace Makers

Part of the recent interest in the paleoecological aspects of modern streams has centered on trace making organisms and the paleoenvironmental significance of their various traces (e.g., Pryor, 1967; Smith and Hein, 1971; Baldwin, 1974; Chamberlain, 1975; Turner, 1978). In the New Hope Creek ephemeral stream channel only *Sphaerium simile* and *Elliptio complanata* were observed directly making traces (Plate 1, Figures 3, 4, and 5). Both clams produced randomly oriented, intersecting furrow systems that cross-cut each other with increasing frequency as the water level in the stream channel subsided and the available space for movement underwater decreased. Pryor (1967) reported that the locomotion activity of mollusks trapped in back-bar sloughs during high water stages in the Whitewater River, western Ohio, and the Wabash River, Indiana, increased measurably as the size of the pools within the sloughs decreased. We observed a similar increase in trace-making activity among individuals of *S. simile* and *E. complanata* as the embayed water within the New Hope Creek ephemeral stream began to disappear. In the case of *S. simile,* the increase in activity took the form of an increase in the production of furrow marks in the substrate as individuals moved from the crests and flanks of bars into the sand-veneered channel areas where burrowing to escape desiccation ensued (Figure 4). When individuals of *E. complanata*

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Table 1. Inventory of mollusks collected from surface of ephemeral stream channel, New Hope Creek valley, Orange County, North Carolina. (Published descriptions and keys used to identify specimens included: Tryon, 1873; Clench, 1959; Basch, 1963; Johnson, 1970; Burch, 1975a and 1975b; Emmerson and Jacobson, 1976; and Pennak, 1978).

TAXA	RELATIVE ABUNDANCE (N= 832)	DISTRIBUTION WITHIN CHANNEL*				
		Point Bar	Channel Bar	Sand-veneered Channel	Gravel-filled Channel	Chute
BIVALVIA						
Sphaeriidae						
Sphaerium simile (Say, 1816)	73.6%	3,2	3,2	3	0	0
Musculium transversum (Say, 1829)	0.9	3,2	2	0	0	0
Pisidium casertanum (Poli, 1791)	1.2	3	3,2	0	0	0
P. variabile Prime, 1852	0.9	0	2	0	0	0
Unionidae						
Elliptio complanata (Lightfoot,1786)	2.3	3,2,1	3,2	3,2,1	2,1	1
GASTROPODA						
Ancylidae						
Ferrissia rivularis (Say, 1817)	1.2	3	3	0	0	0
Ferrissia sp.	0.3	0	1	0	0	0
Planorbidae						
Helisoma anceps (Menke, 1830)	7.6	3	3,1	3	0	0
Planorbula sp.	0.1	0	3	0	0	0
Gyraulus sp.	0.6	1	1	0	0	0
Physidae						
Physa heterostropha (Say, 1817)	0.6	3	0	3	0	0
Lymnaeidae						
Lymnaea columella Say, 1817	0.3	3	0	0	0	0
Pleuroceridae						
Goniobasis symmetrica (Haldeman,1841)	7.0	3,1	3,1	3	0	0
Viviparidae						
Campeloma decisum (Say, 1816)	3.2	3	3,1	3	3,1	0
	100.0%					

* 3= articulated or entire shells, 2= disarticulated valves, 1= identifiable fragments, 0= not observed.
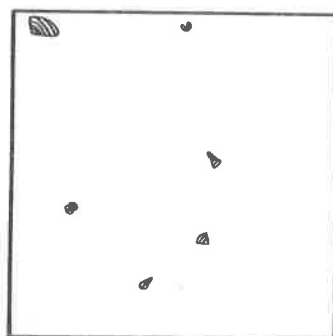
▲ Sphaerium valve
ꝏ Sphaerium in burrow
🐚 Sphaerium agape
🐚 Elliptio valve
◊ Lymnaea on side
🐚 Goniobasis on side

Figure 2. Mollusks distributed on point bar (quadrat E in Figure 1). Each side of quadrat is 0.6 m long.

Sphaerium simile was by far the most abundant component of the surface collections, and occurred in the highest concentrations in sand-veneered channels surrounding the point bar and channel bars (average density = 206/m^2). Helisoma anceps was second in abundance and was found on and near the sand bars. The shells of Goniobasis symmetrica were the third most abundant component, and were found mainly on the bars and in sand-veneered channel areas. Campeloma decisum was fourth in abundance and was found throughout the stream channel except in the chutes. Elliptio complanata ranked fifth numerically and was found in all parts of the channel.
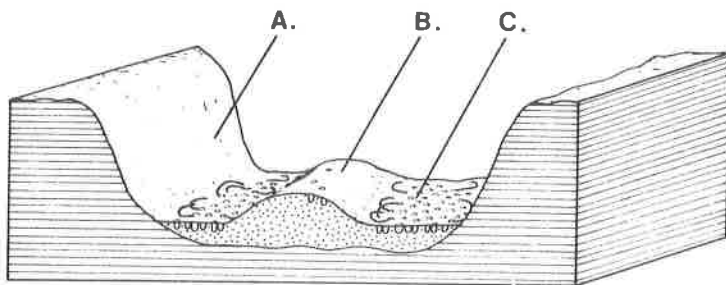
Figure 4. Schematic block diagram of ephemeral stream channel showing surrounding and subjacent floodplain deposits (A), channel bar with few scattered burrows made by *Sphaerium simile* (B), and sand-veneered channel areas with abundant furrows and burrows made by *S. simile* (C). (Not drawn to scale.)

failed to reach the protection of the standing water in scour holes before subaerial exposure, they dug subvertical burrows inclined towards the remaining pools of water. Although no traces produced by gastropods were found within the channel, we observed *Goniobasis symmetrica* making narrow, non-overlapping grazing trails on rocks in New Hope Creek and collapsed, horizontal burrows on point bars in upstream tributaries. *Campeloma decisum* came close to making burrows when individuals attempted to escape desiccation by nestling beneath pebbles or wood in the sand-veneered channels (Plate 1, Figure 6); in their natural habitat within creek pools these organisms may produce burrows. As evaporation and seepage continued to lower the water level below the floor of the ephemeral stream channel, *S. simile* and *E. complanata* situated at the bottoms of burrows eventually became desiccated and expired.

The traces produced by *S. simile* include three types. About half of the traces are randomly oriented, intersecting furrows, approximately 1 cm wide and 0.5 to 1 cm deep. The furrows have marginal ridges, are several centimeters long, and are occasionally terminated by subcylindrical, vertical burrows about 1 cm wide and 1 to 2 cm deep. This variety of trace is very similar to the ichnogenus *Scolicia* (Hãntzschel, 1975, figure 66, 4a; Turner, 1978, text-figures 2 and 3). Another type of furrow is U-shaped in plan view with the same average dimensions as the randomly oriented furrows. Each U-shaped furrow is terminated at one end by a vertical burrow (Plate 1, Figure 4). These are made by *S. simile* duing the last hours of submergence of sand-veneered channel areas when the ranges of moving individuals become severely restricted within remaining pools. A superficial resemblance between these traces and the ichnogenus *Taphrhelminthopsis* is notable (Hãntzschel, 1975, figure 70, 6a). Finally, where the burrows of *S. simile* are very closely spaced (Plate 1, Figure 3, bottom half), a trace resembling *Cylindricum* may result (Hãntzschel, 1975, figure 35, 4a and 4b).

The traces produced by *E. complanata* are very similar to those described by Pryor (1967) for unionids from the Wabash River, Indiana, and Whitewater River, western Ohio. Furrows made by *E. complanata* are deeper, wider versions of the structures generated by *S. simile*. They measure about 4 cm wide, 3 to 4 cm deep, and several tens of centimeters in length. Pebble entrainment is a common feature associated with these furrows (Plate 1, Figure 5). A few furrows are terminated with subvertical, subcylindrical burrows, 3 to 5 cm wide, that are inclined towards nearby scour holes and penetrate as far as the contact between unconsolidated ephemeral stream sand and the subjacent, slightly indurated, floodplain deposits. The furrows produced by smaller individuals of *E. complanata* are comparable to *Scolicia*. Some of the furrows made in gravelly areas lack marginal ridges.

Preservation Potential

The subsurface samples contained well preserved shells in "life positions" that probably were entombed several years before we visited New Hope Creek. The excavation methods we used obliterated any traces that might have been preserved.

We believe that the shells and traces in this ephemeral stream are susceptible to

three main sources of taphonomic damage, considering the general environment of the valley: 1) erosion by flood waters flushing out the channel and scouring down to the underlying floodplain deposits; 2) dissolution of shells by acidic groundwater; and 3) compaction, disruption, and partial to complete physical obliteration of traces in unconsolidated sediment. Probably some sort of early cementation is necessary for the preservation of traces. The shells, however, if sealed in a lenticular sand body made of channel deposits and surrounded by a more or less impermeable envelope of floodplain sediment, could remain essentially undisturbed within the sedimentary package of the valley for millions of years. Even if affected by post-depositional reworking and dissolution, comparatively thick-shelled clams and snails with thick periostracum layers (e.g., *Elliptio complanata*, *Campeloma decisum*, and *Goniobasis symmetrica*) could possibly persist as identifiable fragments indicative of an eco-logically heterogeneous assemblage (see Lazar, 1960).

CONCLUSIONS

1. Depressions on the surfaces of floodplains adjacent to trunk streams are among the few fluvial subenvironments in which the spotty fossil record of upland streams is likely to be preserved. These features not only act as traps that remove sand and gravel from the environment of sediment transport in stream valleys during seasonal floods, but also concentrate benthic organisms displaced by the floods into localized, potentially preservable assemblages.

2. Freshwater mollusks that were carried into one of these depressions in New Hope Creek valley during spring floods were derived from a variety of upstream mollusk-substrate associations and community types, and represent an ecologically mixed but biostratonomically in-place assemblage. Upstream riffle communities contributed about 29 percent of all taxa collected, whereas upstream pool communities contributed about 71 percent. In terms of individuals, upstream riffle communities contributed about 33 percent of the fauna and upstream pool communities contributed roughly 67 percent. Pools may contribute more taxa and individuals due to a lack of rheotactic, thigmotactic, and/or morphologic adaptions to flowing water among pool dwellers, or because pools contain a more densely populated and comparatively species-rich molluscan community (see Hynes, 1972, p. 121-182; Patrick, 1970; McNaughton and Wolf, 1979, p. 474).

3. Distributional patterns of the shells and traces made by *Sphaerium simile* may be useful paleoecological guides to the identification of subenvironments like the New Hope Creek ephemeral stream channel. When the sizes of the pools within the channel shrank between flood stages in the creek valley, large numbers of *S. simile* that had been flushed into the channel moved down the sides of bars and became concentrated in the sand-veneered channels surrounding the bars. As the pools disappeared, *S. simile* perforated the channel floor with small vertical burrows (Figure 4). The resultant *Cylindricum*-like burrows associated with *Taphrhelminthopsis*-like furrow systems are a record of the final hours of submergence of the channel floor. If preserved, perhaps on bedding planes within a discontinuous, shoestring sand body (= channel deposits) surrounded by mudstone (= floodplain deposits), the shells of *S. simile* in "life positions" and the patchy distributions of distinctive traces should suggest deposition in temporary, freshwater pools within an intermittent or ephemeral stream channel.

4. The preservation potential of freshwater organisms should not be under-estimated. Skeletons and trace fossils produced by these organisms should be diligently searched for in the study of freshwater sedimentary rocks to add an ecological dimension and overall measure of refinement to interpretations of depositional environments (for example, see Olsen and others, 1978).

ACKNOWLEDGMENTS

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A GEOCHEMICAL EXPLORATION PROGRAM

FOR URANIUM AND GOLD IN SELECTED TRIASSIC

BASINS IN NORTH CAROLINA

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ABSTRACT

A stream sediment (minus 80-mesh and minus 60-mesh panned concentrates) and lithogeochemical survey for gold did not locate any Triassic-age placer deposits in the northern portion of the Wadesboro and southern portion of the Sanford basins in North Carolina. A stream sediment geochemical program for uranium funded by the North Carolina Energy Institute did identify one anomalous site (8.5 ppm U; 5 ppm Th) near Exway, North Carolina and eighteen possibly anomalous sites (1-1.6 ppm U). Five of the eighteen samples with uranium levels in the 1-1.6 ppm range have high thorium levels (112-853 ppm) and may indicate a monazite source for the uranium.

Gold values as high as 0.83 ppm in the stream sediments and 9.3 ppm in the panned concentrates were obtained during the survey. Small (<.5mm) flattened grains of gold (1-4 grains) were observed along with coarse kyanite and/or monazite in some of the panned concentrates. A distinctive pattern of high gold values in the sediments was observed in the vicinity of Mangum, N. C. where Minard (1976) reported values as high as 2.1 ppm from a Triassic lithology. Follow-up gold analyses on over 400 rock samples from twenty-eight exposures near Mangum failed to obtain any high values (<55 ppb). The presence of coarse kyanite, monazite and gold in panned concentrates may be from a source younger than the Triassic lithologies that the streams currently drain or from adjacent Paleozoic rocks.

INTRODUCTION

A lithogeochemistry, stream sediment and panned concentrate survey for gold was carried out in the northern portion of the Wadesboro and southern portion of the Sanford Triassic basins of North Carolina. The objective was to attempt to locate fossil placer gold deposits in Triassic age rocks in the area. The area was chosen because of its close proximity to present gold deposits in Carolina Slate Belt rocks and because similar gold deposits may have been exposed during the infilling of the Triassic basins.

An occurrence of gold in Triassic age sedimentary rocks in North Carolina was originally reported by Marcou (1862) and confirmed by Becker (1895). According to Carpenter (1972) over 250 present gold occurrences have been noted (Figure 1) within a maximum distance of 65 km and a minimum distance of .1 km of the Durham, Sanford and Wadesboro (Deep River Basin) basins in North Carolina. If similar Paleozoic age rocks bearing lode gold occurrences close to the Triassic basin had been exposed to weathering during the Triassic, then gold may have been transported into the basins as they were filled and placer deposits may have formed. The Paleozoic rocks containing the gold deposits must have been exposed during the Triassic because metamorphic detritus including kyanite has been found by Thayer (1970) in a basin to the west.

Dennison and Wheeler (1975) and Lee (1978) have indicated that depositional environments in Triassic basins in North Carolina are favorable for uranium deposition. A stream sediment geochemical survey for uranium was carried out to determine if there was any near surface indication of uranium mineralization.
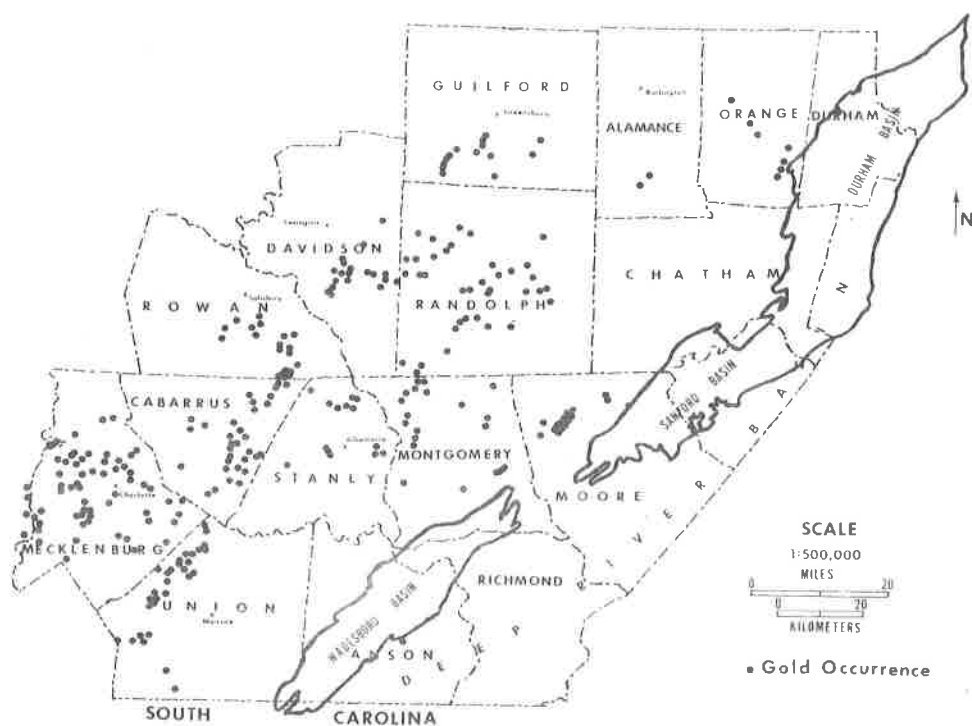
Figure 1. Gold occurrences near the Deep River Triassic Basin, N. C. (after Carpenter, 1972.

GENERAL GEOLOGY

The Sanford and Wadesboro Triassic basins are subdivisions of a larger 170 km long Triassic basin in North Carolina known as the Deep River basin. The general geology of the northern portion of the Wadesboro basin has been described by Randazzo (1965) Randazzo, Swe and Wheeler (1970) and Randazzo and Copeland (1970); Conley (1962) and Reinemund (1955) have described the geology of the southern Sanford Basin. The geology of this basin is also included in a recent report by Wilson et. al. (1978).

According to Wilson et. al. (1978), the Deep River Triassic basin is a graben. Sedimentary rocks in the basin were derived from Paleozoic sources to the east and west and were deposited as alluvial fans that grew outward into the basin. Where the lithologies have been studied in detail, they are subdivided into three units. The lowest unit, the Pekin Formation, consists of a basal conglomerate in places and arenaceous units with minor siltstone and claystone at the top. The middle unit, the Cumnock Formation, is composed of siltstones and shales that are in part carbonaceous. The overlying Sanford Formation is composed of shales and sandstones. All units have been cut by diabase dikes of late Triassic and possible Jurassic age. Unconsolidated to poorly consolidated Cretaceous and younger sands, gravels and clay overlie Triassic rocks in several portions of the basin (Figures 2, 3-5).

No base metal deposits or uranium mineralization have been noted in Triassic age rocks in North Carolina. Gold in Triassic sedimentary rocks was reported by Marcou (1862) and Becker (1895) at the Womble mine, 3 miles northwest of Moncure in Chatham County, however, no significant production was reported from this locality. In addition, Minard (1976) has reported that 5 of 17 rock samples in the vicinity of Mangum, North Carolina, contained at least 100 ppb Au and one of these contained 2100 ppb. Zircon and monazite rich sands are found at several localities along the Little River in a Triassic outlier, in Moore County southeast of the Sanford basin (Conley, 1971).
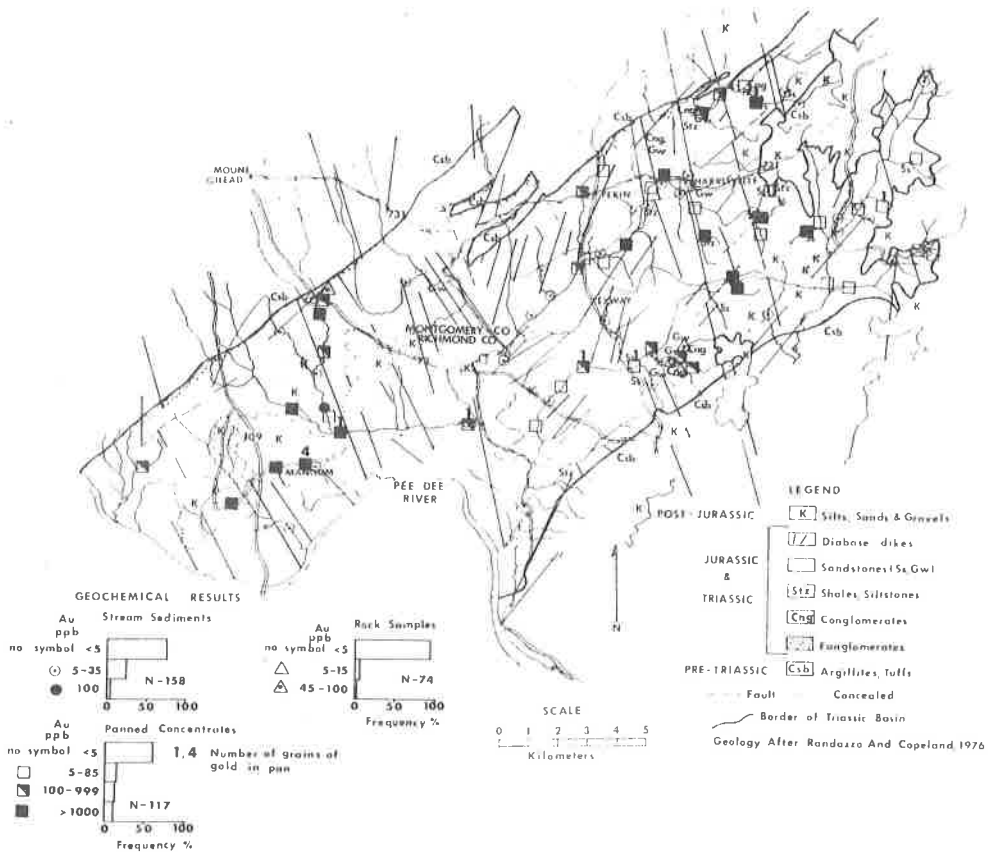
Figure 2. Samples with detectable gold, Northern Wadesboro Basin, N. C.

FIELD AND ANALYTICAL METHODS

Stream sediment samples (263) were collected from active portions of small stream channels in the southern Sanford and northern Wadesboro basins during the summer of 1976. Whenever feasible, a panned concentrate (177 samples) was also collected.   Two or three rock samples (220 total samples) were taken from each outcrop exosed in the area. In a second phase of the program 20 to 30 additional rock samples were taken from 28 exposures within a several kilometer radius of the outcrop near Mangum, North Carolina in the northern portion of the Wadesboro basin where Minard (1976) reported a gold value of 2100 ppb.   Prior to analysis, the panned concentrates were examined for visible gold with a binocular microscope to determine the approximate size and degree of rounding of the gold and to note other associated heavy minerals.

All stream sediments, panned concentrates and rock samples were sent to Bondar-Clegg and Company in Ottawa for analysis. Stream sediments were sieved to minus 60-mesh (<.250 mm) for gold analysis and to minus 80-mesh (<.177 mm) for uranium analysis. The analyst ground the entire panned concentrate until it passed through a 100-mesh screen (<.149 mm). For gold analysis, a 10 gram panned concentrate and sediment was used whenever possible. Rock samples were reduced to minus 100-mesh and blended thoroughly; two 10 gram fractions were then obtained by splitting the sample. Duplicate gold analyses were run on each rock sample.

A furnace extraction utilizing a fire assay procedure that produces a dore bead was carried out on each sample analyzed for gold. The bead was digested in aqua regia and analyzed for gold by atomic absorption. The analyst reports a percision of ± 50% at the 10 ppb gold level and at a level of 20-50 ppb gold of ± 20% with this technique.
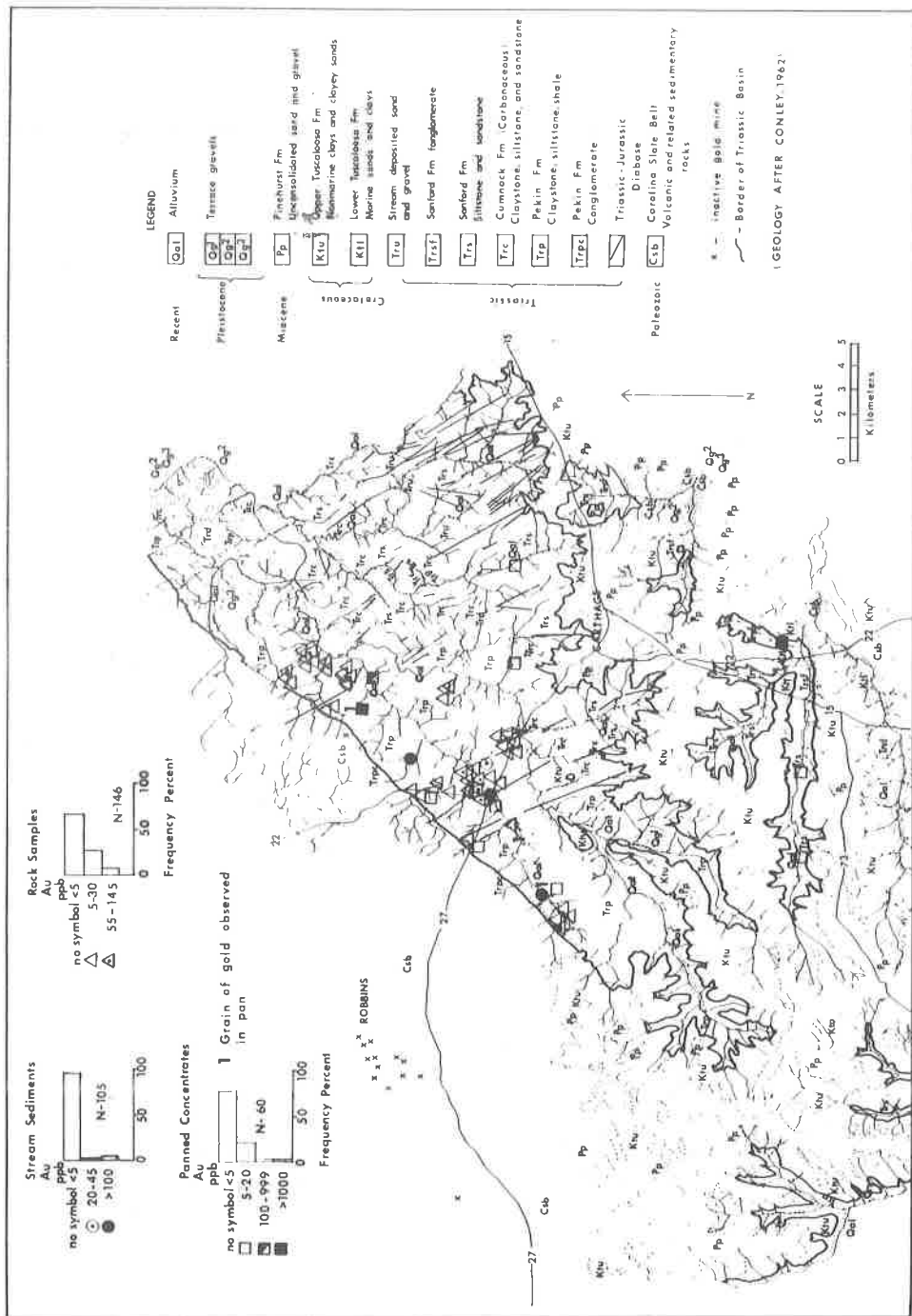
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Figure 3. Samples with detectable gold, Southern Sanford Basin, N. C.

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235 samples had sufficient minus 80-mesh stream sediment for uranium analysis and .5 g was digested in HNO_3 and analyzed for uranium by Bondar and Clegg utilizing a fluorimetric technique. Uranium precision as eported by the analysts is + 100% at .1 ppm and + 20% at 1 ppm. Upon receipt of the initial uranium results it was decided to analyze all samples with analytical values in excess of .9 ppm uranium for thorium. The thorium analyses were carried out by Bondar and Clegg by X-ray fluorescence.

RESULTS

Gold

Wadesboro Basin: The majority of the rock samples, stream sediments and panned concentrates did not contain significant gold concentrations (>100 ppb) (Figure 2). Seven rock samples contained detectable gold (>5 ppb). Four samples that contained at least 45 ppb gold were re-analyzed with negative results (<5 ppb). Only one stream sediment sample of the 158 analyzed contained significant gold (120 ppb). Nineteen panned concentrates had at least 100 ppb and fourteen of these contained greater than 1000 ppb. All samples that contained visible gold in the panned concentrates had analytical values in excess of the lower detection level >5 ppb. There were eleven samples where no gold was seen in the pan but that had values in excess of 1000 ppb. Five of the panned concentrates with high gold values in excess of 1000 ppb and the one stream sediment with a high of 120 ppb are located within a few kilometers of the Triassic sedimentary outcrop cut by a diabase dike near Mangum, North Carolina where Minard (1976) reported a gold value of 2100 ppb. A detailed rock sampling program was carried out on all the exposures in the vicinity of Mangum. Four hundred and sixteen rock samples and eleven unlithified Cretaceous (?) sediment samples were collected from 35 outcrops including the one with the high reported gold values. None
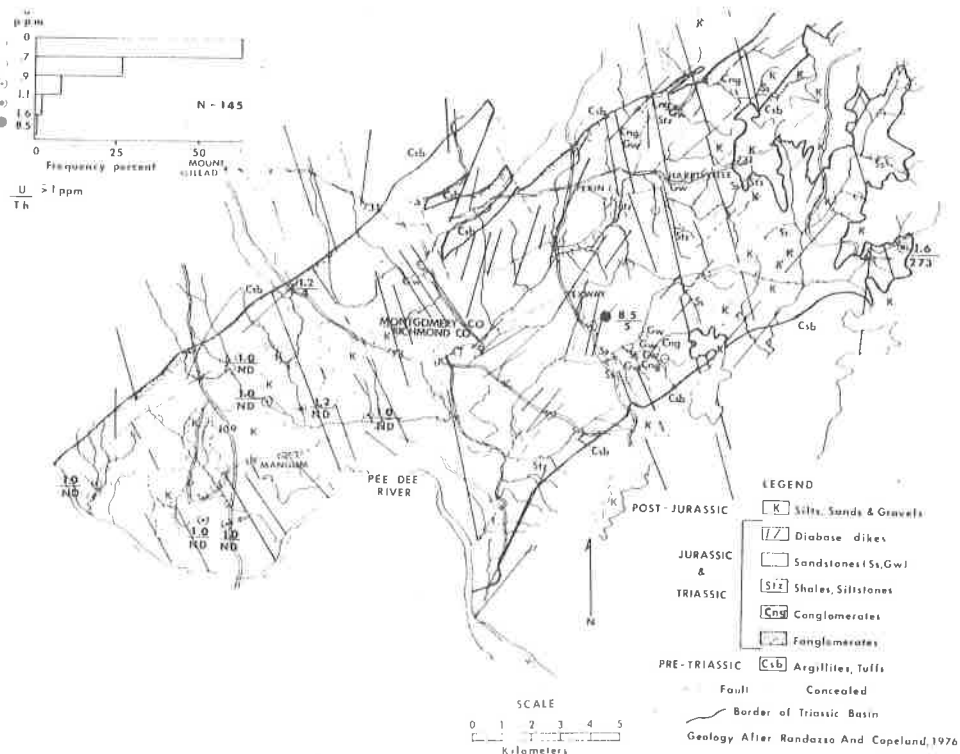

Figure 4. Uranium and thorium in stream sediments, Northern Wadesboro Basin, N. C.

of the 416 rock samples analyzed contained significant gold. The highest gold value obtained for any Triassic lithology was 50 ppb and the highest from Minard's (1976) locality near Mangum was 30 ppb. None of the panned concentrates from the unlithified Cretaceous (?) sediment samples taken within an eight km radius of Mangum had high gold concentrations (<15 ppb). However, 9 of the 11 had some coarse kyanite present in the panned concentrates. There are several areas in the Wadesboro basin with high gold values in the panned concentrates but rocks from these areas were not sampled because of the negative results encountered in the Mangum area.

Sanford Basin: Most samples from this basin did not contain detectable gold. The stream sediments with higher gold values (>100 ppb) and panned concentrates with higher gold values (>100 ppb) are located either along the western edge of the basin along Richland Creek or from tributaries of Richland Creek that drains the Carolina Slate Belt volcanics to the west (Figure 3). One exception is the high gold value (in panned concentrates) obtained in The Little River area to the southeast (Figure 3). Panned concentrates from this area also contain monazite. Two panned concentrates that had 1 grain of visible gold from two different locations did not have high gold values and indicates that the gold was lost prior to analysis in the preparation stage. Fifty four of the rock samples from this area contained detectable gold (>5 ppb) and the majority of these are located along the western edge of the basin. The twelve rock samples with the highest gold values (25-145 ppb) were reanalyzed and all had gold values less than those originally reported (<15 ppb). None of these sample locations with initial high gold values has had follow up work done on them.

Binocular Examination of Panned Concentrates: All of the visible flakes of gold in the panned concentrates were small (<.5 mm) and flattened with rounded edges. Numbers of visible grains in each pan are recorded on Figures 2 and 4. The most common other accessory minerals noted in the concentrates were a black opaque mineral, kyanite, and in several samples from the Little River area, monazite. Some of the kyanite observed was extremely coarse gained > 5 mm in width.

Table 1. Chemical and scintillometer values for the resampled anomalous sample site 8 in the Harrisville, North Carolina Quadrangle.

Sample Number	U/ppm	Th/ppm	Mn/ppm	Fe/%	L.O.I.%	Scintillometer Values counts per sec.
8A	.7	ND	210	1.25	4.9	70
8B	20	8	995	3.00	7.2	100
8C	.4	5	1020	1.90	6.3	80

Note: 8A is downstream from 8B and 8C and may be contaminated by roadfill.

Uranium

Wadesboro Basin: Of 147 stream sediments analyzed only 4 samples contained greater than 1 ppm uranium (Figure 4). One of these, sample 8 near Exway, had the highest uranium value, 8.5 ppm, recorded in the initial survey and 5 ppm thorium. The stream from which this sample was taken was resampled at 100 feet intervals and analyzed for uranium, thorium, manganese, iron and loss on ignition (Table 1). Scintillometer readings at this locality were also taken and slightly higher scintillometer values coincide with the higher geochemical values. The majority of the other samples in the basin with values in excess of 1 ppm uranium are confined to the southern portion of the basin and have little or no detectable thorium associated with them. The sample with the second highest uranium value (1.6 ppm) in the basin is located on the northeast corner had has a high associated thorium value (273 ppm) that may indicate a monazite source for both the higher uranium and thorium values. No follow up work has been done on the cluster in the southwest or the other sample sites with uranium values >1 ppm.

Sanford Basin: The majority of the stream sediment samples analyzed (82) had uranium values below 1 ppm (Figure 5). Of the eight samples that had possibly significant
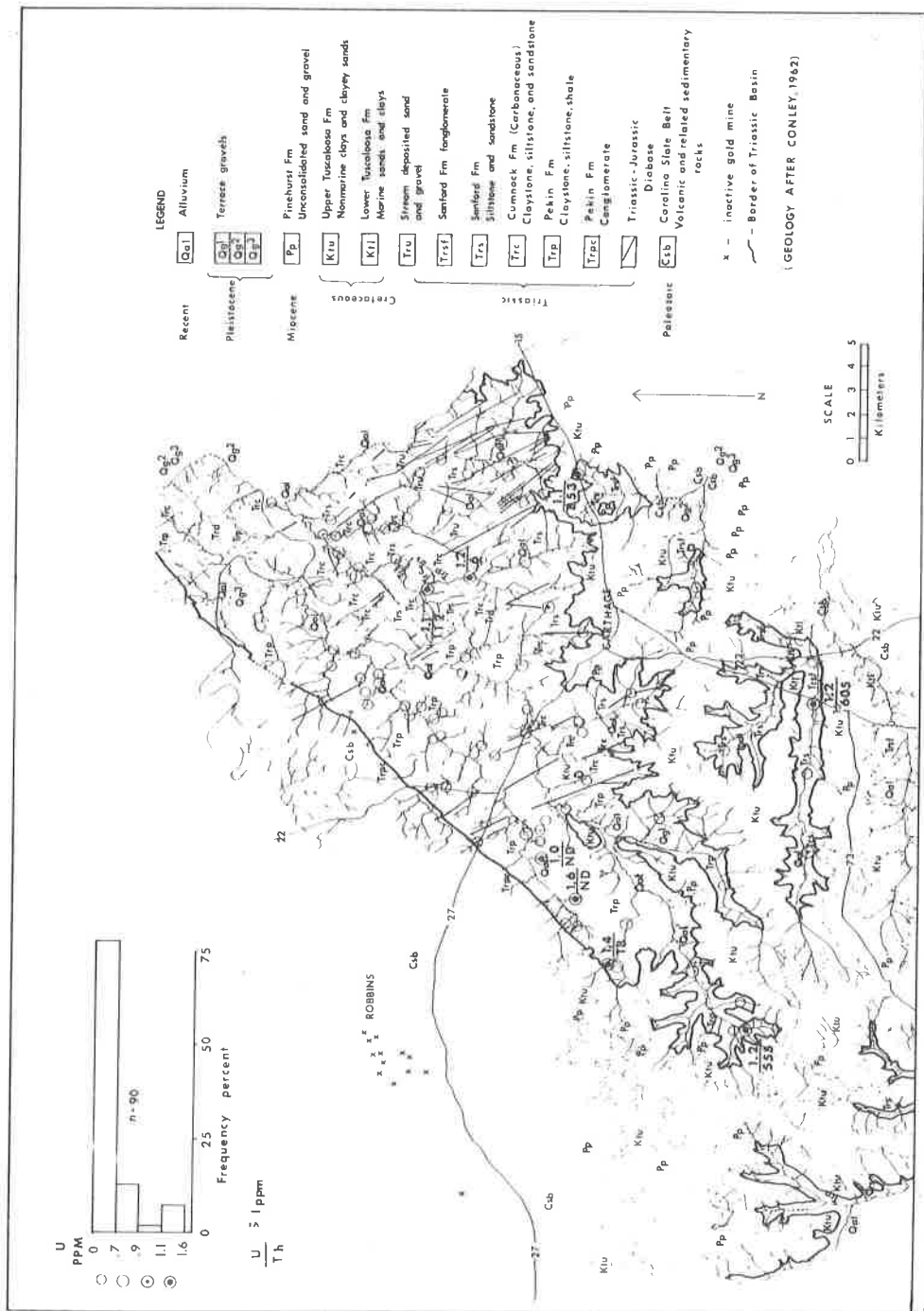
Figure 5. *Uranium and thorium in stream sediments, Southern Sanford Basin, N. C.*

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values (>1 ppm), six are located near the edge of the basin in close association with Cretaceous sediments and/or rocks of the Pekin Formation. High throium values in 3 of the 6 samples indicate a possible monazite source for both the higher thorium and uranium values.

DISCUSSION AND CONCLUSIONS

Gold

No Triassic gold placers were located. There is visible gold in the panned stream concentrates and most of these samples with visible gold have values in excess of 1000 ppb. However, several concentrates with no visible gold also had high values. In two instances where gold was observed in the pan the analysis did not confirm it indicating great care should be taken with preparation of the samples for analyses. Three of the minus 60-mesh sediment samples had high gold values (120-830 ppb) but no gold was detected in the corresponding heavy mineral concentrate taken at the same locality.

Thirty two of the heavy mineral concentrates with high gold values (85-9320 ppb) had corresponding minus 60-mesh sediment values at or below the detection limit of 5 ppb. Although not conclusive, this indicates that in a stream sediment survey for gold more gold is recovered in panned concentrates than stream sediment. Visible gold grains are small (<.5 mm), flat with rounded edges, and often have coarse kyanite (>5 mm) associated with it in the panned concentrates. Over 600 Triassic rocks were analyzed for gold and no gold value in excess of 120 ppb was obtained. Therefore, gold in stream sediment samples in the Triassic basins noted in this study has probably not been derived from Triassic sedimentary rocks. The source of the higher gold values obtained in samples from Richland Creek that parallels the western edge of the southern portion of the Sanford basin could be explained if gold was being carried from the known and undiscovered occurrences in Slate Belt rocks immediately to the west. It is also possible that both the gold and/or kyanite may have been transported into the region from the Inner Piedmont or Slate Belt during the Cretaceous and younger periods. Weathering of Cretaceous, and younger sediments and rocks may free the gold, kyanite, and monazite which are found in present drainage sediments. These possibilities are suggested based on the occurrence of transported kyanite in present stream sediments of the High Rock Quadrangle just to the west of the Triassic basins in a study completed by White and Stromquist (1961) that must have come from the Piedmont and on occurrences of gold in basal coastal plain sediments (Tuscaloosa Formation) as reported by Minard (1971) in South Carolina.

Uranium

No clear uranium patterns are apparent from the survey and no uranium occurrences were located. However, thirteen samples containing at least 1 ppm uranium and low thorium values are possibly anomalous (Figure 4, 5). These samples with high thorium values and uranium values in the 1-1.6 ppm range probably have a monazite source for the slightly higher uranium values. A value of 1 ppm as possibly anomalous may appear low but according to Overstreet (1970) a warm humid environment such as found in the southeast would promote considerable leaching. Thus the majority of the uranium would have already been removed from the surface environment and a lower threshold value (1 ppm) as chosen, would be expected. Since uranium concentration levels in stream sediments in this area are low another exploration technique such as a hydrogeochemical survey for uranium in this region might yield more significant results.

The high uranium value at locality 8 in the northern Wadesboro basin has been reconfirmed. However, this uranium anomaly may be a spurious one but it does not appear to have been caused by the scavenging effects of maganese and iron hydroxides and organic material.

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A CASE FOR SUBSTRATE INFLUENCE ON INFRABASAL-CONE MORPHOLOGY OF TWO PALEOZOIC STEMLESS CRINOID GENERA FROM EASTERN KENTUCKY

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ABSTRACT

The Late Paleozoic crinoids *Agassizocrinus* and *Paragassizocrinus* were stemless crinoids that lived with proximal portions of their dorsal cups inserted into the substrate. This semi-infaunal life mode has been demonstrated by means of specimens preserved in life position. In these genera, the most proximal (lowermost) plates in the cup, the infrabasals, are fused and secondarily calcified forming a conical plug of stereom, known as the infrabasal cone, which was used to insert the cup into the substrate and anchor it in place. The shape of the infrabasal cone, however, appears to reflect the nature of the substrate. *Agassizocrinus*, which occurs in North American Chesterian (late Viséan-Namurian A) rocks, is typically found in skeletal or oolitic calcarenites. It characteristically exhibits a more rounded or turbinate infrabasal cone and cup, an apparent adaptation for firmer, often mobile, sandy substrates. *Paragassizocrinus*, on the other hand, is typically found in muddy carbonates and shales from the Pennsylvanian of North America, and its more steep-sided, conical cup appears to be an adaptation for life on more unstable, muddy substrates. The conical shape apparently allowed easier insertion and retention in such substrates. Similar relationships have been noted in the conical coralla of solitary Scleractinian corals.

A trend toward development of increasingly conical infrabasal cones and cups in *Agassizocrinus* from a Chesterian carbonate sequence in eastern Kentucky appears to correlate with increasing mud content, and presumably less stable substrates, in the sequence. The nature of burrow walls and the attendant fauna also indicate increasingly unstable substrates upward in section. In this sequence, each successive, ascending calcarenite unit contains more mud than underlying calcarenites. Although a different species of *Agassizocrinus* predominates in each calcarenite unit, each successive species has a more conical infrabasal cone and cup, apparently in response to increasingly unstable muddy substrates. The culmination of the trend toward increasingly conical cups is represented by *Paragassizocrinus* from Pennsylvanian sediments in the same area.

INTRODUCTION

During the Paleozoic, a small number of largely unrelated crinoid genera independently evolved a stemless life mode. The stemless life mode in Paleozoic crinoids developed to its greatest extent during the Carboniferous and Permian when at least nine crinoid genera developed this life mode. The best known and most successful of these genera in terms of speciation, distribution, and numbers of individuals are *Agassizocrinus*, a Chesterian (upper Viséan-Namurian A) guide fossil, and *Paragassizocrinus*, a Pennsylvanian guide fossil (Figure 1), both of which are found in eastern Kentucky. *Agassizocrinus* occurs in Chesterian portions of the Newman Limestone, a nearshore, shallow-water carbonate sequence, in east-central and extreme eastern Kentucky (Ettensohn, 1975), whereas *Paragassizocrinus* occurs locally in the Kendrick and Magoffin beds of the Pennsylvanian Breathitt Formation (Strimple and Knapp, 1966; Ettensohn, 1980) (Figure 2). The Kendrick and Magoffin beds are prominent marine horizons in the dominantly clastic Breathitt delta-plain sequence of eastern Kentucky; they are Morrowan and Atokan in age respectively.
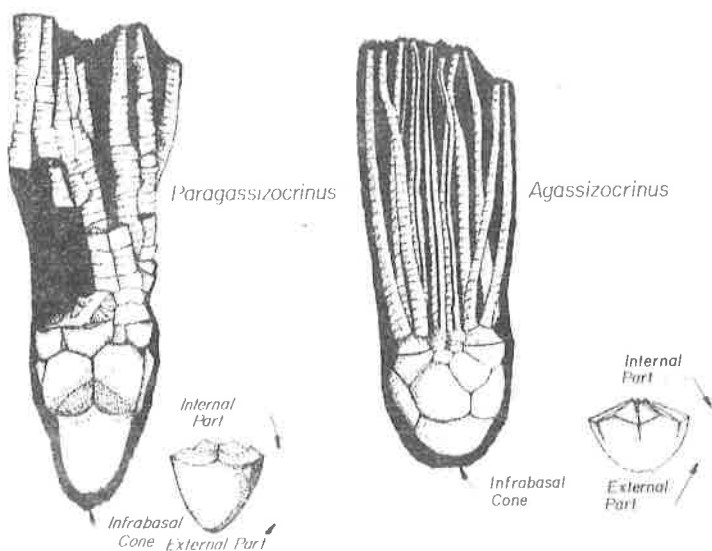
Figure 1. Typical Paragassizocrinus and Agassizocrinus species showing the nature of the dorsal cups and infrabasal cones; the morphology of each infrabasal cone is shown in detail. Drawings based on P. larri (high-cone ecophenotype; SUI 42421) and A. lobatus (UI X-5171); magnification, X2.3.
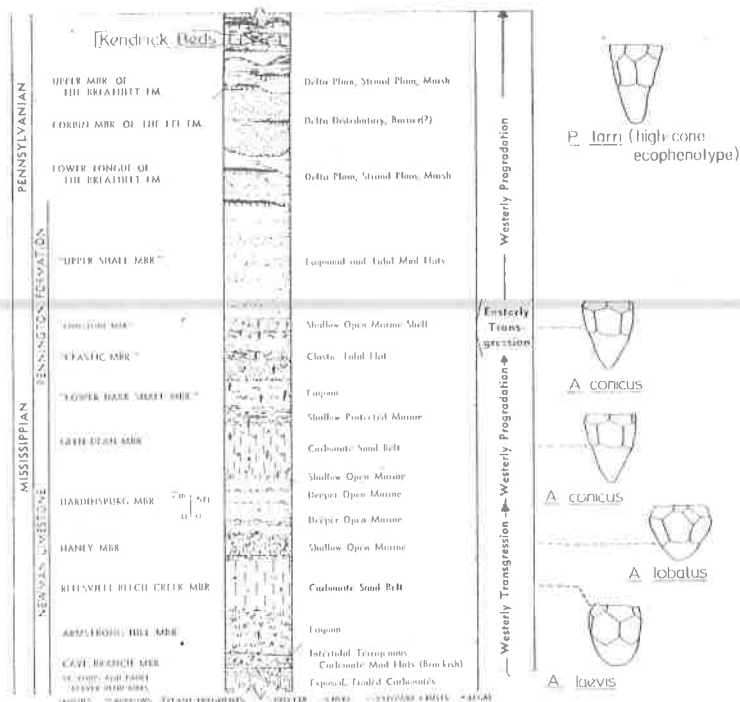

Figure 2. Upper Mississippian (Chesterian) - Lower Pennsylvanian stratigraphy in eastern Kentucky showing the accompanying change in shape of infrabasal cones in the Carboniferous stemless crinoids Agassizocrinus and Paragassizocrinus with progressive change in substrate type.

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These two genera, like most Paleozoic stemless crinoids, were relatively large, thick-plated forms. This heavy construction is thought to have been an adaptation for life in relatively high-energy environments (Ettensohn, 1975, 1980). The basal plates of some species attained thicknesses of 0.7 cm, whereas the infrabasal plates of some species fused into nearly solid, conical plugs of stereom (Figure 1) up to 2 cm high and 2 cm in diameter at the widest point. The heavy, thickly plated cups of these stemless crinoids almost certainly necessitated a life on the bottom. These forms were simply too heavy to float or swim in the fashion of some Mesozoic and Cenozoic comatulid crinoids. In fact, *in situ* specimens of *Agassizocrinus* from the Reelsville-Beech Creek and Haney members of the Newman Limestone in northeastern Kentucky clearly indicate that *Agassizocrinus* lived with parts of their dorsal cups inserted into the substrate (Ettensohn, 1975). The similar appearance of many other stemless crinoids, like *Paragassizocrinus*, probably reflects convergent evolution for a similar life mode. Because these crinoids abandoned their stems in early adolescence and assumed a new life mode sitting on or partially buried within the substrate (Figure 3), substrate-organism relationships assume special importance in the study of these crinoids.

The part of these crinoids that was inserted into the substrate, and hence most likely to be influenced by it, is the infrabasal cone (Figures 1 and 3). In *Agassizocrinus* and *Paragassizocrinus*, the five infrabasal plates in the proximal (lower) part of the cup are fused and heavily calcified to form a nearly solid, conical plug of stereom with a conical central cavity to receive parts of the viscera (Figure 1). The heavily calcified infrabasal cones in these genera were used to insert the cup into the substrate and then served as ballast to anchor them in place. Moreover, this heavily calcified cone served to lower the crinoid center of gravity toward the substrate, thereby enhancing the stability of the crinoid.

DISCUSSION

The shape of the infrabasal cones, and to a lesser extent, that of the entire crinoid cup appear to reflect the nature of the substrate. *Agassizocrinus* typically occurs in the skeletal or oolitic sands (grainstones) which are common in many Chesterian rocks of North America; both the cups and infrabasal cones in most *Agassizocrinus* species are generally more rounded or turbinate in shape (Figures 1 and 2). *Paragassizocrinus*, on the other hand, occurs most commonly in muddy, argillaceous limestones or shales which characterize much of the Pennsylvanian shallow, open-marine deposition in North America; the cups and infrabasal cones in most *Paragassizocrinus* species are more steep-sided and conical (Figures 1 and 2). The low, rounded, turbinate infrabasal cones appear to be an adaptation to firmer, sometimes mobile, sandy substrates, whereas the steep-sided, conical cones appear to be an adaptation for life on soft, less stable, muddy substrates. Similar adaptations in solitary Scleractinian corals were noted by Vaughan and Wells (1943). They noted that solitary corals living on soft, unconsolidated substrates typically exhibit more steeply conical coralla than those living on firmer, sandy substrates; those corals living on firmer, sandy substrates typically exhibited more shallow, disoidal coralla.

The Conical Cone

In muddy, unconsolidated sediments, a conical cup and infrabasal cone allowed easier insertion and retention therein. The steep-sided, conical shape allowed penetration of the soft sediment-water interface into more solid, and slightly more compacted underlying sediments (Figure 4). Penetration of the firmer underlying muds effectively increased the buoyancy of the crinoid on the muddy substrate. Further-more, as the crinoid grew and weight was added, the cup would have slowly sunk downward into yet firmer underlying sediments. As the cone increased in size, moreover, the bearing area of the cup, or that part of the cup in contact with the sediment, also increased, further enhancing buoyancy. In some species, the bearing area was further increased by an outflaring of the distal margins of the infrabasal cone (Figure 4) or through an outflaring of the overlying basal plates (Ettensohn, 1980). The
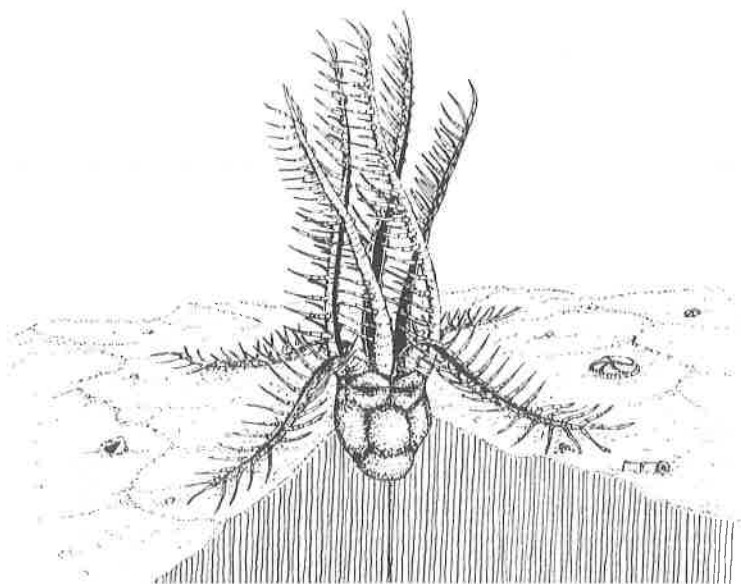
Figure 3. Inferred life mode of Agassizocrinus and Paragassizocrinus based on in situ specimens of Agassizocrinus from the upper Newman Limestone in eastern Kentucky (from Ettensohn, 1975).
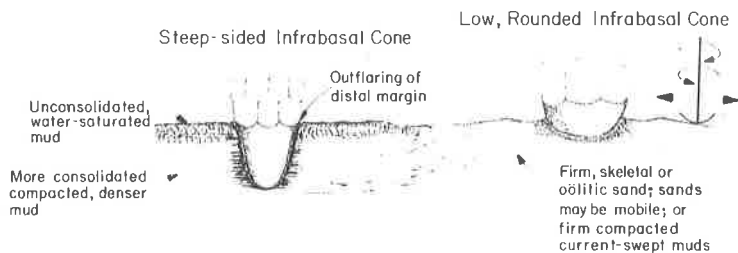

Figure 4. Inferred relationships between the two major types of infrabasal cones and substrate types. The schematic diagram to the right of the low, rounded infrabasal cone shows possible directions of movement for this cone type.

adaptive strategy of increasing buoyancy in soft sediments through increasing the length of submerged portions of the animal, has been called the "iceberg" adaptation by Thayer (1975). Such an adaptation is clearly present in some species of *Agassizocrinus* and *Paragassizocrinus* (Figure 2). The major disadvantage of this cone type would seem to be the fact that it allowed for little in-place movement of the cup in response to changing current directions.

The Bowl-Shaped Cone

The rounded, bowl-shaped infrabasal cone, which is more common in *Agassizocrinus* (Figures 1 and 2), appears to represent an adaptation for life on firmer, sandy substrates, where relatively high-energy conditions frequently kept the sand in motion. The rocks in which this type of infrabasal cone occurs typically exhibit evidence of high-energy conditions, such as the presence of ooids, crossbedding, scours and a heavily constructed attendant fauna. Such a shape also would have proved adaptive on firm, current-swept, mud substrates. The advantage of the low, rounded infrabasal cone in the above environmental conditions is that it allows flexibility of in-place movement in areas of dominant horizontal water movement where crinoids preferred to

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Table 1. Criteria examined in each of the five units for inferences regarding substrate stability.

UNIT	DOMINANT LITHOLOGY	AVERAGE PERCENT INSOLUBLE RESIDUE	AVERAGE PERCENT MUD (CARBONATE & ARGILLACEOUS, IN POINT COUNTS)	SIGNIFICANT ATTENDANT FAUNA	PRESENCE OF BURROWS; NATURE OF BURROW WALLS IN THIN SECTION
Kendrick Bed, Breathitt Fm.	Argillaceous carbonate mud-stone & dark shale	93	100	Largely productid & inarticulate brachiopods & semi-infaunal pelecypods; nekto-benthic forms.	Absent or rare; burrow walls very indistinct.
Limestone Mbr., Pennington Fm.	Argillaceous carbonate pack-stone & wacke-stone	20	55	Locally diverse; productids common.	Common; burrow walls moderately distinct to very indistinct.
Glen Dean Mbr., Newman Limestone	Argillaceous carbonate pack-stone & wacke-stone	25	25	Locally diverse; productids common, infaunal pelecy-pods present.	Common; burrow walls moderately distinct to very indistinct.
Haney Mbr., Newman Limestone	Argillaceous carbonate pack-stone	3	22	Diverse; produc-tids & infaunal pelecypods present.	Abundant; burrow walls moderately distinct to indis-tinct.
Reelsville-Beech Creek Mbr., Newman Limestone	Oolitic-skeletal grainstone	0.5	1	Rare; thick-shelled gastropods only.	Absent; due to very mobile substrates.

feed. Such crinoids were free to rotate in any direction or rock back-and-forth in response to changing current directions (Figure 4). This rocking movement also would have allowed the crinoids to accommodate slight changes in the underlying substrate as sand moved into and out of crinoid habitation areas. Hence, even though these crinoids apparently lived on mobile substrates, this adaptation probably prevented imminent burial in all but strong current regimes.

The validity of these interpretations regarding the adaptive shape of infrabasal cones is suggested by a trend toward development of an increasingly conical cup in the stemless genus *Agassizocrinus* in a Chesterian carbonate sequence from eastern Kentucky; species of *Paragassizocrinus* found in overlying Pennsylvanian shales and carbonates from the same general area exhibit even more conical cups and infrabasal cones (Figure 2). In this sequence (Figure 2), the carbonates become increasingly muddy upward in section and presumably formed less stable substrates with time (Table 1). Even though an upward trend toward increasingly unstable substrates is suggested by the generally increasing percentages of both carbonate and argillaceous muds (insoluble residues, Table 1), this criterion alone cannot be used to infer unstable substrates, for compacted muds can also form firm, stable substrates. To further test the hypothesis of decreasing substrate stability, the lithology, attendant fauna, and the nature of burrow walls were examined (Table 1). In examining attendant fauna, particular attention was given to the presence of forms like productid brachiopods and infaunal pelecypods, which were better able to live on or within muddy substrates. The nature of the burrow walls in these units was also examined, because Rhoads (1970) demonstrated that the walls become increasingly indistinct as substrate sediments become more unstable. Many of the *Agassizocrinus* specimens examined were still in life position (Ettensohn, 1975).

As indicated, *Agassizocrinus* typically has a more rounded, turbinate cup, an apparent adaptation for firmer, sandy substrates, an observation which parallels the observations of Vaughan and Wells (1943) for Scleractinian corals. However, in the upper Newman sequence of eastern Kentucky, each successive limestone unit becomes more muddy than underlying limestones, and although a different *Agassizocrinus* species predominates in each unit, each successive species developed a more conical cup, seemingly in response to a more unstable, muddy substrate. Even though the nature of burrow walls is somewhat variable in most of the units containing *Agassizocrinus*,

a trend toward increasingly indistinct burrow walls in each successive unit is apparent (Table 1). Also apparent is the fact that productids and infaunal or semi-infaunal pelecypods generally become more important parts of the attendant fauna in each successive, ascending unit (Table 1). Together, these observations do indeed suggest that each successive carbonate substrate become a little more unstable.

In the Reelsville-Beech Creek, a species of *Agassizocrinus* with a rounded turbinate cup (*A. laevis,* Figure 2) occurs in the skeletal and oolitic grainstones which predominate throughout the member. The presence of ooids, scours, and crossbedding in the member suggests a high-energy environment. Burrows are totally absent, probably reflecting mobile substrates in high-energy conditions. The absence of mud, the dominance of sand-size grains and the grain-supported nature of the sediment suggest firm, though mobile, substrates. The overlying Haney Member is lithologically more variable than the Reelsville-Beech Creek, but all included lithologies contain argillaceous or carbonate muds. In the Haney, a species with a more conical cup (*A. lobatus,* Figure 2) occurs largely in argillaceous skeletal packstones which contain burrows exhibiting moderately distinct to indistinct walls in thin section. The presence of mud and at least some indistinct burrow walls strongly suggests less cohesive and less stable substrates in the Haney. In the Glen Dean and limestone members, a species with an even more conical cup (*A. conicus,* Figure 2) predominates in argillaceous skeletal packstones and wackestones which contain burrows exhibiting moderately distinct to very indistinct burrow walls, apparently depending upon the amount of mud present. Carbonate and argillaceous muds comprise a greater percentage (25-55% based on point counts, Table 1) of these rocks than they do in previously described rocks (0.5-22%) from the Reelsville-Beech Creek and Haney members. The abundance of mud and the increasing indistinctness of many burrow walls suggest that many more of the substrates were soft and unstable during Glen Dean and Pennington (limestone member) carbonate deposition.

Although *Paragassizocrinus* is not closely related to *Agassizocrinus*, it occurs in Pennsylvanian rocks from the same general area and represents the culmination of this trend toward conical cups in stemless crinoids. A high-cone ecophenotype of *P. tarri* occurs in the dark, argillaceous, carbonate mudstones and micaceous shales of Morrowan age in the Kendrick Bed of the Breathitt Formation (Figures 1 and 2). Burrows are rare in the Kendrick shales, apparently because of anoxic conditions just beneath the surface, but where they do occur, they are very indistinct. The nature of burrows, the abundance of mud and the restricted fauna of semi-infaunal pelecypods and productid brachiopods occurring with the crinoids suggest very soft, unstable substrates. Another steep-sided, conical species of *Paragassizocrinus* (*P. platicrenatus*) occurs in similar sedimentological and paleontological conditions in shales of Atokan age from the Magoffin Bed of the Breathitt Formation in eastern Kentucky (Ettensohn, 1980).

CONCLUSIONS

In the stratigraphic sequence just mentioned, an increasing content of carbonate and argillaceous muds and a probable decrease in substrate stability parallel the development of increasingly conical cups in the stemless crinoids. The parallel nature of these trends suggests that substrate stability was probably the causative factor in the occurrence of the increasingly conical cups. Whether or not the evolution of these forms occurred in eastern Kentucky or occurred elsewhere and the forms migrated into the area in response to substrate changes, is not known. However, all three *Agassizocrinus* species found in the Newman Limestone (Figure 1), plus additional species of the genus, are also known from Chesterian rocks in other parts of the United States (Springer, 1926; Burdick and Strimple, 1971). Although the Chesterian environmental and ecological setting for *Agassizocrinus* in these other areas is not as well known as it is in eastern Kentucky, a similar upward increase in the amount of fine-grained clastics generally characterizes the Chesterian sequences in these areas as well. The high-cone ecophenotype of *Paragassizocrinus tarri*, on the other hand, is known only from the Pennsylvanian of eastern Kentucky. Finally, the possibility that this evolutionary sequence of cone types is a correlate of some other unrecognized

trend must be mentioned. Although other such trends are not readily apparent, the possibility cannot be dismissed.

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