Appalachian State University
Boone, North Carolina

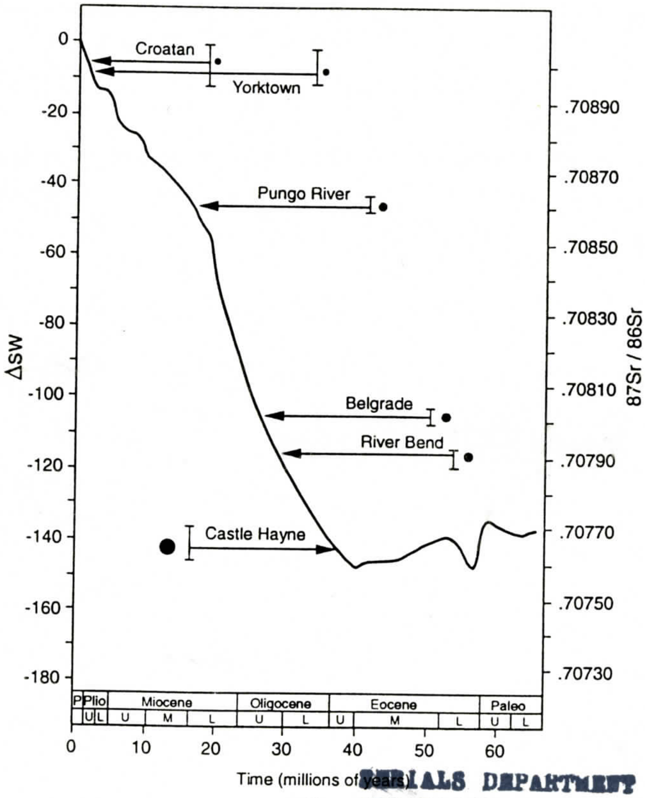
Southeastern Geology: Volume 33, No. 2
March 1993

Editor in Chief: S. Duncan Heron, Jr.

Abstract

Academic journal published quarterly by the Department of Geology, Duke University.

SOUTHEASTERN GEOLOGY



VOL. 33, NO. 2 MARCH 1993

SOUTHEASTERN GEOLOGY

PUBLISHED

at

DUKE UNIVERSITY

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Duncan Heron

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SOUTHEASTERN GEOLOGY is a peer review journal.

ISSN 0038-3678

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THE USE OF STRONTIUM ISOTOPES IN STRATIGRAPHIC STUDIES: AN EXAMPLE FROM NORTH CAROLINA

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ABSTRACT

The $^{87}Sr/^{86}Sr$ was determined on 154 Cenozoic and latest Cretaceous samples of carbonate shells, limestone and phosphatic material from North Carolina. Measurements were made on samples from the Peedee, Castle Hayne, River Bend, Belgrade, Pungo River, Yorktown, Croatan and Talbot Formations collected at six localities in order to evaluate the potential influence of fossil or sample type on strontium isotope measurements. The strontium isotope measurements were mostly made on non-diagnostic fossil material - oysters, barnacles, mollusk and echinoid fragments. No differences were found among the fossil groups of the same age, but phosphatic material was found to give considerably less consistent results.

The age of deposition for each unit was assigned by comparing $^{87}Sr/^{86}Sr$ results with the seawater strontium curve. The Castle Hayne $^{87}Sr/^{86}Sr$ is equivalent to seawater during four intervals in the Eocene and latest Paleocene. The River Bend Formation yields a mid-Oligocene age and the overlying Belgrade $^{87}Sr/^{86}Sr$ is equivalent to a late Oligocene age, some 3 Ma younger than the River Bend. The upper Pungo River Formation near Aurora gives an age near the early-middle Miocene boundary. At Aurora, the Yorktown gives a latest Pliocene-earliest Pleistocene age. The overlying Croatan gives a $^{87}Sr/^{86}Sr$ equivalent to mid-Pleistocene seawater. The Talbot Formation gives a seawater value indistinguishable from modern seawater. These results are in general to precise agreement with age assignments made using fossils. Through most of the Oligocene to Recent, strontium isotope results can be used to determine the age of deposition to ± 1 million years or better. During periods when the seawater strontium ratio is changing slowly or varying within a narrow range, such as the Eocene and Paleocene, only general age limits can be determined even though the strontium isotope data are of the same quality.

INTRODUCTION

The variation of the $^{87}Sr/^{86}Sr$ ratio in seawater with time has offered the promise of determining the age of marine carbonate and evaporite rocks since it was first proposed by Wickman in 1948. The realization of this promise was made possible by the development of high resolution mass spectrometers. Burke and others (1982, Figure 1) used results of more than 700 high precision measurements to define seawater $^{87}Sr/^{86}Sr$ variation during Phanerozoic time. There were periods of both increasing and decreasing strontium isotope ratios and certain intervals appeared very favorable for applying the technique to determine the age of strontium bearing marine samples. The period from latest Eocene to Recent was clearly one of the most favorable intervals to apply strontium isotopes to the solution of stratigraphic problems. Elderfield (1986) and Veizer (1989) have provided excellent summaries of the principles governing the use of strontium isotopes in stratigraphic studies.

The path of seawater $^{87}Sr/^{86}Sr$ shown on Figure 2 is a compilation of results from a

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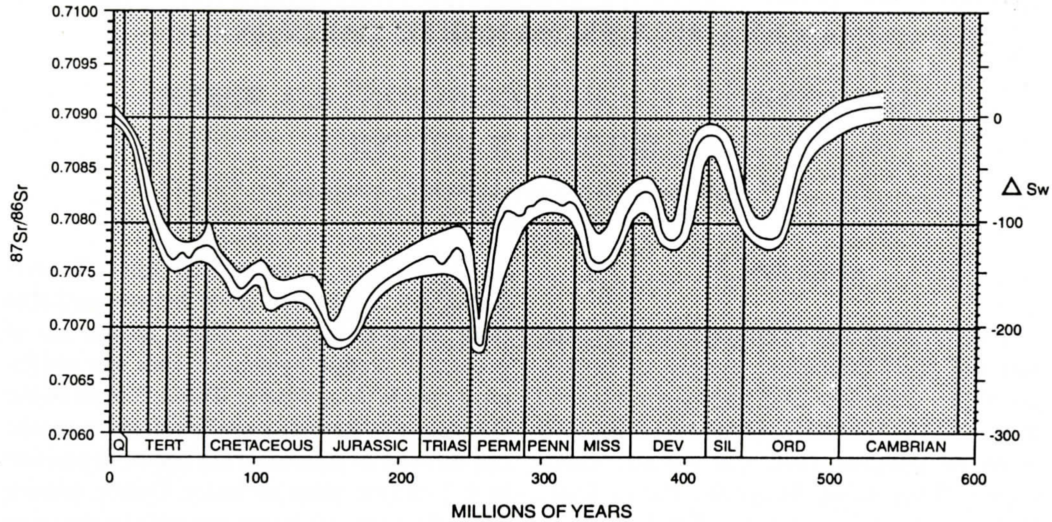

Figure 1. - The variation of $^{87}Sr/^{86}Sr$ in Phanerozoic seawater, from Burke and others (1982).

number of DSDP sites reported in the literature for the Oligocene and younger and well constrained outcrop results for the Eocene and Paleocene (DePaolo and Ingram, 1985; Koepnick and others, 1985; Hess and others, 1986; DePaolo, 1986; McKenzie and others, 1988; Miller and others, 1988, Hess and others, 1989; Hodell and others, 1989; Hodell and others, 1990; Capo and DePaolo, 1990; Miller and others, 1991; Hodell and others, 1991; Denison and others, in press). The North Carolina samples analyzed in our study are mostly from shallow shelf environments. Numerical ages have been assigned to some of the rock units based upon a comparison of isotopic ratios to the actual seawater ratio at any time. Jones and others (1991) have used strontium isotopes to help resolve long standing disagreements in the age assignment of a well known Pliocene fossil site in Florida.

We have determined the strontium isotope ratio of 154 Cenozoic samples of carbonate shells, limestone, and phosphatic material from the Peedee, Castle Hayne, River Bend, Belgrade, Pungo River, Yorktown, Croatan and Talbot Formations in North Carolina. Our results can be used to define the age of several rock units with considerable accuracy. Other rock units were deposited during periods when the seawater strontium isotope ratio was changing slowly, or varying within a fairly narrow range. For these units only a general age can be assigned on the basis of the isotope results.

A large number of determinations were made in order to evaluate the potential influence of fossil or sample type on strontium isotopic composition. Our results demonstrate the consistency of a large number of measurements from carefully chosen samples. No systematic differences were found among carbonate fossils and limestones, but phosphatic material was found to give considerably less consistent results.

The North Carolina Coastal Plain sediments represent a favorable test for strontium isotopes as a stratigraphic tool. There is a rich shelly fauna, a variety of phosphatic material (shark teeth, bones, nodules), as well as limestones that are suitable for strontium analysis. The limestones, fossiliferous sands, and shales have not been deeply buried nor subjected to extensive recrystallization. The Coastal Plain has, however, received sediments during only limited times in the Cenozoic. As a consequence, the older units have been exposed during several extended intervals. During some of these intervals there has been erosion, substantial dissolution of original components and some cementation of dissolution voids.

The time of deposition and, in some cases,

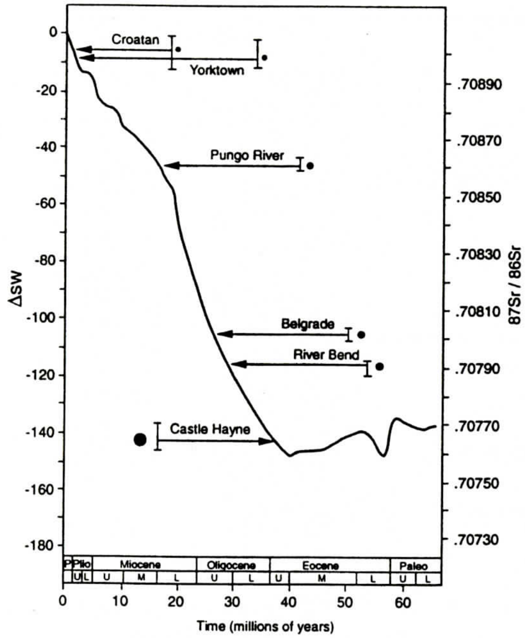

Figure 2. - The $^{87}Sr/^{86}Sr$ variation in Cenozoic seawater. The line is based on DSDP samples for Oligocene and younger time. Compiled from published results (DePaolo and Ingram, 1985; Koepnick and others, 1985; Hess and others, 1986; DePaolo, 1986; McKenzie and others, 1988; Miller and others, 1988; Hess and others, 1989; Hodell and others, 1989; Hodell and others, 1990; Capo and DePaolo, 1990; Miller and others, 1991; Hodell and others, 1991). Eocene and Paleocene values based on outcrop samples from Alabama and Mississippi (Denison and others, in press). The results of analyses for North Carolina units are shown for comparison. The vertical bars show the total range in strontium isotope values and the circles show the mean and error of all carbonate determinations from each unit. The time scale is from Berggren and others (1985).

identification of the stratigraphic units was not well understood when our study began (e.g., the River Bend and Belgrade Formation samples were initially identified as part of the Castle Hayne and Pungo River Formations). Our original goal was to use these isotope determinations to calibrate or define the change in the strontium isotope ratio of Cenozoic seawater. This proved impossible because of uncertainty in stratigraphic ages. We eventually relied entirely, as have most recent workers, on DSDP samples (Koepnick and others, 1985). Recent biostratigraphic work on microfaunas shows that the present North Carolina outcrop age assignments are in general to specific agreement with those reached using the strontium isotope method and therefore to DSDP age assignments.

COLLECTION OF DATA

The samples analyzed were collected by B. A. Bishop from sections he had measured during 1976-77. The sections presented here (figures 5-10) represent the exposures at the time they were measured. Even sections measured at nearly the same time (e.g., our section AP and locality 5 of Ward and others, 1978) show discrepancies in thickness and stratigraphic assignments that cannot be reconciled. Nearly all the isotope ratios were determined during 1977-78. A few analyses were made, particularly on limestone samples, during 1985-86, in order to develop a more complete evaluation.

Whole fossils as well as shell fragments were used in these analyses. Some of the fossils were chalky and porous whereas others were nearly modern in appearance. No differences were found in the results from diverse sample types, including both originally aragonite and calcite shell material. We believe this is an unusual circumstance. Our experience from other areas indicates that shell material that was originally low magnesium calcite retains original seawater values better than shells that were originally aragonite.

The limestone samples were crushed, washed and sieved in order to remove magnetic minerals by processing the crushed sample through a magnetic separator. This removes many iron bearing potassium minerals, such as glauconite, that could contribute radiogenic strontium.

The cited error on the individual measurements (Table 1) is our estimate of reproducibility at the 95% confidence level. The errors cited in Table II are the standard deviation of weighted individual measurements. The iso-

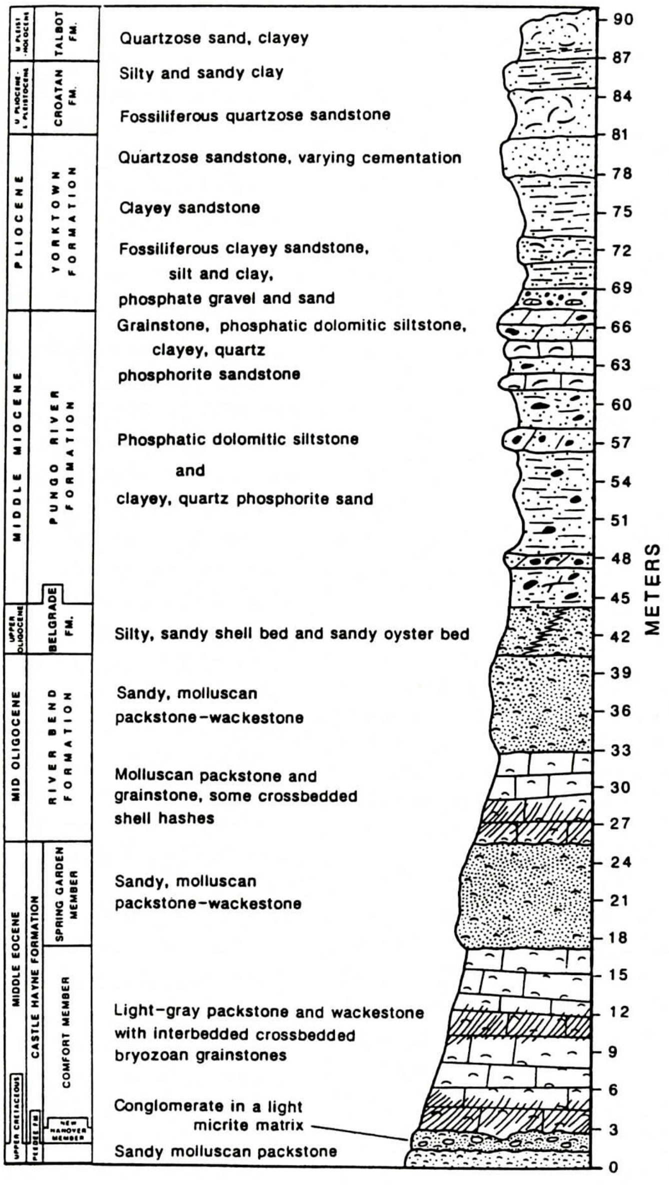

Figure 3. - Composite stratigraphic section of Cenozoic rocks in southeastern North Carolina. Paleocene stratigraphy and ages modified from Ward and others (1978). Neogene stratigraphy and ages adopted from Riggs and other (1982), Snyder and others (1982), and Hazel (1983).

tope measurements were made with the double focusing mass spectrometer described by Burke and others (1982). The measurements were made by comparing an unknown sample with a strontium standard (Burke and Hetherington, 1984). The standard (NBS/SRM 987) has an assumed $^{87}Sr/^{86}Sr = 0.71014$ and the results from the unknown are normalized to this value. The strontium was chemically separated from the samples using techniques described by Otto and others (1988).

We have calculated the strontium isotopic ratios as a difference from modern seawater. This technique, suggested by DePaolo and

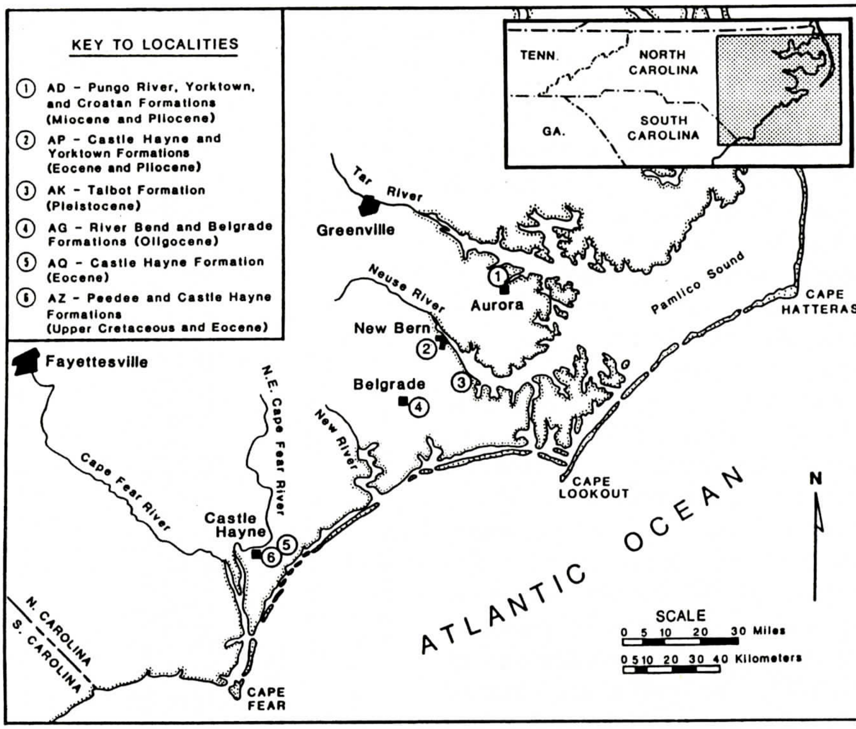

Figure 4. - Map showing the localities sampled for strontium isotope analysis.

Ingram (1985), eliminates mass spectrometer differences and therefore allows direct comparison of results from any laboratory. The calculation is simple:

$\Delta sw = (^{87}Sr/^{86}Sr \text{ unknown } ^{87}Sr/^{86}Sr \text{ seawater}) \times 10^5$

Thus a measured strontium isotope value of 0.70800±2 is Δ-107±2 [(0.70800 - 0.70907) x 10^5]. The Δsw of +106.7±0.3 for the assumed $^{87}Sr/^{86}Sr$ of NBS/SRM 987 (0.71014) compares well with measurement from other laboratories.

STRATIGRAPHIC FRAMEWORK

The Cretaceous and Cenozoic rocks on the North Carolina Coastal Plain comprise a generally seaward thickening wedge of clastic and carbonate rocks. Clastic sedimentary rocks were deposited on the crystalline basement of the Piedmont beginning in mid-Cretaceous time. The Cenozoic section has been the subject of considerable shifting in both the age and the stratigraphic assignment of strata from specific areas. We have chosen to adopt the stratigraphic-age revision of Ward and others (1978) for the Paleogene, and Riggs and others (1982) and Hazel (1983) for younger rocks. Zullo and Harris (1987) have provided a comprehensive review and analysis of correlations for Eocene through lower Miocene strata in North Carolina.

In the localities studied here, the Cretaceous is overlain in outcrop by the Castle Hayne Formation. Ward and others divide the Castle Hayne into three members (Figure 3). Hazel and others (1984) have reviewed the controversy concerning the age of the Castle Hayne and present evidence for a middle Eocene age. Zullo and Harris (1987) argue that the upper unit of the Castle Hayne is late Eocene.

The Castle Hayne is unconformably overlain by the River Bend Formation. It has a lower fossiliferous limestone grading vertically into a sandy, slightly phosphatic limestone. Ward and others (1978) cite evidence for mid-Oligocene age (late Vicksburgian) for the base, extending through late Oligocene.

Overlying the River Bend is the Belgrade

Formation. It consists of a sandy member (the Pollocksville) and a slightly calcareous, sand-shell member (the Haywood Landing) containing local thin clays. The Pollocksville Member is characterized by the giant oyster *Crassostrea gigantissima*. Ward and others (1983) assigned the Belgrade to the late Oligocene.

The Pungo River Formation contains phosphatic sands interbedded with dolomites (Snyder and others, 1982). The extensive foraminiferal assemblages in the Pungo River indicate a middle Miocene age of deposition (Katrosh and Snyder, 1982). The Pungo River is not seen in direct contact with the underlying Oligocene units. It is overlain by the Yorktown Formation in the Aurora area and this, in turn, by the Croatan Formation. The stratigraphy and paleontology have been studied extensively because of the excellent exposures developed during exploitation of phosphate deposits (Riggs and others, 1982; Scarborough and others, 1982). The sands of the Yorktown contain a foraminiferal assemblage indicating a mid-Pliocene age (Snyder and others, 1983). An unconformity separates the Yorktown and overlying Croatan (Riggs and other, 1982). The Croatan is considered to be latest Pliocene to Pleistocene in age (Hazel, 1983). The Pleistocene Talbot Formation unconformably overlies several of the older Cenozoic units. It is composed of poorly consolidated sands containing a rich megafauna.

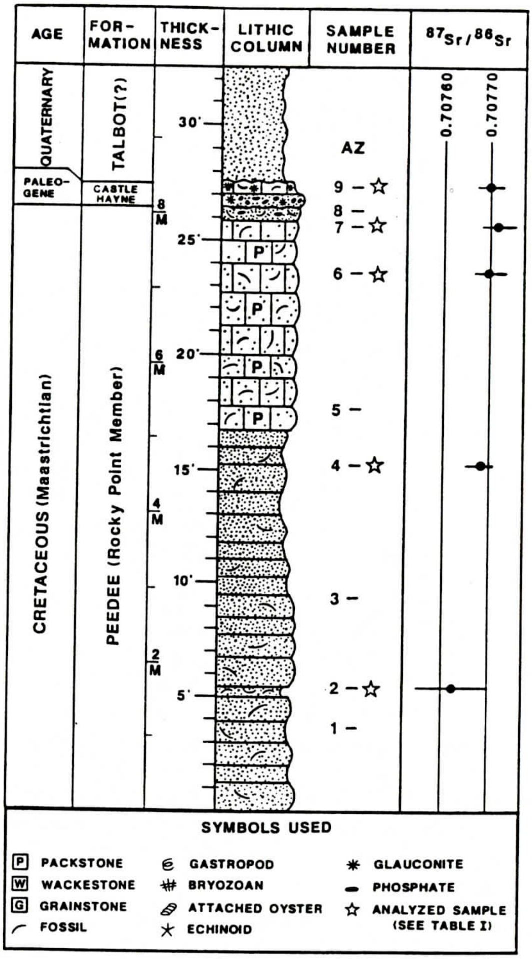

Figure 5. - Peedee (Rocky Point Member), Castle Hayne and Talbot (?) exposure (AZ) in the Martin-Marietta quarry, about 3.5 miles (5.6 km) northeast of Castle Hayne, New Hanover County. Zullo and Harris (1987) show a more detailed composite section of the Castle Hayne from this area. On this and following figures, the $^{87}Sr/^{86}Sr$ and error shown is for carbonate samples. In the case of multiple analyses from a single horizon, the value shown is the mean and standard deviation of carbonate analyses.

ISOTOPIC RESULTS

Samples were collected from six localities (Figure 4) on the Coastal Plain of which five are quarries. These localities expose units as young as Holocene and as old as Late Cretaceous. Four of the quarries contained more than one sampled unit.

A limited section of the Castle Hayne Formation was exposed along with more extensive strata of the Peedee Formation (Maastrichtian) in a quarry northeast of Castle Hayne (Section AZ, Figure 5). The Castle Hayne here consists of about 1' (0.3m) of sandy limestone over a thin phosphatic pebble conglomerate. The sandy limestone and sandstones of the Peedee contain abundant bivalve mollusks and mollusk molds. Peedee oyster shells from four separate intervals (Table I) yield a mean of 0.70769 ± 4 (Δsw-138). These results were also used by Koepnick and others (1985) for the definition of the Cretaceous curve of seawater

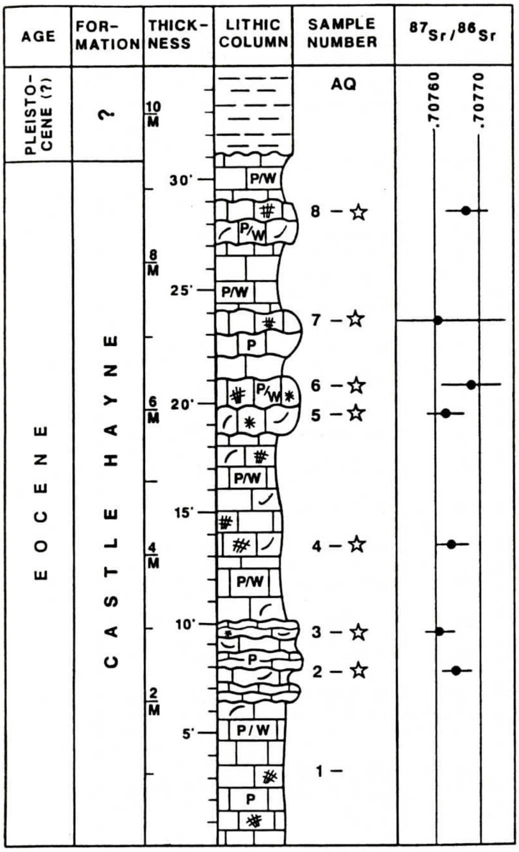

Figure 6. - Castle Hayne and Pleistocene (?) exposure (AQ) in the then Ideal Cement quarry about 4.5 miles (7 km) northeast of Castle Hayne, New Hanover County. Zullo and Harris (1987) provide a more detailed measured section.

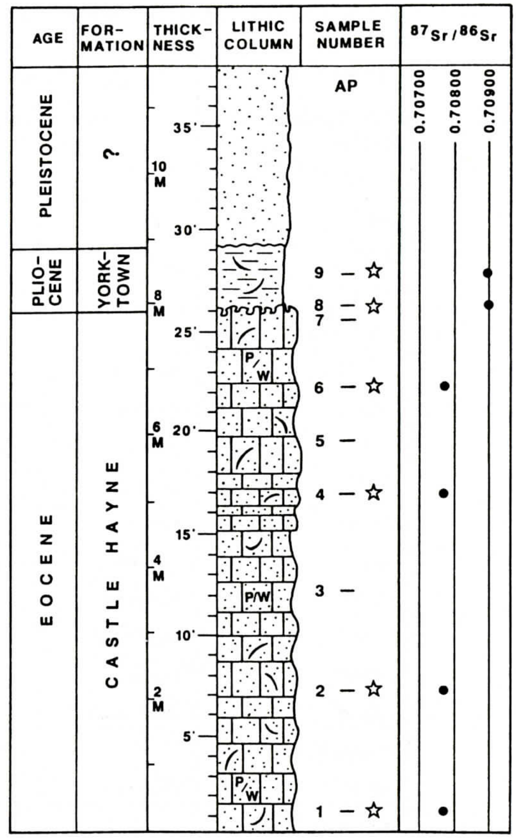

Figure 7. Castle Hayne, Yorktown and Pleistocene exposure (AP) in the Martin-Marietta quarry near Belgrade, Onslow County.

$^{87}Sr/^{86}Sr$. The nonmagnetic fraction of the Castle Hayne limestone yields a $^{87}Sr/^{86}Sr$ of 0.70770 ± 3 (Δsw-137), a ratio indistinguishable from other Castle Hayne values.

More substantial sections mapped as Castle Hayne Formation were collected from two additional localities (Sections AQ and AP). One of the localities (Section AQ, Figure 6) was chosen as the type section for the Castle Hayne by Ward and others (1978). Here, Hazel and others (1984) have shown the Comfort (middle) Member of the Castle Hayne to be middle Eocene, although there has been much disagreement over the exact age assignment. Our results on nine shell and limestone fractions (Table I) collected throughout the 30' (9m) exposure are consistent. The mean of these determinations (Table II) is 0.70764 ± 3 (Δsw-143). One analysis of a single shark tooth gave a 0.70789 ± 2 (Δsw-118) ratio, well outside of error of the nine carbonate determinations. The mean of Castle Hayne carbonate values (Δsw-143) is found in seawater during four periods (Figure 2) in the Paleogene. The results can, therefore, be used only to limit the possible age to four periods no younger than latest Eocene and no older than latest Paleocene.

Another extensive section of Castle Hayne, the Spring Garden (upper) Member, was collected in a quarry near New Bern (section AP, Figure 7). Here sandy limestones are overlain by about 3' (1 m) of silty, clayey sandstone of

Table 1. $^{87}Sr/^{86}Sr$ Analyses and strontium contents of North Carolina samples

Section Formation	Material Analyzed	Sr ppm	$^{87}Sr/^{86}Sr$	Δsw
Peedee				
AZ-02	oyster	952	0.70763±7	-144
AZ-04	oyster	903	0.70769±4	-138
AZ-06	oyster	ND	0.70770±3	-137
AZ-07	oyster	920	0.70772±5	-135
Castle Hayne				
AQ-02	pecten	670	0.70763±2	-144
AQ-02	limestone	395	0.70767±5	-140
AQ-03	pecten	740	0.70765±6	-142
AQ-03	limestone	346	0.70758±3	-149
AQ-04	pecten	560	0.70764±4	-143
AQ-05	limestone	375	0.70762±4	-145
AQ-06	limestone	360	0.70768±7	-139
AQ-07	limestone	322	0.70761±14	-146
AQ-08	pecten	540	0.70767±5	-140
AQ-08	shark tooth	790	0.70789±4	-118
Castle Hayne				
AZ-09	limestone	306	0.70770±3	-137
Castle Hayne				
AP-01	bivalve	ND	0.70768±8	-139
AP-02	bivalve	ND	0.70763±4	-144
AP-02	limestone	601	0.70758±6	-149
AP-04	limestone	470	0.70765±6	-142
AP-06	limestone	263	0.70766±2	-141
River Bend				
AG-01	barnacle	1190	0.70790±6	-114
AG-01	shark tooth	1500	0.70788±3	-119
AG-01	*Anomia sp.*	450	0.70790±3	-117
AG-01	*Anomia sp.*	330	0.70792±2	-115
AG-03	*Anomia sp.*	840	0.70791±2	-116
AG-04	barnacle	420	0.70790±4	-117
AG-05A	limestone	350	0.70789±5	-118
AG-05B	limestone	410	0.70792±3	-115
AG-05C	phosphate nodule	260	0.70808±2	-99
AG-05C	*Astrahelia sp.*	4120	0.70794±3	-113
Belgrade				
AG-05C	*Crassostrea sp.*	300	0.70800±3	-107

Section Formation	Material Analyzed	Sr	$^{87}Sr/^{86}Sr$	Δsw
AG-05C	*Crassostrea sp.*	580	0.70804±5	-103
AG-05C	oyster	480	0.70803±2	-104
Pungo River				
AD-01	bone and tooth	1200	0.70849±5	-58
AD-02	bone and tooth	870	0.70855±4	-52
AD-03	barnacle	690	0.70864±1	-43
AD-03	bone and tooth	1250	0.70858±8	-49
AD-03	barnacle	690	0.70864±1	-43
AD-03	bone and tooth	1250	0.70858±8	-49
AD-03	*Ecphora sp.*	1220	0.70862±11	-45
AD-04	barnacle	1380	0.70862±8	-45
AD-04	shark tooth	ND	0.70861±2	-46
AD-05	barnacle	2460	0.70861±5	-46
AD-05	bone and tooth	1030	0.70859±9	-48
Yorktown				
AD-08	bivalve	1472	0.70899±5	-8
AD-08	phosphatic frag	1042	0.70853±5	-54
AD-09	phosphatic frag	1192	0.70839±9	-68
AD-10	phosphatic frag	833	0.70844±3	-63
AD-11	phosphatic frag	998	0.70841±2	-66
AD-11	phosphatic frag	403	0.70896±1	-11
AD-12	echinoid	371	0.70895±4	-12
AD-13	echinoid	ND	0.70899±2	-8
AD-14	echinoid	425	0.70896±3	-11
AD-15	echinoid	506	0.70893±6	-14
AD-16	phosphate	1040	0.70879±8	-28
AD-16	phosphate	1040	0.70879±8	-28
AD-16	oyster	850	0.70893±3	-14
AD-17	phosphate	1021	0.70874±5	-33
AD-17	oysters	844	0.70901±3	-6
AD-18	barnacle	1767	0.70894±3	-13
AD-19	oyster	1627	0.70897±8	-10
AD-19	barnacle	2199	0.70900±5	-7
AD-19	phosphate +teeth	1037	0.70875±5	-32
AD-20	barnacle	2200	0.70901±3	-6
AD-20	bivalve	908	0.70903±3	-4
AD-20	phosphate	1145	0.70886±8	-21
AD-20	oyster	948	0.70899±7	-8
AD-21	oyster	1555	0.70894±7	-13

Section Formation	Material Analyzed	Sr	$^{87}Sr/^{86}Sr$	Δsw
AD-21	bivalve	836	0.70895±4	-12
AD-22	barnacle	1625	0.70900±6	-7
AD-23	barnacle	1651	0.70901±4	-6
AD-24	barnacle	1924	0.70895±2	-12
AD-25	barnacle	1600	0.70897±3	-10
AD-29	barnacle	1164	0.70899±3	-8
AD-30	barnacle	2533	0.70896±3	-11
AD-31	barnacle	1690	0.70900±2	-7
AD-32	barnacle	1830	0.70899±2	-8
AD-37	barnacle	2063	0.70900±7	-7
AD-38	barnacle	1882	0.70895±8	-12
AD-39	oyster	679	0.70896±6	-11
AD-39	barnacle	1623	0.70895±7	-12
AD-39	echinoid	637	0.70901±2	-6
AD-40	barnacle	2341	0.70901±5	-6
AD-41	barnacle	1575	0.70895±4	-12
AD-42	barnacle	1202	0.70895±4	-12
AD-43	echinoid	750	0.70894±3	-13
AD-43	barnacle	ND	0.70894±4	-13
AD-44	barnacle	1942	0.70899±4	-8
AD-45	barnacle	2140	0.70900±4	-7
AD-46	barnacle	3152	0.70899±4	-8
AD-46	oyster	710	0.70892•3	-15
AD-46	bivalve	1983	0.70897±5	-10
AD-46	bivalve	1905	0.70896±2	-11
AD-46	coral	1620	0.70902±2	-5
AD-47	bivalve	2420	0.70904±6	-3
AD-47	bivalve	2229	0.70901±5	-6
AD-47	bivalve	1774	0.70900±2	-7
AD-48	oyster	1756	0.70900±7	-7
AD-48	bivalve	1788	0.70897±5	-10
AP-08	bivalve	1758	0.70898±3	-9
AP-08	bivalve	1792	0.70897±2	-10
AP-08	bivalve	1667	0.70899±6	-8
AP-09	gastropod	1867	0.70894±6	-13
AP-09	gastropod	1314	0.70898±3	-9
AP-09	gastropod	1714	0.70904±5	-3
Croatan				
AD-49	oyster	1025	0.70901±3	-6

Section Formation	Material Analyzed	Sr	$^{87}Sr/^{86}Sr$	Δsw
AD-49	bivalve	2084	0.70894±4	-13
AD-49	bivalve	2084	0.70894±4	-13
AD-49	bivalve	1905	0.70898±3	-9
AD-49	bivalve	1842	0.70902±2	-5
AD-49	coral	1620	0.70907±6	0
AD-49	bivalve	1983	0.70898±4	-9
AD-50	coral	5680	0.70900±2	-7
AD-50	barnacle	2326	0.70906±5	-1
AD-50	oyster	1187	0.70903±2	-4
AD-50	bivalve	2057	0.70901±3	-6
AD-50	bivalve	1844	0.70900±5	-7
AD-51	oyster	1145	0.70898±3	-9
AD-51	gastropod	1152	0.70902±9	-5
AD-51	bivalve	2210	0.70900±7	-7
AD-52	bivalve	1760	0.70905±7	-2
AD-52	coral	2290	0.70909±4	+2
AD-52	bivalve	1900	0.70896±3	-11
AD-52	gastropod	1760	0.70902±2	-5
AD-52	oyster	1760	0.70902±2	-5
AD-53	coral	5990	0.70900±3	-7
AD-53	coral	2060	0.70899±3	-8
AD-53	oyster	880	0.70903±5	-4
AD-53	bivalve	1900	0.70899±3	-8
AD-53	bivalve	1790	0.70899±4	-8
AD-54	coral	1916	0.70902±3	-5
AD-54	bivalve	2171	0.70901±3	-6
AD-54	bivalve	ND	0.70899±2	-8
Talbot				
AK-01	*Mulina sp.*	1330	0.70907±5	0
AK-01	*Dinocardium sp.*	2080	0.70909±4	+2
AK-01	*Polinices sp.*	1180	0.70910±5	+3
AK-01	gastropods	1400	0.70909±1	+2
AK-01	*Rangia sp.*	1210	0.70908±3	+1
AK-01	*Ostrea sp.*	710	0.70909±3	+2
AK-01	*Anomia sp.*	670	0.70908±3	+1
AK-02A	microfossils	1120	0.70907±6	0
AK-02B	microfossils	2200	0.70910±2	+3
AK-02C	*Anomia sp.*	690	0.70906±3	-1
AK-02C	*Anomia sp.*	1130	0.70908±2	+1

Section Formation	Material Analyzed	Sr	$^{87}Sr/^{86}Sr$	Δsw
AK-03	gastropods	1200	0.70903±9	-4

Table 2. Summary of $^{87}Sr/^{86}Sr$ data from North Carolina Cenozoic-Cretaceous localities.

Formation	Section	Material Analyzed	Number of Analyses	Mean $^{87}Sr/^{86}Sr$	Δsw	Standard Deviation
Peedee	AZ	shells	4	0.70769	-138	4
Castle Hayne, Comfort Member	AQ	shells	4	0.70765	-142	2
		limestone	5	0.70763	-144	4
		all carbonates	9	0.70764	-143	3
		all samples	10	0.70766	-141	9
Castle Hayne	AZ	limestone	1	0.70770	-137	-
Castle Hayne, Garden Spring Member	AP	shells	2	0.70765	-142	3
		limestone	3	0.70763	-144	4
		all samples	5	0.70764	-143	4
River Bend	AG	shells	6	0.70791	-116	2
		limestone	2	0.70791	-116	2
		all carbonates	8	0.70791	-116	2
		phosphates	2	0.70798	-109	14
		all samples	10	0.70792	-115	6
Belgrade	AG	shells	3	0.70802	-105	2
Pungo River	AD	shells	5	0.70863	-44	1
		phosphates	6	0.70857	-50	4
		all samples	11	0.70859	-48	4
Yorktown	AP	bivalves	3	0.70899	-8	3
		gastropods	3	0.70898	-9	1
		all shells	6	0.70899	-8	2
Yorktown	AD	bivalves	9	0.70899	-8	1
		barnacles	21	0.70898	-9	1
		oysters	8	0.70896	-11	1
		echinoids	6	0.70897	-10	3
		corals	1	0.70902	-5	-
		phosphates	9	0.70862	-45	17
		all shells	45	0.70898	-9	1
		all samples	54	0.70893	-14	2
Croatan	AD	bivalves	19	0.70901	-6	1
		gastropods	2	0.70902	-5	1
		corals	10	0.70902	-5	1
		oysters	8	0.70900	-7	1
		barnacles	2	0.70903	-4	4
		all shells	41	0.70901	-6	1
Talbot	AK	shells	12	0.70908	+1	2

the Yorktown Formation. Two analyses of picked shells and three nonmagnetic fractions of sandy limestone (Table II) yield a mean of 0.70763 ± 4 (Δ-145) indistinguishable from the Comfort Member section at Castle Hayne, but not diagnostic as to age. Six shells from the overlying Yorktown yield a mean of 0.70899 ± 2 (Δ-8), identical to the value for Yorktown fossils from other localities. The results indicate a late Pliocene or early Pleistocene age based on comparison with the DSDP results of Capo and DePaolo (1990) and Hodell and others (1990). This is slightly younger than the Yorktown age assignment, based on paleontological studies at the Aurora mine (Section AD).

A quarry near Belgrade (Figure 8) exposes sands, clays, and sandy limestones of the River Bend Formation (Section AG). Ward and others (1978) assign a mid to late Oligocene age to these rocks. The upper unconformable surface is extensively bored and covered by a thin layer of dark gray, pebbly, phosphatic sand considered to be part of the Belgrade Formation by Ward and others (1978). Numerous huge oysters, *Crassostrea gigantissima*, are found attached to the upper bored surface. Eight shell and limestone and two phosphatic samples were analyzed from the River Bend section. The carbonate samples (Table II) yield a mean of 0.70791 ± 2 (Δsw-116). The phosphatic material gave erratic results; a shark tooth is identical within error of the carbonate. A phosphatic nodule was significantly higher (Table I). Analyses of the two Belgrade *Crassostrea* shells and another oyster that grew on the eroded and burrowed River Bend surface give a mean of 0.70802 ± 2 (Δsw-105), slightly higher than the older limestones to which they are attached.

The results are consistent and in agreement with the age range based on fossil evidence. A value of 0.70791 (Δsw-116) is equivalent to mid-Oligocene (30 ± 1 Ma) (Hess and others,1986; Hess and others, 1989; Miller and others, 1988; DePaolo and Ingram, 1985). The Belgrade oysters have ratios that indicate they are nearly 3 Ma younger than the limestone to

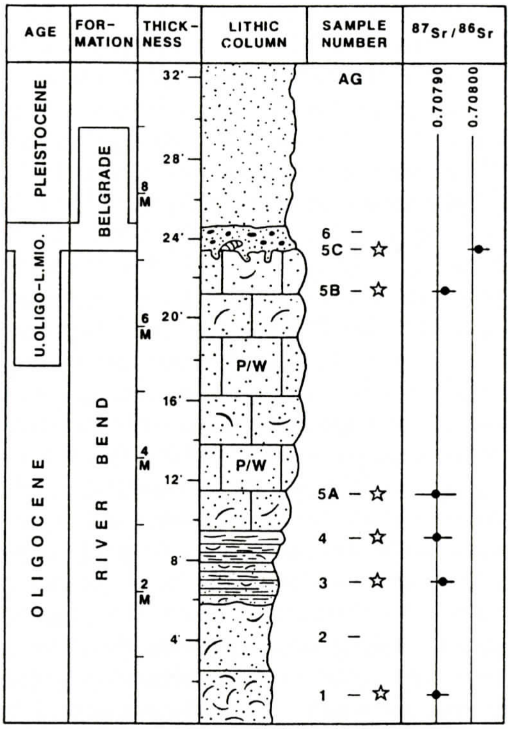

Figure 8. - River Bend, Belgrade and Pleistocene exposure (AG) in the Martin-Marietta quarry near Belgrade, Onslow County.

which they were attached. The isotope data indicate a late Oligocene age (27 ± 1 Ma) for the Belgrade in this quarry, in agreement with lthe assignment by Ward and others (1983).

The Pungo River Formation was sampled from one quarry (Section AD) in the Aurora area where it is overlain by an extensive exposure of Yorktown and Croatan Formations (Figure 9). Eleven samples were analyzed, five shells and six phosphatic samples. Table II shows that the mean of all samples is 0.70859 ± 4 (Δsw-48). Shells give more consistent results with a mean of 0.70863 ± 1 (Δsw-44). A comparison with the seawater line indicates an age near the early-middle Miocene boundary ([16.0 ± 0.5 Ma] DePaolo, 1986; Hess and others, 1986; Hodell and others, 1988; Hodell and others, 1991). Riggs and others (1985) cite published and unpublished paleontologic data indicating deposition of the Pungo River began about 19 Ma and continued cyclically for about

6 million years, the youngest Pungo River being about 13 Ma. Our results are from the uppermost Pungo River in the Aurora area.

The Yorktown Formation overlies the Pungo River in the Aurora (AD) quarry (Figure 9). This, in turn, is unconformably overlain by the Croatan Formation. The stratigraphy and paleontology in this quarry and immediate area have been studied extensively because of the phosphate deposits in the Pungo River and Yorktown (see Riggs and others, 1982; Scarborough and others, 1982; Abbott and Ernisse, 1983). A total of 51 strontium isotope ratios were determined from material collected in the 44' of exposed Yorktown (Table I). With the exception of the phosphatic material, the data are consistent. We do not attach any significance to the small-scale isotope variations that do not strictly follow a systematic increase in ratio with stratigraphic position. The variations are ascribed to minor diagenetic alteration. In order for these small-scale variations to be considered meaningful, the variation should be documented by multiple analyses from the same interval and should be recognized at the same stratigraphic horizon at other geologic locations. The mean of all carbonate fractions is 0.70898 ± 1 (Δsw-9), the phosphatic material 0.70862 ± 17 (Δsw-45). Most of the phosphatic material was collected within 10' (3 m) of the Pungo River contact. The results suggest the Pungo River may be the source for some of the Yorktown phosphate since the $^{87}Sr/^{86}Sr$ values are identical within error of phosphatic values from the Pungo River. Table II shows that all groups of fossils had indistinguishable values. The Yorktown planktonic foraminifera were used by Snyder and others (1983), to assign ages between just below the base of N19 to middle N20. Capo and DePaolo (1990) and Hodell and others (1990) show seawater strontium values of Δsw-9 in the latest Pliocene and earliest Pleistocene (~1.4 to 2.1 Ma), indicating an age of N21 or N22.

About 20' (6 m) of Croatan sand and clay overlies the Yorktown. Hazel (1983) has reviewed data bearing on the age and correlation of the Yorktown-Croatan in the Aurora area. He assigns the lower Croatan, the only part we sampled (Figure 9), to the latest Pliocene. The Croatan is overlain by a thin veneer of Quaternary sand. Forty-one strontium isotope measurements (Table I) were made on a variety of fossil material collected from approximately 10' (3m) of lower Croatan (Figure 9). The mean of these determinations is 0.70901 ± 1 (Δsw-6). All the fossil groups are within error of this value (Table II). Seawater strontium shows a Δsw-6 between 0.8 and 1.2 Ma ago (Capo and DePaolo, 1990; Hodell and others, 1990). This equivalent isotope age is mid-Pleistocene based on the mean of many measurements and, therefore, slightly younger than the assigned paleontological age.

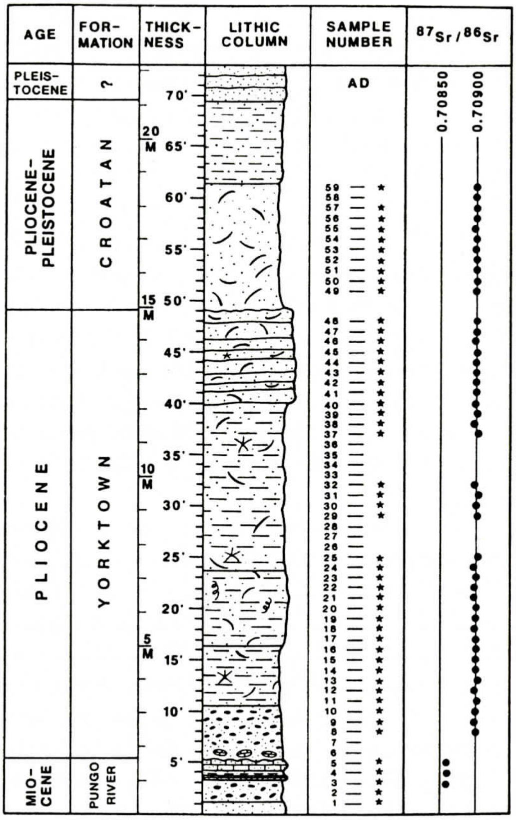

Figure 9. - Pungo River, Yorktown, Croatan and younger sand exposure (AD), the Texas Gulf phosphate mine about 7 miles (11 km) north of Aurora, Beaufort County.

The Pleistocene Talbot Formation (Section

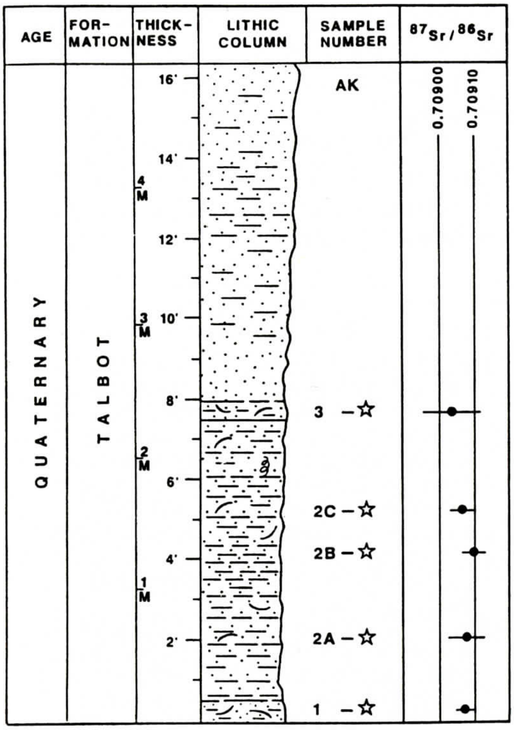

Figure 10. Talbert exposure (AK) along the Neuse River (Flanner Beach) about 11 miles (18 km) south of New Bern, Craven County.

AK, Figure 10) contains a diverse megafauna. Twelve determinations (Table I) were made on shells from the Talbot. The resulting mean of 0.70908 ± 2 (Δsw+1) is within error of modern seawater (Table II). All the fossil groups were within error of this value. Our data would, therefore, indicate a young age for the Talbot, either Holocene or later Pleistocene.

DISCUSSION AND CONCLUSIONS

The extensive analyses done on the samples from North Carolina show there is a great consistency in the strontium isotope measurements on a variety of fossil and limestone samples. No difference is found in the results from various fossil groups and these, in turn, are within error of the calcite fraction of the limestones examined from the same stratigraphic section. Phosphatic material did not yield consistent results for reasons that are not clear to us at this time. Other workers have reported erratic results from phosphatic material. Staudigel and others (1985) found that fish teeth showed considerably more isotopic scatter (their Fig. 1) than published results from carbonate. Nelson and others (1986) found dramatic differences in the $^{87}Sr/^{86}Sr$ of modern and prehistoric seal bones which they ascribed to diagenetic alteration. Thirteen of our nineteen analyses of phosphatic material were outside error of our estimate of the value of contemporaneous seawater based on carbonate samples. Results were both above and below contemporaneous seawater. An explanation can be made for the results (some phosphate is almost certainly recycled from underlying formations), but results from each formation require a different, or somewhat different explanation. We cannot give a general explanation for the erratic results.

We believe that the data demonstrate the usefulness of strontium isotopes in stratigraphic studies. The material analyzed was, for the most part, long-ranging, nondiagnostic fossil shells and unpromising-looking sandy, glauconitic, limestones, some with extensive moldic porosity. Historically our best results have come from imporous limestones with a low terrigenous content, and these North Carolina samples did not generally qualify on either count. Nonetheless, the results from the nonmagnetic portion of the limestones (effectively removing the glauconite) were indistinguishable from high quality shell material.

The path of seawater strontium during the Phanerozoic and, more particularly, the Cenozoic, includes intervals of rapid change as well as intervals of little or ambiguous change. Because of this limiting factor, we were able to place rather broad limits on the age of the Castle Hayne Formation but could narrowly define the age of the younger rock units, even though the strontium isotope data from the units are of identical quality. The Castle Hayne could only be constrained to four possible periods, no younger than late Eocene and no older than latest Paleocene. Our results indicate that the River Bend Formation, where sampled, represents a narrow time interval during mid-Oligocene time rather than the extended period of deposition suggested by Ward and others (1978). Our limited data from the Belgrade Formation support the late Oligocene age of deposition, only about 3 million years younger than the River Bend. Analysis of Yorktown and Croatan results enabled us to define the age of these units precisely and to suggest slightly younger ages than those based on detailed paleontologic studies.

The ultimate utility of strontium isotopes in stratigraphy is limited by the slope of the seawater strontium curve and diagenesis. Diagenesis has not had a perceivable effect on strontium isotopes in these North Carolina Coastal Plain sediments. This is probably due to very shallow burial, a young to very young age and isolation from sources of foreign strontium. Examination of the data points of Burke and others (1982) that defined the strontium isotope variation in Phanerozoic seawater shows very clearly the increasing data scatter with increasing age. Paleozoic samples have generally undergone much deeper burial and a more complex thermal history than, for example, Neogene samples. Even the results from DSDP samples show considerable small scale scatter (see the comparisons of data sets by Koepnick and others, 1988, and Miller and others, 1988). The scatter is due to analytical uncertainty in the isotope measurement, diagenetic alteration of the original seawater ratio and stratigraphic misassignment. The analysis of several samples from a single horizon can lower the analytical uncertainty. The consistency of multiple analyses is a criterion (the best in our opinion) for the retention of the original seawater ratio when used with petrographic evaluation. Of the three causes of data scatter, stratigraphic misassignment is the least amenable to quantitative error reduction.

ACKNOWLEDGMENTS

We had the help of a number of our former workers over the years. J. B. Otto and W. K. Blank did the chemical separations and supervised the determination of the strontium content. W. H. Burke helped in choosing samples and in the analysis of the isotopic results. D. S. Jones and W. B. Harris provided suggestions that lead to substantial improvement of the manuscript. Paul D. Fullagar reviewed an earlier version of the manuscript and offered advice and encouragement.

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SOUTHEASTERN GEOLOGY
V. 33, No 2, March 1993, p. 71-79

HYDROTHERMAL ALTERATION AND MINERALIZATION AT THE JACKSON DOME VOLCANIC COMPLEX, MISSISSIPPI

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ABSTRACT

The Jackson Dome, which lies directly beneath the city of Jackson, Mississippi, is cored by Late Cretaceous alkalic intrusive and volcanic igneous rocks that have domed the adjacent and overlying Cretaceous and younger Coastal Plain formations. Igneous rocks have undergone extensive hydrothermal alteration and locally contain hydrothermal veinlets containing sphalerite, galena, chalcopyrite, pyrite, hematite, and varying amounts of associated dolomite, calcite, adularia, albite, and quartz. Geologic relationships, alteration and hydrothermal veinlet mineralogy, trace element geochemistry, and isotopic data indicate that basin brines were the altering fluids and the likely source of metals. Therefore, the Jackson Dome appears to represent a near-ideal environment for the formation of metallic sulfide mineralization, where basin brines are heated by the cooling igneous rocks, and deposit their metals as magmatic sources of reduced sulfur are encountered. If so, then this dome is the first documented occurrence of metallic-sulfide mineralization in the Gulf Coast with an igneous heat source for hydrothermal fluids.

INTRODUCTION

Metalliferous hypersaline formation waters in general, and those from the Mississippi Salt Dome Basin in particular, are widely regarded as modern analogs to the solutions that formed Mississippi Valley-Type (MVT) sediment-hosted Pb-Zn deposits that occur along margins of major sedimentary basins (e.g., Sverjensky, 1984). Additionally, basin brines are interpreted to have played major roles in forming Pb-Zn+Ag mineralization (Kyle and Price, 1986) and Sr deposits (Saunders and others, 1988) in Gulf Coast salt dome caprocks within basins. Na-Ca-Ca oil field brines from Upper Jurassic and Lower Cretaceous Formations in central Mississippi, which contain up to several hundred ppm Pb+Zn (Carpenter and others, 1974; Kharaka and others, 1987; Saunders and Swann, 1990), are some of the most metal-enriched formation waters yet documented. The intrusion of the Jackson Dome alkalic igneous complex through these formations during the Late Cretaceous set up a possible mineralizing system. This study, which presents evidence from existing hydrocarbon exploration wells that penetrate only the top of the complex, indicates that igneous rocks have undergone extensive hydrothermal alteration and local metal enrichments. Geologic relationships, alteration and base-metal sulfide mineralogy, trace-element geochemistry, and light-stable isotopic analyses indicate that basin brines were responsible for hydrothermal alteration and were the probable metal source.

GEOLOGIC SETTING

The Jackson Dome lies directly beneath the city of Jackson, in west-central Mississippi, and is located within the Mississippi Salt Dome Basin (Figure 1). The basin contains Mesozoic and Cenozoic units up to 6000 m thick and hosts approximately 50 salt domes (Halbouty, 1979). The Jackson Dome is roughly circular (Figure 1) based on drilling and gravity data, and has a diameter of approximately 40 km. Structural relief of approximately 1000 m is apparent for the base of the Cretaceous section in the dome. The Jackson Dome produces regional magnetic and gravity anomalies and is cored by a Late Cretaceous hypabyssal and

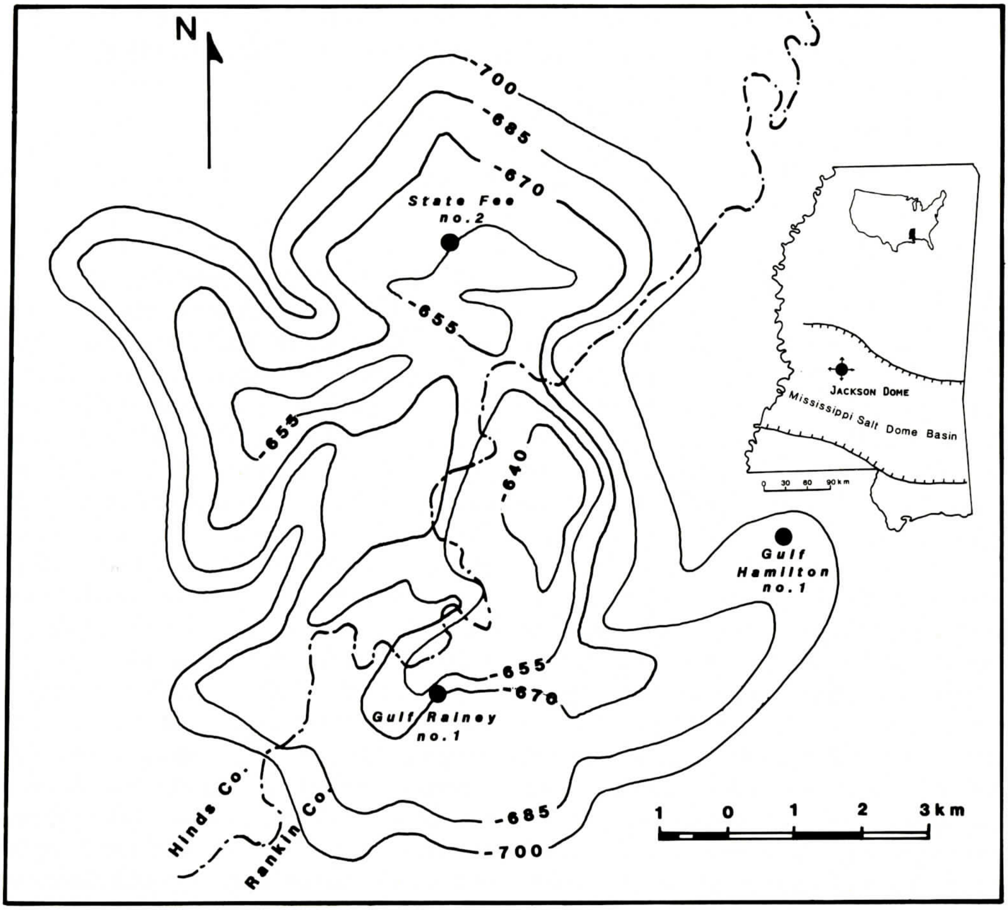

Figure 1. Structure contour map drawn on the base of the Paleocene Clayton Formation (contours in m relative to MSL) at the Jackson Dome showing the location of the wells included in this study. Modified from Monroe and Toler (1937).

intrusive alkalic igneous complex. The shallowest igneous rocks are apparently sills or laccoliths that lie at a depth of at least 900 m. Of the 250 hydrocarbon exploration drilled into the dome, apparently only 1 well penetrated the main body of the intrusion (Gulf Rainey-1, Figure 1).

Volcanic debris is abundant in the Upper Cretaceous Tuscaloosa Group sediments in the area (Monroe, 1933; Harrelson, 1981; and McKibben, 1988) suggesting that the complex vented at that time. By the end of the Cretaceous, the volcanic complex had been eroded below sea level and supported an extensive reef system (McKibben, 1988). This Upper Cretaceous reef complex was buried by Tertiary sediments and eventually became the host rock for significant natural gas accumulations. K-Ar age determinations from igneous rocks near the top of the dome are consistent with stratigraphic evidence for the age of volcanism. Whole rock and biotite age dates range from 69-79 Ma (Saunders and Harrelson, 1992), and probably represent the last stages of magmatism.

The Jackson Dome is one of many Upper Cretaceous alkalic igneous bodies encountered by drilling in the northern Gulf Coast region (Moody, 1949; Kidwell, 1951). Rock textures vary from porphyritic (probably hypabyssal intrusions as opposed to lavas) to equigranular coarsely crystalline. Saunders and Harrelson

(1992) grouped the igneous/volcanic rocks of the Jackson Dome into 2 general types: 1) phonolites, which usually contain phenocrysts of sanidine and locally nepheline; and 2) mafic alkalic rocks consisting of nephelinites, ijolites, and jacupirangite. The latter rocks are characterized by their relative abundances of nepheline, clinopyroxene (aegerine or titanaugite), alkali feldspar, biotite, and magnetite. Whole-rock chemistry, age and mineralogy of some of the rock types are very similar to the Upper Cretaceous Magnet Cove carbonatite complex in central Arkansas (U.S.A.) leading Saunders and Harrelson (1992) to suggest that the Jackson Dome itself may be a carbonatite complex.

HYDROTHERMAL ALTERATION AND MINERALIZATION

Monroe and Toler (1937) first suggested that igneous rocks of the Jackson Dome had undergone hydrothermal alteration, although Harrelson (1981) interpreted this alteration to be the result of subaerial weathering. The present study, which is based on petrography and X-ray diffraction analysis of approximately 200 samples from 3 wells, supports the earlier interpretation. Calcite and dolomite are the most abundant alteration minerals. In some samples, carbonate alteration is pervasive and the original rock type can only be determined by the shapes of outlines of former phenocrysts. Chlorite, clay (smectite), and sericite are also common alteration products of feldspars, feldspathoids, ferromagnesium minerals, and finely-crystalline groundmass. In addition, analcite locally replaces the groundmass, alkali feldspars, and nepheline. Secondary anatase generally comprises 1-2% of altered rocks, and typically occurs along original grain boundaries of altered sphene, titaniferrous magnetite, titanaugite, and Ti-rich andradite garnet. In addition, pyrite and hematite locally replace magnetite. Of the primary igneous minerals, biotite and apatite are the only phases largely unaffected by alteration, although dolomite locally replaces biotite along the basal cleavage plane. Many of the most altered samples contain veinlets up to 2 cm wide of some of the common alteration minerals along with some other hydrothermal phases. Dolomite and calcite are the most common minerals in the hydrothermal veinlets, followed by lesser amounts of albite, quartz, adularia (hydrothermal K-feldspar), siderite, and specular hematite. Pyrite is generally present in the veinlets and in the altered rock adjacent to the veinlets. In addition, epidote locally occurs in veinlets as aggregates of radiating fibrous crystals in a carbonate matrix.

Relatively unaltered alkalic rocks from the Jackson Dome have SiO_2 contents ranging from 27 to 48 wt.%, contain up to 14.5% Na_2O+K_2O, with Na_2O typically greater than K_2O, are enriched in titanium (TiO_2 ranging from 1 to 9%), and are nepheline normative (Saunders and Harrelson, 1992). Eleven samples of altered rocks from one well from the Jackson Dome were analyzed for major and minor elements (Table 1). Altered samples have SiO_2, TiO_2, Al_2O_3, and total Fe contents similar to unaltered samples. Primary differences appear to be: 1) CaO is generally higher in altered rocks; 2) Combined Na_2O+K_2O content is lower, with K_2O>Na_2O in altered rocks; 3) MgO may be depleted in the altered rock, although there is significant overlap in MgO contents of the altered vs. unaltered rocks; 4) Loss on ignition (LOI) values, generally reflecting H_2O and CO_2, are higher in the altered rocks. In addition, Ba is locally enriched in the altered rocks, exceeding 10,000 ppm in two samples (Table 1). No Ba-bearing phases have been identified in thin section or from X-ray diffraction analysis, but Harned (1960) observed barite replacing alkali feldspar in a sample from the Jackson Dome. In general, the chemical data are consistent with the observed replacement of feldspars and feldspathoids with calcite, clay, sericite, and chlorite replacement of clinopyroxene, and with biotite remaining stable.

Pyrite and base-metal sulfide minerals are locally present in veinlets and disseminations in pervasively altered igneous rocks. Pyrite

Table 1. Whole rock chemical analysis — Gulf Raney No. 1 well.

Sample	1	2	3	4	5	6	7	8	9	10	11
Depth (m)	911	919	924	926	931	933	933.5	936	1016	1031	1081
Major Oxides (wt.%)											
SiO_2	31.40	24.79	32.61	32.00	29.46	43.54	44.89	42.02	46.38	48.63	31.22
TiO_2	6.87	9.57	6.66	6.38	6.92	4.39	4.41	4.09	3.02	2.52	12.13
Al_2O_3	13.03	8.36	10.94	12.63	10.63	18.14	6.58	9.99	17.04	17.60	12.68
Fe_2O_3 (total iron)	16.41	19.13	15.55	16.18	12.37	10.08	11.67	16.54	10.27	7.59	12.24
MgO	2.60	3.25	2.83	2.99	3.03	1.61	2.08	2.28	2.12	2.14	3.59
CaO	10.33	14.54	12.17	11.51	13.13	4.69	13.11	5.94	1.90	1.82	7.26
MnO	0.18	0.23	0.21	0.25	0.15	0.15	0.34	0.60	0.33	0.22	0.23
Na_2O	0.87	0.84	1.06	1.98	0.97	1.4	0.56	0.85	1.6	1.35	1.16
K_2O	2.75	1.45	1.90	2.04	1.53	5.91	1.74	2.96	4.16	5.58	1.74
P_2O_5	0.63	1.89	1.23	0.86	1.21	0.65	0.56	1.53	0.56	0.36	4.54
LOI	14.4	15.5	14.4	10.6	16.9	8.9	14.1	12.8	12.2	11.7	12.8
Minor Elements (ppm)											
Ba	1585	857	1089	13780	21880	1751	472	908	1362	1411	797
Sr	1250	658	863	1061	688	1600	416	808	1054	1221	872
La	30	93	53	51	51	50	108	148	95	116	95
Zr	436	303	386	605	401	412	241	559	630	488	735
Y	23	32	32	31	25	23	34	61	37	30	46
Nb	37	29	29	67	20	32	74	151	227	103	120
Co	30	41	38	52	36	24	29	29	23	15	51
V	237	253	219	208	141	193	160	268	88	112	205
SUM (%)	99.9	99.8	99.9	100.0	100.2	100.1	100.0	99.9	100.1	99.9	99.9

Note: Values for Co and V represent acid extract analyses. Analyses conducted by Acme Analytical Laboratories, Vancouver, B.C.

locally comprises up to 5% of altered rocks and commonly appears to have replaced magnetite. Chalcopyrite, bornite, and chalcocite occur locally as complex intergrowths associated with pyrite in a sample of altered ijolite. Coarsely crystalline chalcopyrite and sphalerite have been observed as the primary metallic minerals in a 4 mm-wide dolomite veinlet in altered phonolite that contains lesser amounts of pyrite and galena. Sphalerite in this veinlet is locally color-zoned, with purple and yellow growth bands alternating with the typical light-green color. In addition, sphalerite, chalcopyrite, galena, and pyrite are present in a 2mm-wide veinlet composed primarily of specular hematite and dolomite.

TRACE-ELEMENT GEOCHEMISTRY

Trace-element geochemical analyses were conducted on 60 samples of cuttings (from intervals with significant amounts of altered igneous rock) and small core samples from two wells. The samples were analyzed by ICP and graphite-furnace AA procedures for Ag, As, Au, Cu, Hg, Mo, Pb, Sb, Zn, Cd, and Ga. The chemical data indicate local metal enrichments, with maximum values of 3400 ppm Zn, 5.6 ppm Ag, 503 ppb Au, 133 ppm Pb, 477 ppm Cu, and 251 ppm As. Statistical analysis shows that zinc is strongly associated with cadmium (correlation coefficient=0.98), silver (0.76), and to a lesser extent lead (0.49) at the 95% confidence level. Lead is more closely associated with antimony (0.71) and arsenic (0.60). Gold and copper do not correlate strongly with any of the other elements. Whereas none of the reported values represent "ore-grade" levels of any metals, these data in combination with petrographic evidence suggest that the hydrothermal fluids that altered the igneous rocks probably contained base and possibly precious metals.

ISOTOPIC ANALYSES

Samples of crosscutting veinlets were separated from the rock matrix for isotopic analyses. The major mineralogy of the samples was established using a combination of X-ray diffraction and transmitted- and reflected-light microscopy. Carbonates were the most abundant and common phases in the veinlets and were separated for carbon and oxygen isotopic analyses. In most samples, either dolomite or calcite was the predominant carbonate phase, but locally either the other carbonate or minor amounts of siderite were also present as subordinate phases (Table 2). Hence, carbon and oxygen isotopic data reported (Table 2) represents in some cases the composite contribution of the major and minor carbonate phases. Similarly, minor amounts of sphalerite and other sulfide minerals may have contributed a small portion of the sulfur as reported from pyrite.

Carbon and Oxygen

The $\delta^{18}O$ values for the carbonates vary rather widely (Table 2), from +10.9 to +24.9‰ relative to SMOW ($\delta^{18}O_{SMOW} = 1.03\delta^{18}O_{PDB} + 30.86$), whereas $\delta^{13}C$ values have a more restricted range of +0.7 to -6.2‰ (PDB). A plot of $\delta^{18}O$ vs $\delta^{13}C$ for the samples analyzed (Figure 2) indicate the samples appear to fall into 2 distinct groups: Group 1, consisting primarily of dolomite and $\delta^{18}O$ values between +10.9 and +16.3‰ and $\delta^{13}C$ values between -0.6 and -3.6‰; and Group 2, composed primarily of calcite with $\delta^{18}O$ values ranging from +20.5 to +24.9‰ and $\delta^{13}C$ values of +0.7 to -6.2‰.

Homogenization temperatures of over 125 small (<5• µm) 2-phase (liquid>vapor) primary fluid inclusions in quartz and dolomite were determined for several veinlet samples containing Group 1 carbonates, adularia, and albite, and they ranged from 230° to 250°C, with a mode at 240°C. Optical clarity was generally too poor for measuring freezing point depressions except in some very late-stage (clear) dolomite growth bands coating earlier cloudy dolomite. Ice melting temperatures ranged form -5° to -7°C, corresponding to ~8-10.5 wt.% NaCl equivalent, or a solution with total dissolved sold (TDS) content of approximately 85,000 to 110,000 mg/l.

The $\delta^{18}O$ composition of the fluid from which Group 1 samples precipitated can be estimated using the fluid inclusion homogenization temperatures and the dolomite-water isotopic fractionation curve (compiled in Friedman and O'Neil, 1977). Using a temperature of 240°C, the $\delta^{18}O$ composition of the fluid ranged from approximately 0 to +5‰ for Group 1 carbonates. This range is virtually identical to the $\delta^{18}O$ composition of present day Mississippi oil field brines from Cretaceous formations, which range from +0.3 to 5.7‰ (Kharaka and others, 1987). Formation waters in Jurassic units are isotopically heavier, having $\delta^{18}O$ values of +5.1 to +7.3‰, whereas present day meteoric waters in central Missis-

Table 2. Isotopic data.

SAMPLE	WELL	DEPTH (m)	MINERAL	ASSOC. MINERALS	$\delta^{18}O$	$\delta^{13}C$	$\delta^{34}S$
1	GR-1	923	cc	alb, ser,	+23.0	-3.6	
2	GR-1	924	sid+cc	qtz	+22.9	-2.5	
3	GR-1	935	cc	qtz, ad, py	+23.9	-2.6	
				py			-1.6
4	GR-1	955	dol	qtz, alb, sid	+16.3	-3.0	
				py			-2.3
5	GR-1	999	dol	alb, py	+13.3	-2.9	
6	GR-1	999	dol	alb, qtz	+14.2	-2.8	
			py				-1.6
7	GR-1	1060	dol	alb, ep	+10.9	-3.6	
8	GR-1	1096	dol	qtz	+20.5	+0.7	
9	GR-1	1097	cc	qtz, cc, ep	+15.9	-0.6	
10	GR-1	1098	dol	cc, qtz, ep	+12.0	-1.2	
11	SF-2	961	cc	-	+24.9	-6.2	
12	GR-1	926	py	an, ser			-0.6
13	SF-2	938	py	-			+2.3

Abbreviations. Wells: SF-2, State of Mississippi Fee no. 2; GR-1, Gulf- Rainey no. 1. Minerals: alb, albite; cc, calcite; dol, dolomite; sid, siderite; ser, sericite; py, pyrite; qtz, quartz; ep, epidote; an, analcite.
Isotopic analyses conducted by Krueger Enterprises, Inc., Cambridge, Massachusetts

sippi have $\delta^{18}O$ values of -3.2 to -4.7‰ (Kharaka and others, 1987).

Veinlets that contain Group 2 carbonates are generally thinner, and commonly lack associated adularia, albite, pyrite, and contain no 2-phase fluid inclusions. The difference between the isotopic signature of the carbonates probably reflects a lower temperature of formation for the Group 2 samples.

The calculated $\delta^{18}O$ values for the fluids that precipitated the hydrothermal dolomite are permissive evidence that fluids similar to present day formation waters in the Cretaceous section precipitated the hydrothermal veinlets, and by inference, caused the hydrothermal alteration at the Jackson Dome. However, other possibilities cannot be ruled out, although they may be less likely. For example, the calculated $\delta^{18}O$ range could also be the result of meteoric water that underwent extensive isotopic exchange with the igneous rocks. Alkalic silicate rocks associated with carbonatite complexes typically have $\delta^{18}O$ values in the range of +6 to +19‰, whereas the carbonatites themselves range from +6 to +25‰, with most values falling between +6 to +10 per mil (Deines, 1989). In addition, with no constraints on the δD value of the hydrothermal fluid, the possibility that the calculated $\delta^{18}O$ values represent a mixture of primary "magmatic" ($\delta^{18}O$=~+6

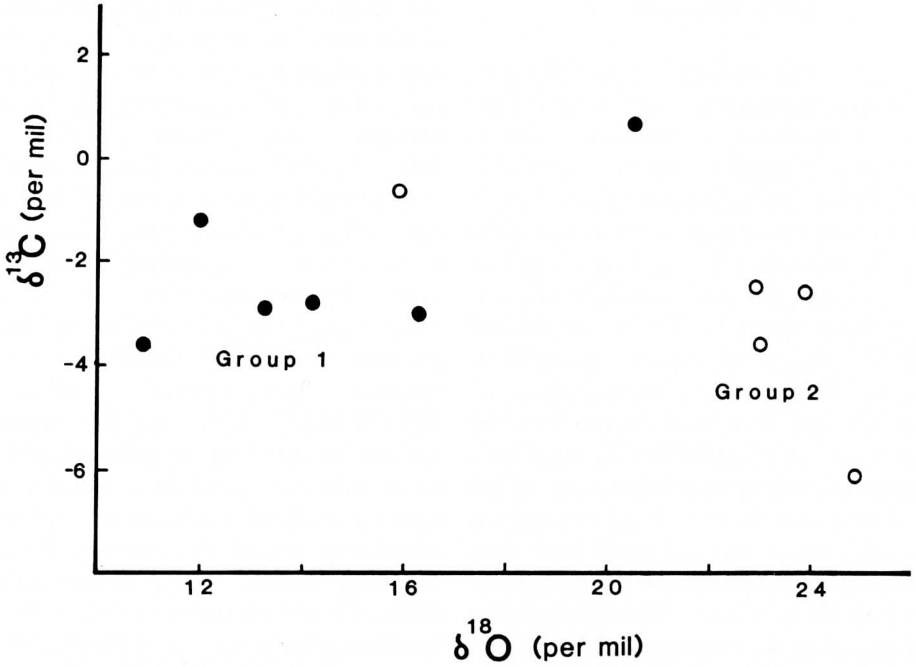

Figure 2. Plot of $\delta^{13}C$ versus $\delta^{18}O$ for dolomite (dots) and calcite (open circles) from hydrothermal veinlets.

to +10‰) and meteoric water cannot be excluded. In fact, the relatively low salinity (by Mississippi oil field brine standards) fluid inclusions in the late clear dolomite might support brine-groundwater mixing concept. However, because the Late Cretaceous igneous rocks of the Jackson Dome were intruded through the Lower Cretaceous formations presently containing brines, these waters would appear to be an important component of the isotopically-heavy fluids that precipitated the hydrothermal dolomite.

Sulfur

The $\delta^{34}S$ values for hydrothermal pyrite range from -2.3 to +2.3‰ CDT (Table 2). Based on the limited amount of sulfur isotope data determined in this study, the probable origin of the sulfur cannot be unambiguously determined. However, the range of values observed is similar to those from porphyry copper deposits (e.g., Ohmoto and Rye, 1979) and sulfides from carbonatite complexes (Deines, 1989), where the bulk of the sulfur is interpreted to have come from igneous sources. Sedimentary sources of reduced sulfur would be expected to yield values either isotopically lighter or heavier than those observed at the Jackson dome. For example, microbial reduction of sedimentary sulfate generally takes place at temperatures less than approximately 80°C and results in isotopically light sulfide (e.g., Ohmoto and Rye, 1979). At the temperature inferred for deposition of hydrothermal sulfide minerals at the Jackson Dome (approximately 240°C), reduction of sedimentary sulfate might occur by thermochemical sulfate reduction (e.g., Orr, 1977). This process does not cause extensive fractionation between the reduced sulfur and sulfate. Late Cretaceous seawater sulfate $\delta^{34}S$ values are close to the present day value of approximately +20‰, and if thermochemical sulfate reduction had operated, then sulfide $\delta^{34}S$ values should have been close to this value, as shown by Heydari and Moore (1989).

DISCUSSION

Geologic relationships, trace element geochemistry, mineralogy, and oxygen isotope analyses of hydrothermal carbonates indicate that Mesozoic formation waters were probably responsible for the hydrothermal alteration at the Jackson Dome. Based on the composition of present day brines in the Mississippi Salt Dome basin, it appears that metalliferous sedimentary brines contributed Pb, Zn, Cd, Ba, and possibly Ag present in the altered and mineralized rocks. However, other metals such as Au, As, and Cu may have been derived from the igneous rocks and remobilized by water-rock interactions. If sedimentary brines were the primary metal source, then that would require that the waters attained elevated metal concentration prior to the emplacement of the igneous rocks of the Jackson Dome. This interpretation would appear to be reasonable based on geologic reconstructions and geochemical trends observed in present-day brines. For example, Nunn and Sassen (1986) have modeled thermal aspects of the developing Mississippi Salt Dome Basin using sedimentation rates, and have calculated that the base of the Cretaceous section reached a temperature of 100°C at about 100 Ma. This temperature approximates the temperature of present-day brines in Cretaceous formations within the basin (maximum= 130°C). Because increased metal content generally correlates with higher temperatures and salinities in present-day brines (Carpenter and others, 1974; Kharaka and others, 1987; Saunders and Swann, 1990), it seems reasonable to assume that Cretaceous formation waters would have attained significant metal contents by 100 Ma. Therefore, igneous rocks of the Jackson Dome with an apparent maximum age of about 80 Ma, would have been intruded at least 20 m.y. after the Lower Cretaceous formations attained their elevated temperatures and presumably high metal contents.

Kharaka and others (1987) used the computer model SOLMINEQ.87 to show that present-day Pb-Zn-rich oil field brines from central Mississippi are approximately saturated with respect to galena and sphalerite under reservoir conditions. In these waters, the elevated metal contents are a direct consequence of very low reduced sulfur contents of the brines. Kharaka and others (1987) used SOLMINEQ.87 to show that the addition of reduced sulfur to these brines will lead to precipitation of almost all of the lead and zinc, and briefly considered the possibility that mixing of deeper, H_2S-bearing brines with metal-rich brines along faults in the basin could lead to a possible ore-forming system. In addition, Kharaka and others (1987) used SOLMINEQ.87 to evaluate the solubility of non-ore minerals in present-day oil field brines under reservoir conditions. Results of the model indicate that the brines are generally saturated with respect to a number of minerals, including calcite, albite, adularia, chlorite, quartz, Ca and Na montmorillonite, illite, and kaolinite, whereas they are somewhat undersaturated with respect to dolomite. It is interesting to note that many of these minerals are present as alteration minerals or in hydrothermal veinlets in the Jackson Dome.

CONCLUSIONS

Data from this study, based on available samples from only the very top of a relatively large igneous complex, indicate that favorable conditions existed for ore deposition at the Jackson dome during the Late Cretaceous. These conditions can be summarized as follows: 1) magmatic heat source capable of driving a large hydrothermal system; 2) probable vertical migration paths for heated waters along the margin of the intrusive complex where it penetrated the sedimentary formations; 3) ample supply of metals already in solution; 4) relatively high hydraulic conductivities of formations hosting metal-rich brines; and 5) an effective metal precipitation process, where magmatic sulfur (either from sulfide dissolution or H_2S gas) mixes with the metal-rich, sulfide-poor brines to precipitate metallic sulfide minerals.

Although the present study does not document the presence of economically attractive metal concentrations, the potential clearly exists that significant metal concentrations could be present at deeper levels. In addition, because Late Cretaceous intrusions similar to the Jackson Dome are common in the northern Gulf Coast region (e.g., Moody, 1949), potential exists for other, perhaps shallower, mineralizing systems elsewhere.

ACKNOWLEDGEMENTS

This study was supported by a grant from the Mississippi Mineral Resources Institute through allotment grant G1104128 from the U.S. Bureau of Mines. Jim Reynolds of FLUID, Inc., kindly provided the fluid inclusion data. Harry Posey reviewed an earlier version of this manuscript.

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SOUTHEASTERN GEOLOGY
V. 33, No. 2, March 1993, p. 81-98

Interpretation of Gravity and Magnetic Anomalies of the Eastern Piedmont Brunswick County, Virginia

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ABSTRACT

Gravity and magnetic models indicate that a steeply dipping, mylonitic shear zone recognized by reconnaissance mapping in the easternmost Piedmont of Brunswick County, Virginia, may be a listric fault. A pronounced 3 to 5 mgals Bouguer anomaly high as well as a band of N10°E trending aeromagnetic anomalies delineate the areal extent and the azimuth of the fault zone. Gravity and magnetic modeling, although non-unique, indicate that the fault plane flattens eastward over a short distance to a depth of 15 km where it joins a near-horizontal surface that cuts across the region. This surface is herein interpreted to be a décollement and is suggested to be a part of the Eastern Piedmont Fault System (EPFS) of Hatcher and others, (1977). We speculate that this listric fault is a splay off the master décollement at a depth of about 15 km and it is similar to those responsible for the Appalachian fold and thrust belt to the west.

INTRODUCTION

A detailed geophysical study was conducted in southern Brunswick County, Virginia, to infer the subsurface structures. The county is located between the Carolina slate belt to the west, the eastern slate belt and the Raleigh belt to the south, and the Goochland terrane and Richmond Triassic basin to the northwest (Figure 1).

This portion of the Virginia Piedmont lacks adequate modern published geologic data. Only two published geologic maps, both at small scale, exist for this area (Calver, 1963; Bobyarchick, 1979). The area is bisected by a previously unmapped mylonitic shear zone (Waller and Corbin, 1988). The Hylas fault to the north (Bobyarchick and Glover, 1978; Nowroozi and Wong,1989), and the Hollister fault to the south (Boltin and Stoddard, 1987; Sacks and others, 1991), have both been extensively studied, and are known to be part of the Eastern Piedmont Fault System (Figure 2) of Hatcher and others, (1977).

Several granitic bodies of the "300 m.y." suite of Fullagar and Butler (1979) are present in the area. Determining the mode of emplacement, the tectonic setting, and knowing whether the granitic bodies in Brunswick County are rooted or not is important for a better understanding of the geology of the eastern Piedmont.

LOCATION

This study encompasses the southern third of the county and covers approximately 100 km^2 (Figure 3). This area is bounded by the Virginia-North Carolina border to the south, the Meherrin River limits the northern margin, the Brunswick-Greensville County line limits the eastern margin, and longitude 78° west line limits the western margin. The area is located approximately 30 km west of Emporia, Virginia, and is south of US Highway 58 near Lawrenceville, Virginia.

Two gravity surveys were conducted along east-west lines S-1 and N-1 for this study (Figure 3). An additional survey line PN-1 was available for use from Waller (1989). A total of 45 km of profile lines with a spacing of 114 m, over 320 new gravity observations, in addition to regional data from Johnson (1975) were used for interpretation.

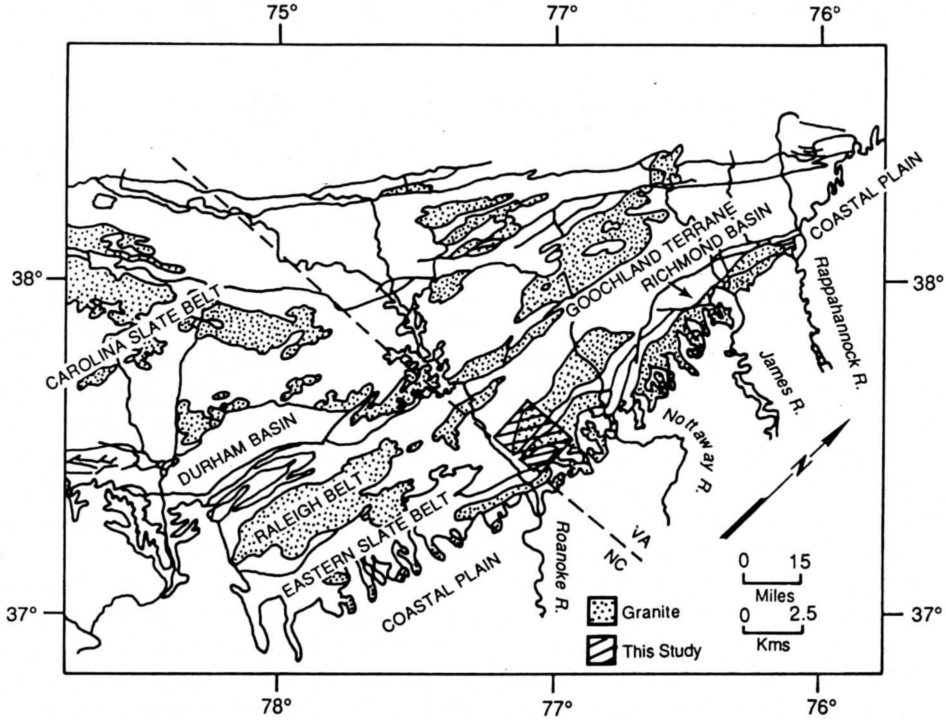

Figure 1: Geology of the study area and vicinity. The study area is indicated by hatched zone, it covers a major part of Brunswick County, Virginia. Several granitic bodies and terranes are indicated, Modified from Williams, 1978.

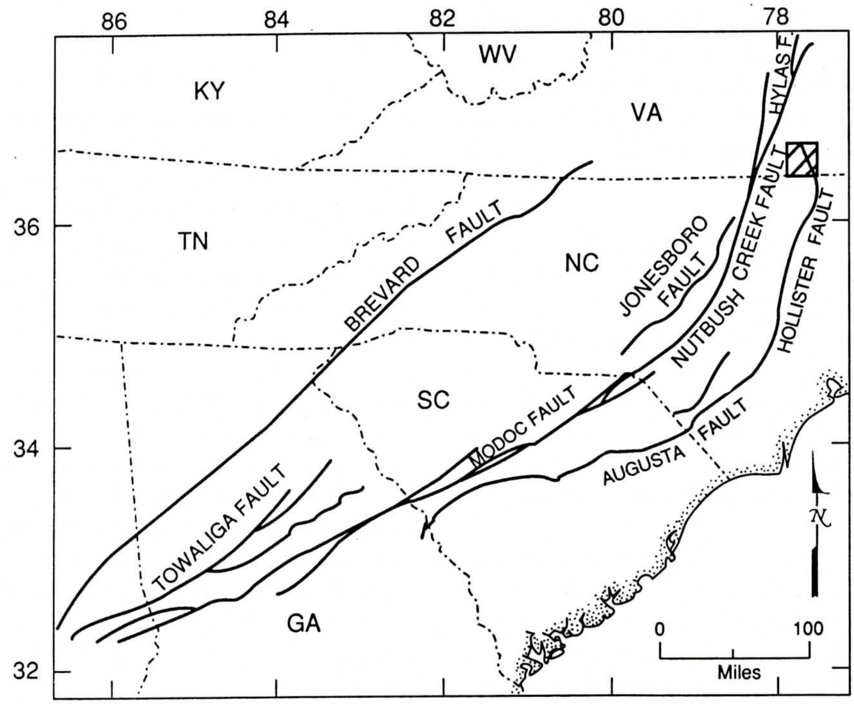

Figure 2: Major fault zones, modified from Hatcher and others, 1977, in relation to the study area.

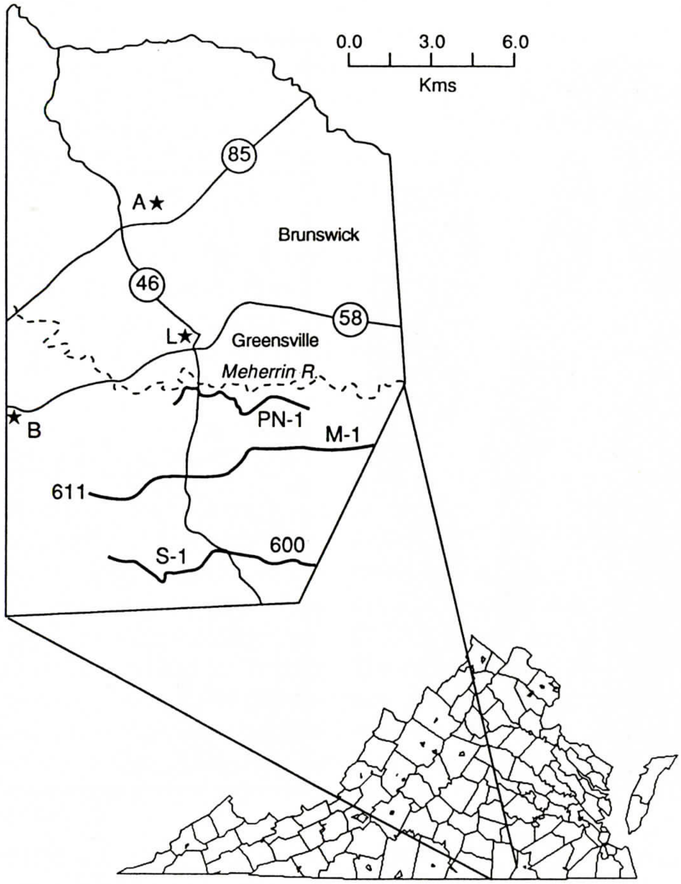

Figure 3: Location of the gravity profiles. Profile PN-1 was surveyed by Waller, 1989. Profiles N-1 and S-1 were surveyed for this work; US Highways 46, 85, 58, and State Roads 600, 667, and 611 are shown. The S-1 and N-1 gravity profiles are along State Road 600/667 and 611 respectively.

GEOLOGIC SETTING

Piedmont geology can be described as a mixture of tectonic terranes of uncertain origin. The "Tectonic- Lithofacies Map of the Appalachian Orogen" (Williams, 1978; Figure 1) and the "Tectonic map of the U. S. Appalachians" (Hatcher and others, 1990) show that the area consists of contrasting units. The rock units range in age from Pre-Cambrian (Grenville 1.1 Ga) to the most recent (Cenozoic sediments). Many of the regional tectonic units are formed by terrane accretion and are considered to be allochthonous, Williams and Hatcher(1983), and Hatcher (1989).

Prevalent throughout the Piedmont of the southeastern United States are "300 my" or "Alleghanian" granites of Fullagar and Butler (1979). The granitic plutons of this study, Figure 4, have previously been described as having "Petersburg" affinity (Calver, 1963; Bobyarchick, 1979). The Petersburg Granite was described by Bloomer (1939) as a gray to pink medium-grained granite, and by Wright and others, (1975) as a medium-grained quartz monzonite. The granites of this study, Figure 4, are predominantly composed of quartz, plagioclase, and potassium feldspar with accessory amounts of biotite. The potassium feldspar commonly occur on megacrysts that are generally aligned parallel with the foliation of the country rocks. Detailed discussions of the granites of this study are published by Wright and others,(1975), Bobyarchick (1979), and

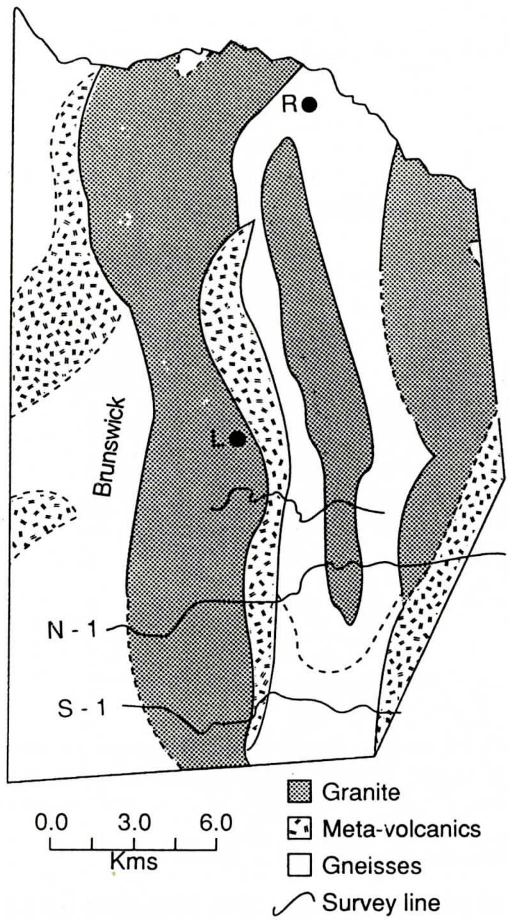

Figure 4: Geological map of Brunswick county, Virginia; the position of the gravity profiles are shown. Letters L and R represent the towns of Lawrenceville and Rawlings respectively. Modified from Bobyarchick, 1979.

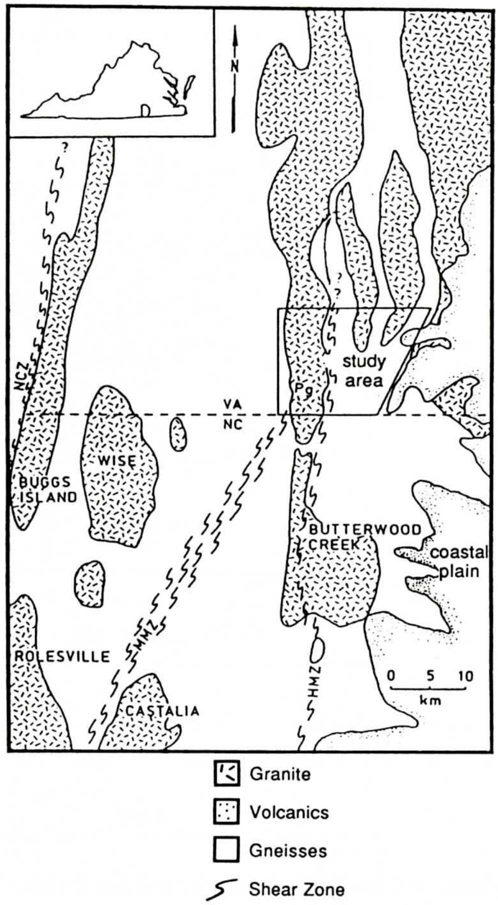

Figure 5: Major plutons and shear zones in the vicinity of the study area. HMZ, MMZ, and NCZ represent Hollister, Macon, and Nutbush Creek shear zones respectively. The mylonitic shear zone in Brunswick county appears to be the northern extension of the Hollister shear zone. Modified from Stoddard and others, 1987.

Bloomer (1939), Fullagar and Butler (1979), Sinha and Zietz (1982), and Whitney and Wenner (1980).

The "Geologic Map of Virginia" (Calver, 1963) shows a thin belt of metavolcanics between the two granites of this study. More recently Bobyarchick (1979) concurred with the above map, but Waller and Corbin (1988) have shown that the metavolcanic unit is a mylonite. The rocks within the zone contain macroscopic kink folds, microscopic mylonitic textures, and a continuation of geophysical anomalies associated with the Hollister fault zone was suggested.

The presence of mylonitic shear zones (Figure 5) that crosscut granite plutons is well documented in the Hollister shear zone that cuts the Butterwood Creek pluton to the south of this study (Stoddard and others, 1987; Sacks and others, 1991). Final movement in the shear zone within this study area must be no older than about the 330 m.y. age of the Petersburg Granite (Wright and othersand others, 1975). No younger age for movement on the shear zone is known at this time.

The mylonite zone in Brunswick County

appears to be the northern extension of the Hollister shear zone of northeastern North Carolina. This is based on trend, roughly N10°E, and its variable nature, it is narrow where cutting granites (0.5 km), and it is more diffuse (about 1.0 km) where not confined by granites.

Both of the above units postdate several major tectonic terranes of the southern Piedmont. These terranes are the Carolina slate belt, the Raleigh belt, and the Eastern slate belt.

TECTONICS

The Eastern Piedmont Fault System of Hatcher and others,(1977) is the key to the tectonics of the region. To understand the tectonics of the area it is important to determine how the fault system interacts with the major terranes. In the Piedmont of southeastern Virginia and northeastern North Carolina, the major terranes are the Carolina slate belt, eastern Carolina slate belt, the Raleigh belt, and the various plutonic bodies that intrude these blocks (Figure 1).

The Eastern Piedmont Fault System of Hatcher and others, (1977) is a series of observed faults and interpreted extensions in the southern Piedmont from Georgia to Virginia (Figure 2). The continuity of the fault is inferred by the occurrence of characteristic linear magnetic anomalies and their coincidence with the cataclastic rocks found within or near the fault zone.

Several lines of thought have developed concerning the faults present in southeastern Virginia and northeastern North Carolina (Figure 2). Bobyarchick(1981) reported that fault patterns in the Eastern Piedmont Fault System are consistent with the geometry expected in a strike-slip fault network. Lefort(1984) postulated that this system comprised a series of wrench faults that confined escaping blocks. Their movements resulted from collisional tectonics due to an impinging block. The movement is similar to the model of Tapponier and Molnar (1976). If it is accepted that the Eastern Carolina slate belt is correlative with the Carolina slate belt, then the presence of the Raleigh belt poses a problem. A model must explain why an older, more highly metamorphosed unit is surrounded by younger rocks of markedly different origin. Farrar (1985) proposes that the younger Carolina slate belt rocks were thrust over the Raleigh belt. This implies that the rocks of the Raleigh belt are true continental basement and not a continental fragment, although, it is possible that they represent an allochthonous unit thrust over a lower décollement. Given the assumed westward direction of tectonic transport of allochthonous blocks, the necessity that there is continental basement to the east of the present position of the Raleigh belt becomes important. It is not clear from Farrar's work (1985) if his décollement is indeed the same listric feature as shown on the COCORP data by Cook and others, (1979). The décollement is meant to be a regional feature upon which all Piedmont terranes have been thrusted. Farrar's décollement may represent a more local thrust surface. It is unlikely that his surface is correlative with the COCORP décollement.

Conversely, Bobyarchick (1981) proposed that thrusting was of minor importance and that strike-slip motions along the major faults were the result of collisional tectonics, with motions similar to those in the Anatolian region of Turkey.

In this model it is envisioned that the various tectonic terranes were being “squeezed” south along the Eastern Piedmont Fault System in response to collision to the north. The probable cause of this motion is assumed to be the initial collision between Africa and North America. The terranes “escaped” south due to a lack of confining blocks in that direction.

Bobyarchick(1988) concluded that the listric geometry of the Eastern Piedmont Fault System may be in agreement with mesocopic structural data that indicate dextral strike-slip motion if it is assumed that strike-slip motion occurred on subhorizontal detachments at or near the base of the crystalline Piedmont allochthon.

Hatcher(1989) has synthesized the tectonic of the U. S. Appalachians; his model calls for diachronous compressional events, as well as accretionary history involving subduction, arc collision and collision of various size blocks. In this model a master décollement which is part of the Eastern Piedmont Fault System is developed under the study area by the Late Carboniferous-Permian time corresponding to the Alleghanian Orogeny.

As discussed above basically there are two main concepts concerning the developments of the fault system in this region, the strike-slip model and the décollement model. The contradictions between these two ideas are obvious. Farrar's model as well as Hatcher's model calls for shallower dipping fault zones that splayed from a décollement between the Raleigh belt and the Slate belt. It is implied that the major boundary faults of the Raleigh belt, Nutbush Creek and Hollister faults (Figure 2) must at least become listric at depth. Bobyarchick's model calls for steeply dipping wrench faults along which tectonic blocks moved transverse to one another. By implication, the faults in this case may be major deep seated crustal breaks.

Seismic reflection and gravity-magnetic data have been interpreted to suggest that the root zone for the major Appalachian décollement is to the west beneath the Inner Piedmont province (Hatcher and Zietz, 1980; Iverson and Smithson, 1982, 1983; Nelson, and others, 1985). Conversely, several major studies using COCORP data have extended the décollement as far east as the Atlantic Coastal Plain (Harris and Bayer, 1979; Cook and others, 1979; Cook, and others, 1981,1983). Based on seismic reflection records off coast of South Carolina, southeast of Charleston area, Behrendt and others,(1983) interpreted a subhorizontal surface at a depth of about 11 km as a décollement and suggested a causal relationship to seismicity in Charleston area. Costain and others,(1989) reviewed potential, seismic, terrestrial heat flow, and electric data in the U. S. Appalachians; they reported that because of the documented mapped continuity of major faults throughout the internal parts of the crystalline Appalachian orogen by drilling and seismic records, perhaps the same continuity in crystalline Piedmont should not be surprising.

By comparing the two models with that

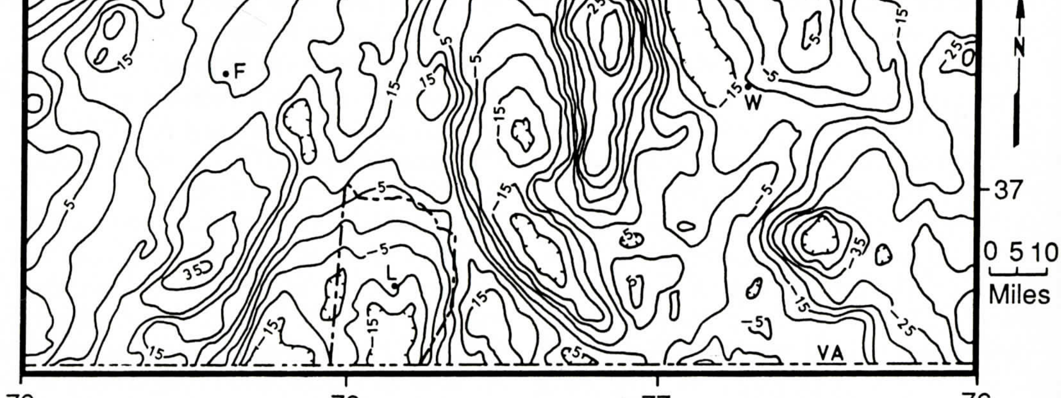

Figure 6: Regional Bouguer gravity map of southeastern Virginia. The border of Brunswick county is indicated by the dashed line. The letters F, L, and W refer to the towns of Farmville, Lawrenceville, and Williamsburg respectively. From Johnson, 1977.

developed for the shear zone based on geophysical data in this work, we propose that the décollement model is more appropriate for this portion of Virginia.

GEOPHYSICAL DATA ACQUISITION

Gravity Data

In this work three wire-line surveying was utilized for station accuracy. Station elevations were recorded using the TOPCON model AT-F3 transit and level. Foreshots and backshots were recorded at each station to enhance accuracy. Our estimated accuracy for elevation is about 20 cm and for latitude is about 50 m. A station spacing of 118 m (400 ft) was chosen. Both north and south geophysical lines (N-1 and S-1, see Figure 3) had USGS benchmarks for control.

Gravity values were recorded using a LaCoste and Romberg Model G gravimeter. Daily drift was corrected by re-occupying selected stations every few hours, base corrections were determined by occupying the base station at the Emporia Courthouse every morning and evening during the survey. The value for the Emporia base station was established as part of a state base network (Johnson and Ziegler, 1977). The base station is located at 36° 41' 04" W and 77° 32' 12" N, has an elevation of 35.036 m, and a gravity value of 979.9004 cm/s^2. It has a Bouguer value of 17.746 milligals. Gravity analysis was performed using a reduction density of 2.67 gr/cc, the International Gravity Formula of 1930, and a modified version of a program by Snowden (1970). Because the topography in this portion of the Piedmont is almost flat (variations in the range of 30 to 60 m), terrain correction is neglected. Regional Bouguer anomaly map of this area given by Johnson (1975) and Johnson and Ziegler (1977) is given in Figure 6.

GROUND AND AEROMAGNETIC DATA

Ground magnetic survey was conducted along the profile lines as well. The results, however, were noisy due to the adverse effects of power lines, transportation facilities, and underground pipelines. Thus the ground survey was only useful in detection of highly magnetic diabase dikes which are prevalent throughout this region.

The "Aeromagnetic Map of Virginia" (Zietz and others, 1977) and the White Plains 15 minute aeromagnetic map (Virginia Division of Mineral Resources, 1975) were included for analysis. Only the western two-thirds of the map in Figure 7 covers the study area.

INTERPRETATION

Regional Aeromagnetic Data

The original data (Figure 7) were contoured at 100 gamma intervals. The values range from a low of 3400 gammas to a high of 4100 gammas. A regional magnetic field of 51,400 gammas was removed from the data. The survey lines were flown at 150 m above terrain with a line spacing of 3.2 km.

Three distinct magnetic zones are observed on the White Plains aeromagnetic map. The zones are named the western zone, the central zone, and the eastern zone. The central and eastern zones are separated by a narrow, en-echelon magnetic pattern marked AA' on Figure 7. The western zone is located west of BB' on Figure 7 and it is characterized by an area of low magnetic signatures (3400 to 3600 gammas) when compared to the rest of the map. The central zone between AA' and BB' has a relatively high magnetic signature (3800 to 4100 gammas). The eastern zone is characterized by intermediate values and a much smoother pattern (3600 to 3800 gammas). The zone separating the central and eastern zones is an en-echelon sequence of sharp magnetic anomalies trending roughly N10°E.

The high magnetic central zone correlates well with the western granite of this study, thus granite may be rich in magnetite content. Other possible explanation for the high magnetic signature of this granite is that it is surrounded by

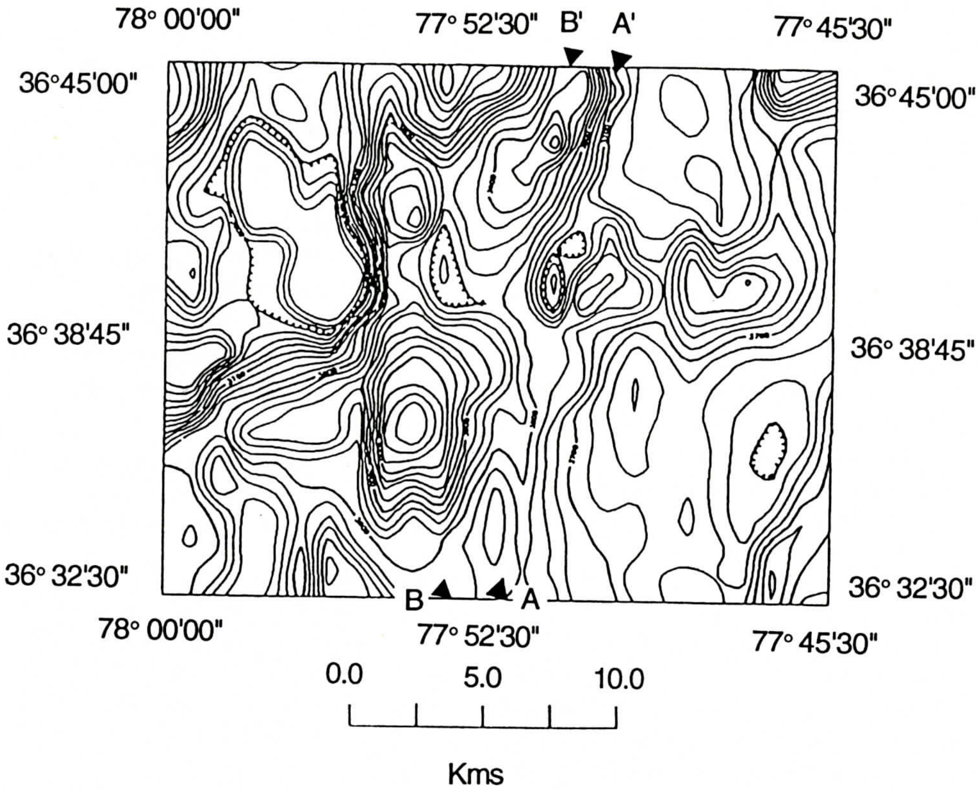

Figure 7: A plot of digitized aeromagnetic map of the White Plains quadrangle; The area covers Brunswick county and vicinity. AA′ and BB′ indicate two linear features which divide the map into three zones; The central zone is the segment between the linear features; the eastern zone is the segment to the east of AA′ and the western zone is the segment west of BB′.

metamorphosed rocks which have been depleted of magnetic minerals or that it is cut by highly magnetic diabase dikes.

The eastern magnetic zone correlates with gneisses. In general susceptibility of metamorphic rocks are between those of igneous and sedimentary rocks, thus the smooth pattern and intermediate values are interpreted to be characteristic of an area which has undergone metamorphism. The western magnetic zone has the lowest magnetic values of the study area. This zone correlates with the northward continuation of the Raleigh belt gneisses. These rocks are metamorphosed to at least amphibolite grade (Stoddard and others, 1987) and possibly granulite grade (Farrar, 1984).

The most significant feature on the White Plains aeromagnetic map is the zone of N10^{o}E trending, slightly en- echelon magnetic anomalies, characterized by associated high and low magnetic anomalies (3600 to 4100 gammas) concentrated along a belt about 1.0 km wide. The trend and location of the N10^{o}E central zone correlates with the previously unmapped mylonitic shear zone (Waller and Corbin, 1988). The geophysical signature of this zone was enhanced by anomaly isolation and second-derivative methods.

A second-order polynomial surface (Davis, 1973) was fitted to the aeromagnetic data to obtain the regional trend which may represent an east-dipping basement (Figure 8). This trend was subtracted from the original aeromagnetic data to isolate the residual anomalies (Figure 9). Comparison with the original field indicates that most of the residual magnetic anomalies now have shorter wave length that are the results of near-surface geologic structures.

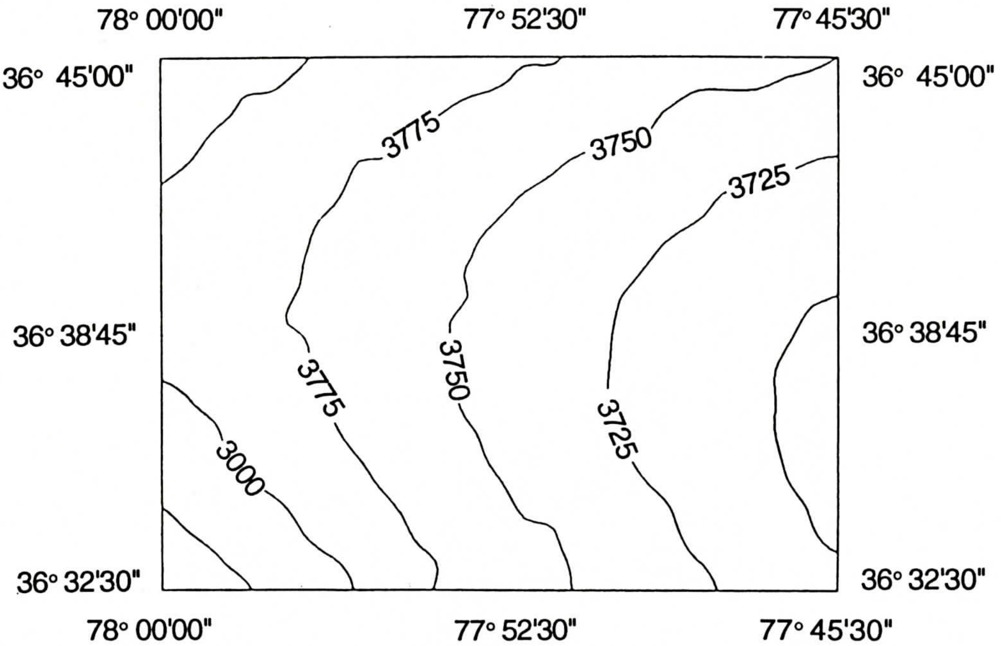

Figure 8: The second order trend surface of the White Plains aeromagnetic map; contour values are in gammas. The scale is the same as in Figure 9.

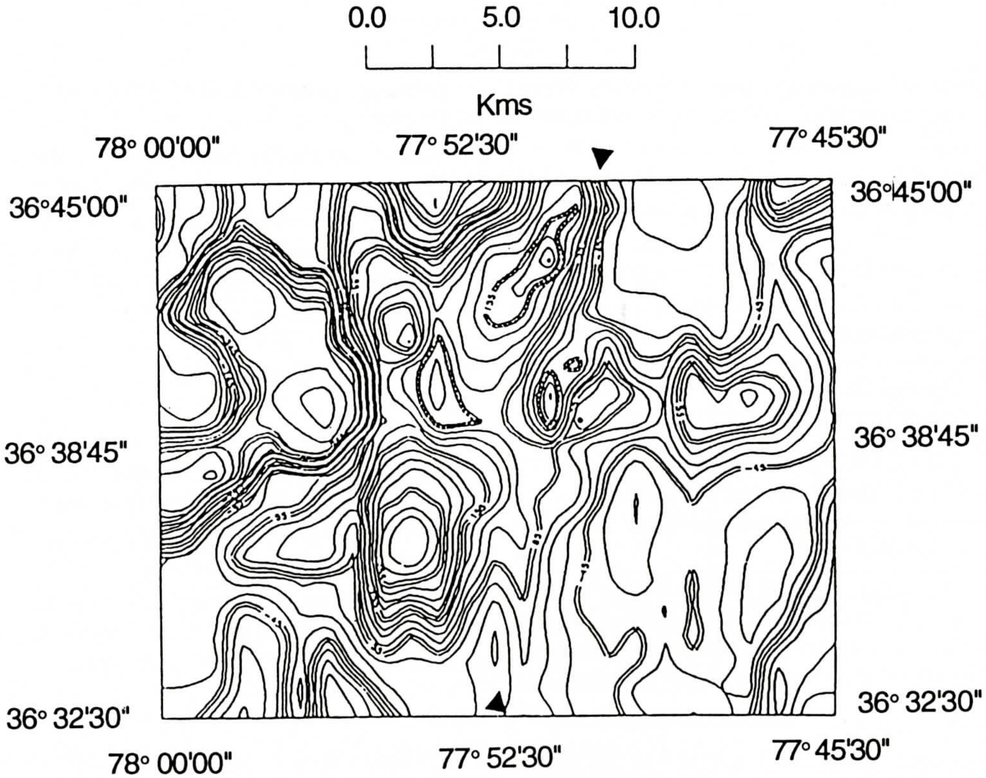

Figure 9: Residual aeromagnetic map of the White Plains quadrangle; contour values are in gammas. The enhanced linear feature with a trend of N10°E is the shear zone shown by the arrows.

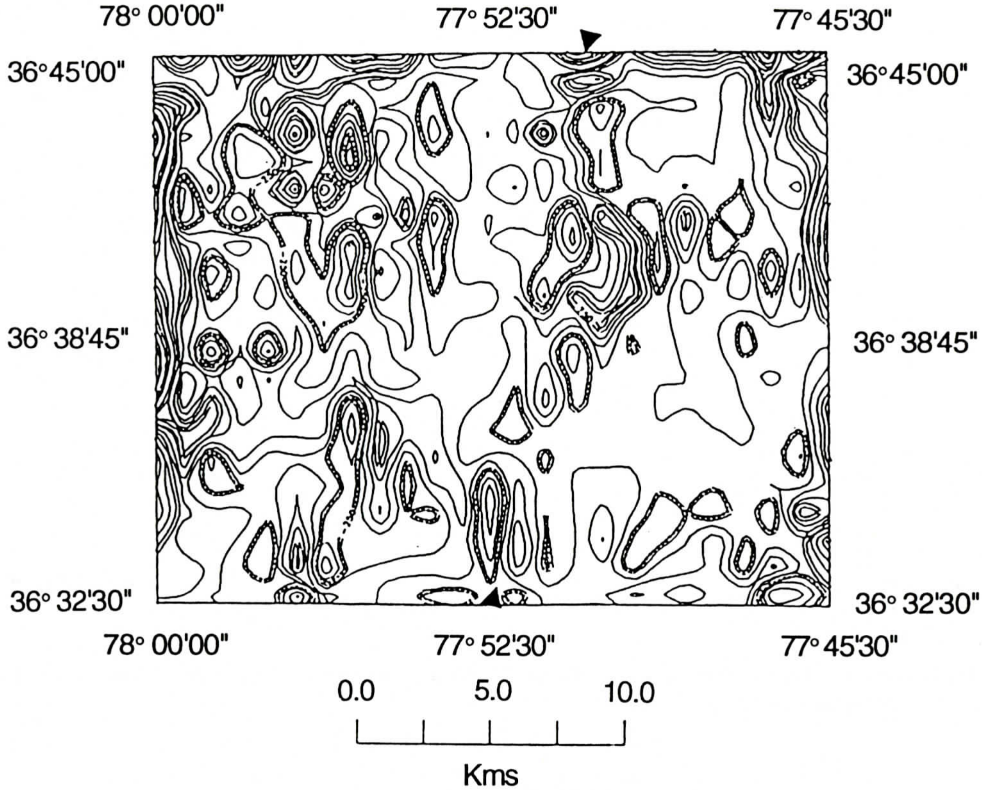

Figure 10: The second derivative map of the White Plains aeromagnetic anomaly which enhances the shallow structure; the position of the shear zone is indicated by arrows.

Table 1. Densities

Unit	Density (gr/cc)
Layered Gneiss	2.65
Western Granite	2.62
Mylonite	2.72
Eastern Gneiss	2.64
Metavolcanics	2.71
Basement (unknown)	2.60
Densities complied from Telford and others (1990), Reilly (1980, and Keller and others (1985).	

A second-derivative analysis was performed also on the aeromagnetic field. Second-derivative analysis enhances the signal from near surface structures and depresses the signal from the deeper structures (Telford and others, 1990). The second-derivative map, Figure 10, enhances the trend of the shear zone, as it is a near-surface structure.

Gravity Data

Two-dimensional modeling was performed on the Bouguer gravity data obtained for the lines N-1 and S-1. A FORTRAN program similar to Talwani and others,(1959) was used to model the subsurface. Geologic contacts and unit densities were determined from published work. Table 1 presents the final adopted values of densities for the different rock types.

Line N-1

The upper portion of Figure 11 shows the observed Bouguer gravity on the northern line

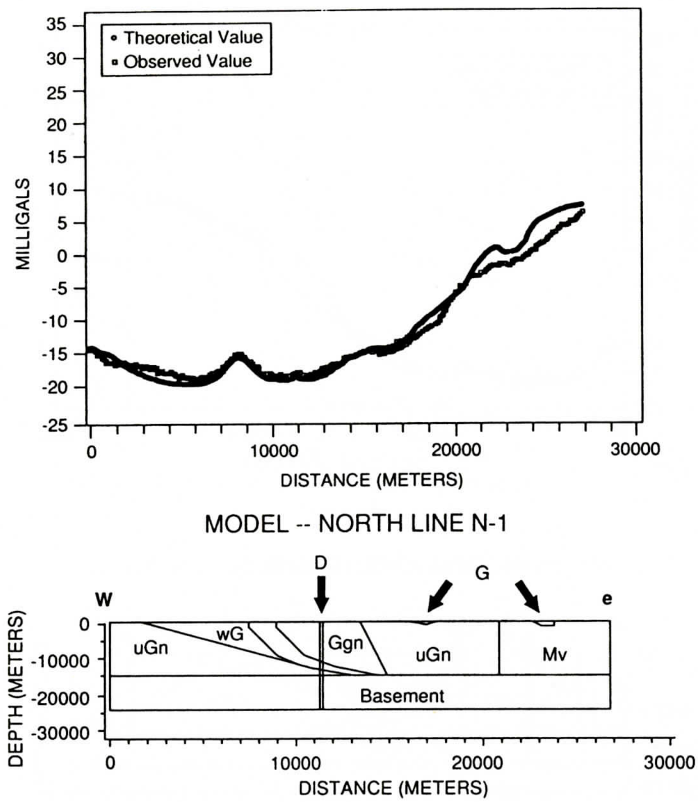

Figure 11: Upper part shows the observed and the theoretical values of the Bouguer anomalies along line N-1, or State Road 611. Squares are the observed values, and the circled pluses are the theoretical values. Lower part shows the adopted geological cross section used for calculation of the theoretical values, The abbreviations have the following meanings: D=diabase, e=east, G=granite, Ggn=granitic gneiss, Mv=metavolcanic, W=west, WG=western granite, Ugn=undifferentiated gneisses, and Umy=mylonite.

(N-1). Bouguer gravity increases from -20 milligals in the west to 5 milligals in the east.

The lower portion of Figure 11 is a two-dimensional, density contrast model of the subsurface geology along line N-1. The modelcovers approximately 30 km west to east.

Most lithologic units in Figure 11 are a combination of field reconnaissance observations and the previous geologic work of Bobyarchick (1979). The units from west to east are layered gneiss (Raleigh belt?), 2- western granite, probably Petersburg, 3- mylonite zone, 4- granite gneiss, 5- layered gneiss, and 6- metavolcanics and metasediments. Diabase dikes are present throughout the region and are present in the study area. The unit beneath the horizontal surface at 15 km is probably Grenville basement or Paleozoic rocks with shelf affinity. Adopted density values in Table 1 are the average values; the densities for the layered gneiss and granite may vary from 2.59 to 3.0 and 2.5 to 2.81 gr/cc respectively (Telford, 1990). A reduction density of 2.67 gr/cc was used for data reduction and the effective densities, the difference between the values in Table 1 and the reduction density, were used in the modelling.

The mylonite unit is best modeled as a steeply dipping unit near the surface which becomes listric to the east at depth, and it joins the horizontal décollement surface at a depth of 15 km. All surface geology is also terminated by the horizontal surface at 15 km.

In this model, the eastern gneiss and eastern

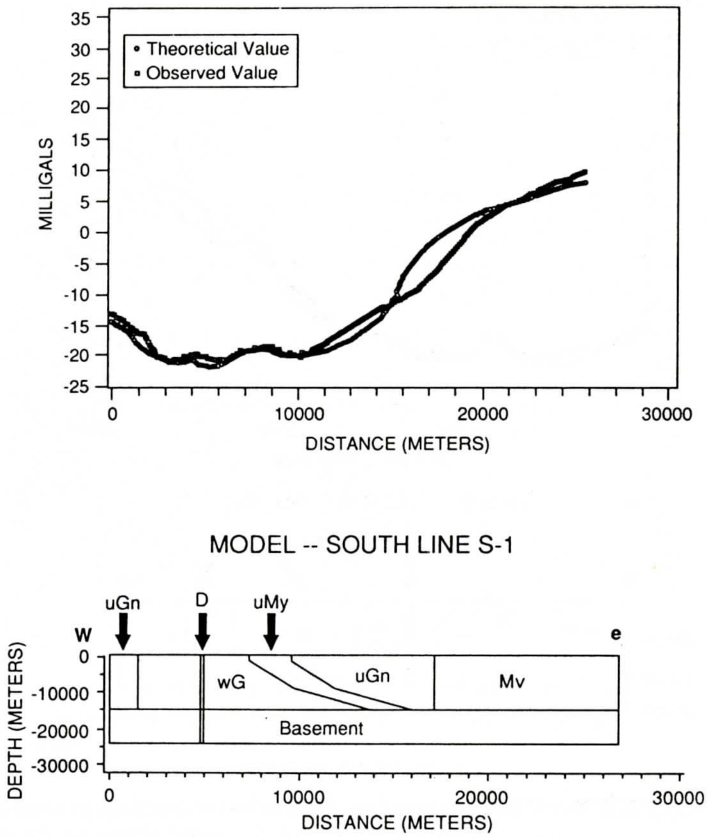

Figure 12: Upper part shows the observed and the theoretical Bouguer anomalies along line S-1, or State Roads 600/667. Lower part shows the adopted geological cross section used for calculation of the theoretical values. Abbreviations are the same as in figure 11.

granite are modeled as one unit. Both of these units have approximately the same density and are indistinguishable by gravitational methods.

From west to east, the contact of the eastern gneiss becomes slightly denser layered gneiss and may represent a gradational change. Bobyarchick (1979) mapped this contact as speculative. In this model the contact is assumed to be sharp but it likely represents a transitional zone, and the horizontal surface at 15 km is proposed to be a décollement.

The upper portion of Figure 11 compares the observed versus theoretical Bouguer gravity generated by the model for line N-1. With few exceptions, the values generated by this model closely approximate the observed Bouguer anomaly collected for this study. A wide range of fault types were used to model the mylonitic zone. Over 20 different variations of mylonite geometry were modeled. No other model matched the observed gravity as well as the one presented in Figure 11; a number of unsuccessful models are given in Corbin (1989).

Line S-1

The upper portion of Figure 12 is a plot of the Bouguer gravity values collected along southern line S-1. Gravity decreases from the west to the east from a value of -13 milligals to 10 milligals. A slight gravity high occurs approximately between 8 to 10 km. This high is likely associated with the mylonite unit.

The lower portion of Figure 12 is a two-dimensional model of the subsurface geology along line S-1. This line is approximately 15

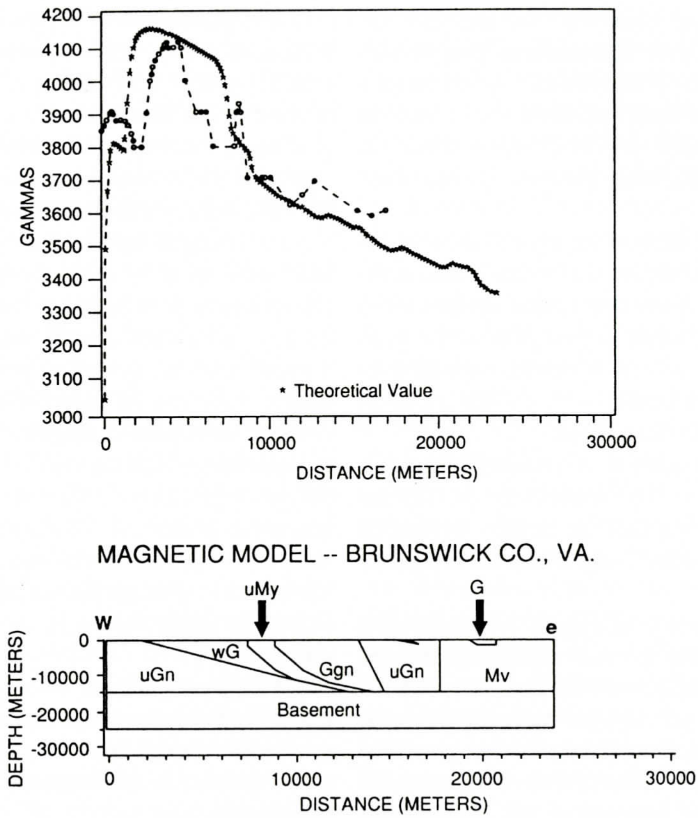

Figure 13: Upper part shows the observed and the theoretical values of the total aeromagnetic field near line N-1. Lower part shows the adopted geological cross section given in figure 11. This cross section was used for calculation of the theoretical magnetic anomaly.

km south of line N-1 near the Virginia - North Carolina border. Modeling in this area is vital to understanding the relationship between the mylonite here and shear zones to the south. We collected 12 km of gravity data in this study, this was augmented on the east by an equal amount of regional Bouguer gravity from Johnson (1975). The model is centered on the mylonite - western granite contact.

In Figure 12 the mylonite is modeled as being wider and less dense. This agrees well with field observations that the intensity of mylonite development decreases to the south. As before, the unit is modeled as becoming listric to the east with depth. The zone eventually joins the horizontal surface at a depth of 15 km.

The upper portion of Figure 12 also shows the observed Bouguer gravity values versus the theoretical gravity generated from the model. The fit between the two curves is not as good as that for the northern line N-1. The more diffuse nature of the mylonite in this region tends to obscure the gravity signature. The lack of fit between the gravity in the eastern half of the profile is due to the lack of details available with the augmented data. Still, this model accurately illustrate the gentle increase in gravity to the east.

Magnetic Model

A two-dimensional magnetic model was also generated for the study area. Because ground magnetics were erratic, aeromagnetic data were utilized for the model; the flight elevation and line spacing were 150 m, and 3.2 km respectively. A two dimensional profile was taken from the White Plains aeromagnetic map. The east-west profile was taken at approximately 36° 36' N latitude which is approximately midway between gravity lines N-1 and S-1.

The upper portion of Figure 13 is the aeromagnetic profile across the White Plains aeromagnetic map. Magnetic values range from a low of 3400 gammas to a high of 4100 gammas. Magnetic values represent variations in the total field intensity with 51,400 gammas removed from the local field.

The magnetic method is included as an additional constrain. Its usefulness is limited mainly in showing that the models developed for gravity can effectively model the magnetic field anomaly.

The lower portion of Figure 13 is a general adaptation of the gravity models developed earlier. The model shows the mylonite as a listric splay fault off a major horizontal detachment. A theoretical magnetic field is generated using a program similar to that of Talwani and Hertzler (1962). Because of the difficulty of field determinations of magnetic susceptibilities, values are estimated from knowledge of the general geology (Bobyarchick, 1979) and from published susceptibilities for average rocks (Telford and others, 1990). Final magnetic susceptibilities used for the modeled units are given in Table 2.

Table 2. Magnetic Susceptibilities

Unit	Susceptibility (emu)
Layered gneiss	0.0160
Western granite	0.0180
Mylonite	0.0175
Eastern gneiss	0.0170
Metavolcanics	0.0170
Basement (unknown)	0.0170

The upper portion of Figure 13 compares the theoretical versus observed magnetic field generated by the model. One drawback to the method is the lack of details that can be modeled using magnetics, but comparison with the observed field shows a general correlation between observed fields and calculated fields.

As speculated earlier, the field in this area can be modeled by magnetic zones. The western area is an area of lower magnetic susceptibilities. This corresponds with the gneisses present west of the main granitic body. The central third can be modeled as the unit possessing the highest susceptibility. The cause of the unusually high susceptibility of granite in this area probably is due to high content of magnetite in the rock. The eastern third is modeled as a unit of intermediate susceptibility. Variations in geology across the area are represented by slight variations in magnetic signature.

The two-dimensional model developed from gravity data generates a theoretical magnetic profile that fairly approximates a two-dimensional profile taken from the local aeromagnetic field.

DISCUSSION

The models presented give a consistent picture of the subsurface of Brunswick County. Although non-unique, the gravity and magnetic signatures of the previously unmapped mylonitic shear zone is best modeled as a listric splay off a major décollement at a depth of 15 km. The surface geology is interpreted to be allochthonous and presumably thrust into position from the east. The geology beneath the décollement is consistent with densities similar to either Grenville basement or shelf clastics.

Previously, two simplified models were proposed concerning the subsurface nature of the Eastern Piedmont Fault System. The prevailing models were strike-slip versus thrust fault.

Comparison of both models with the geophysical models developed for Brunswick County presents favorable evidence to the décollement model in southeastern Virginia. It is probable that the models presented are not only applicable to Virginia, but they may be general models, and may provide evidence for the development of the eastern Piedmont above the master décollement.

By showing the applicability of the décollement model in southern Brunswick County, an argument has been put forward in favor of the thrust fault, or décollement model. The depth of the proposed décollement agrees well with several seismic studies to the north (Bollinger and Sibol, 1985; Harris and others, 1982) and to the south (Cook and others, 1979,1981,1983), Behrendt and others,(1983) and Costain and others,(1989). Based on seismic reflection data Cook and others,(1983) reported that a southeast-dipping reflection project to the surface location of the Augusta fault, furthermore, this fault converges to a listric fault to the east at a depth of about 15 km. The listric fault modeled in this work appears as the northward extension of the décollement associated with the Augusta and Hollister faults at the surface. It also appears likely that the décollement present in the southeastern United States is the eastern extension of the master décollement responsible for thrusting in the Valley and Ridge Province (Harris and Bayer, 1979).

Bobyarchick (1988) proposed a model for Piedmont development above a master décollement which includes some aspects of the geophysical models in this report. His model presents a dextral sense of motion present on the mylonite zone as observed in field. The dextral motion probably represents a later stage reactivation of the thrust fault. The exact timing of the movements is unknown.

The main body of granite in our model is interpreted to be allochthonous as are all other surface units in the area. Based on gravity models the granite may extend to a depth of 5 to 15 km. The juxtaposition of the granite against the fault zone, the elongate shape of the granite, and the coincidence of the foliation of the granite with the strike of the Hollister shear, Figure 5, all suggest that the granite was emplaced before the time of shearing. A similar model was proposed by Guineberteau and others, (1987). This portion of Virginia had to be at a sufficient depth to allow for the formation of both granite and mylonite textures, although not necessarily at the same time.

It appears very likely that the shear zone in the Brunswick County in this study, Figure 4 and 5, represents a northward extension of the Hollister shear of northeastern North Carolina. This makes documentation of the northward extension of the shear into northern Brunswick and western Dinwiddie Counties important. It is possible that the Hylas shear zone west of Richmond, Virginia, curves to the east south of the Richmond Triassic basin. The area north of Brunswick County could provide evidence of a relationship between the two shear zones.

This study indicates that the shear zone in the Brunswick County is recognizable by detailed gravity and magnetic surveys. In this case the mylonite of the shear zone gives an isolated positive gravity signature surrounded (and probably masked) by the main, semi-circular, negative anomaly of the study area. However, the positive signature appears to decrease to the north and disappears completely to the south near the state line. The nature of the gravity field in North Carolina is unknown because no studies of this type have been conducted in that area.

The shear zone also has a significant aeromagnetic signature. A pattern of N10^{o}E trending anomalies is clearly coincident with the mylonite. The continuous nature of the pattern is clear evidence that the shear continues southward into North Carolina and northward into northern Brunswick County. To the south where granite does not occur, shearing spreads over a wider area, resulting in less mylonitization and a lower density than to the north. The shear must represent a fundamental break between two units of differing magnetic susceptibilities through the length of the region. Thus, the aeromagnetic pattern should be constant across the area while the gravity pattern would be expected to decrease where the shear is spread over a wider area. This is exactly the pattern seen in southern Brunswick County, Virginia.

CONCLUSIONS

Brunswick County, Virginia is transacted by a nearly north - south trending, hitherto unmapped, steeply dipping mylonitic shear zone with a distinct gravity and magnetic signature. Geophysical modeling and reconnaissance geological mapping suggests that the shear zone has regional significance and may extend at both ends.

The mylonite zone is represented by a 3-5 milligals, 0.5 to 1 km wide distinct gravity pattern, and is defined by a N10°E trending 0.5 to 1 km band of en-echelon aeromagnetic anomalies. The location, width, and trend of both anomalies correlates well with the field-mapped position of the mylonite zone.

Removal of the regional magnetic trend from the local field enhances the anomalous patterns related to the shallow structures; and the second-derivative analysis of the local aeromagnetic field confirms that the anomalous patterns are due to local near surface geology.

The granite located to the west of the mylonite zone appears to have an uncharacteristically high aeromagnetic signature; while the gneisses, which are ubiquitous throughout the area, are characterized by a broad wavelength, anomalously low patterns.

Although nature of potential data preclude a unique solution, both gravity and magnetic modeling suggest that the shear zone is nearly vertical near surface but flattens in a short distance and becomes near horizontal at a depth of 15 km. At this point the shear zone merges with a horizontal surface that occurs across the region. The horizontal surface at 15 km likely represents a major décollement that influenced the tectonic development of the area. If the shear zone of this study is an extension of the Hollister zone, then it represents a major northern continuation of the eastern Piedmont Fault System.

Acceptance of the décollement model for the eastern Piedmont of Virginia implies that the granitic bodies present in this area are not rooted at depth. As with all rocks present above the décollement they are most likely allochthonous and were transported to their present position from the east.

ACKNOWLEDGEMENTS

We thank Stanley S. Johnson, Department of Mines, Mineral and Energy, Virginia Division of Mineral Resources; and Ramesh Venkatakrishnan, Golder Associate, for their interest in this work. We have benefitted from the comments by R. D. Hatcher, Jr., Department of Geological Sciences, University of Tennessee and an anonymous reviewer, we thank them for their critical reviews which helped us to improve this work.

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SOUTHEASTERN GEOLOGY
V. 33, No. 2, March 1993, p. 99-110

LATE TERTIARY TO EARLY QUATERNARY SEDIMENTATION IN THE GULF COASTAL PLAIN AND LOWER MISSISSIPPI VALLEY

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ABSTRACT

The regional setting of Late Tertiary to Early Quaternary (non- glacially derived) coarse sands and gravels that outcrop from the Upper Mississippi-Ohio Valley (Lafayette Formation) to the lower Gulf Coastal Plain (Citronelle Formation) is reviewed in view of recent advances in paleoclimatic, eustatic, and tectonic studies.

The gravels, whose age ranges between Pliocene and Early Pleistocene, are predominantly alluvial fan-braided stream deposits that form an arc around the Allegheny Provinces. Gravel fractions are composed of chert derived from Middle Paleozoic rocks of the Allegheny Province while the sandy quartose fraction were derived from the crystalline Appalachians. Considerable recycling through Cretaceous and Tertiary units has occurred.

It is proposed that coarse-grained Late Tertiary-Early Quaternary sedimentation was triggered by the breaching and removal of the Ft. Payne chert (Miss.), the Tuscaloosa Formation (K), and possibly other units during uplift and rejuvenation of the Nashville Dome which began approximately five millions years ago (Reesman and Stearns, 1989). The continued erosion of the Ft. Payne, reworking by streams, and the influence of local uplifts has redistributed sediments resulting in the age of individual deposits varying from Pliocene to Early Pleistocene with younger sediments located near the coast and farther away from the Dome as proposed by Brown (1967).

INTRODUCTION

Coarse, reddish lenticular sands and gravels crop out from the Upper Mississippi Valley (Potter, 1955; Olive, 1980) to the Gulf Coast (Doering, 1956). These deposits unconformably overlie Paleozoic to Miocene rocks and are unconformably overlain by Pleistocene deposits. Suggested ages range from Miocene (Alt, 1974; May, 1981) to Pleistocene (Doering, 1956).

These widespread coarse sand and gravel deposits contrast sharply with fine sands, silts and clays that characterize the Quaternary and much of the Tertiary in the Gulf Coastal Plain and represent a unique depositional regime. The climatic eustatic or tectonic implications of these deposits have not been examined in light of recent advances in paleoclimatic eustatic and seismic stratigraphic studies.

Poor discontinuous outcrops, the lack of fossils or other datable material, and bounding unconformities have made regional correlation tenuous and have added to controversy over the age and regional significances of these deposits.

The purpose of this study is to re-evaluate the tectonic, eustatic, and climatic significance of these Plio-Pleistocene gravels in light of recent advances in paleoclimatic, seismic, stratigraphic, and neotectonic studies, in order to examine the geological setting of the Southeastern United States during the Late Tertiary through the Early Quaternary.

DISTRIBUTION

Important units include the Citronelle Formation of the Gulf Coast (Mason, 1916; Doering, 1956) the Lafayette gravels of the Upper Mississippi Valley (Potter, 1955; Horberg, 1951; Lamar and Reynolds, 1951; Leighton

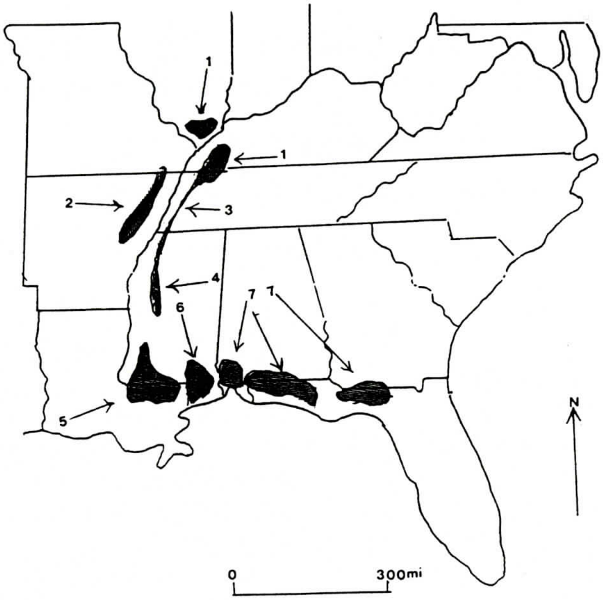

Figure 1. Distribution of Plio-Pleistocene graveliferous deposits in the Upper Mississippi Valley and Gulf Coastal Plain. 1) Lafayette gravels (Potter, 1955; Olive, 1980). 2) Crowley's Ridge (Guccione, Pryor and Rutledge, 1990). 3) Plio-Pleistocene gravels Western Tennessee (Blythe, McCutchen and Stearns, 1975). 4) Upland gravels Western Mississippi (Autin, 1977). 5) Citronelle Formation Southeast Louisiana (Self, 1984,86). 6) Citronelle - South Mississippi (Smith and Maylan, 1983). 7) The Citronelle Formation at South Alabama and West Florida (Isphording and Lamb, 1971).

and Williams, 1949; Pryor and Ross, 1962; Ross, 1964; Ruby, 1952; Olive, 1980); the gravels of Crowley's Ridge (Potter, 1955; Guccione, 1984; Guccione and others, 1990) and Western Tennessee (Blythe, McCutchen and Stearns, 1975), and the Highland Terrace upland gravels of Western Mississippi (Autin, 1977). The distribution of these units is shown in Figure 1.

Similar deposits extend into the Atlantic Coastal Plain (Schlee, 1957; Doering, 1960; Rader, Newell and Mixon, 1987) and in the Lake Wales trend of peninsular Florida (Alt and Brooks, 1965), but stratigraphic relationships are problematical.

AGE

Late Tertiary to Early Quaternary coarse sands and gravels unconformably overlie Paleozoic through Upper Miocene units. Assigned ages range from Upper Miocene through Early Pleistocene.

Isphording (1983) and May (1981) suggest that some units mapped as "Citronelle" or "High Terrace" in Mississippi may be part of the Miocene Catahoula Formation and that these materials may represent cyclic continental regression. The "Citronelle" in peninsular Florida is considered Miocene by Alt and Brooks (1965), Ketner and McGreavy (1959), and Isphording (1983), using terrace stratigraphy and heavy mineral analysis, suggested that may be equivalent to the Ecor Rouge Formation which is unconformably overlain by the Citronelle in Mobile County, Alabama.

Considerable controversy has developed over the age of the Citronelle at its type locality at Citronelle, Mobile County, Alabama. Many authors consider the Citronelle to be Pliocene (Mason, 1916; Carlston, 1951; Springfield and LaMoreaux, 1957) while others (Doering, 1956, 60; Roy, 1939; Brown, 1944; and Jones and others, 1956) assign an Early Pleistocene age based on an reinterpretation of the type section.

Vertebrate fossils discovered in Mobile County, Alabama indicate that Citronelle deposition could not have begun before Middle Pliocene (Isphording and Flowers, 1983). Uranium-thorium dating of ironstones and an extrapolation of erosion rates in Alabama gives an age of 3.6x10^6 years (Hemphillian)(Maxwell, 1971) while vertebrate fossils in Taylor County, Georgia also indicate a Pliocene age (Voohiers, 1970). Potter (1955) considers the Lafayette Pliocene while Olive (1980) indicates a Miocene(?)- Pliocene age with palynological evidence strongly suggesting a Pliocene age. Some of these gravels are then reworked into an upper Pleistocene unit. The Crowley's Ridge deposits are considered equivalent to the Lafayette and are therefore considered Pliocene (Guccione and others, 1990). Pollen studies of upper Citronelle sediments in the Florida Panhandle suggest that deposition continued into the Early Pleistocene (Marsh, 1964).

The Citronelle and its possible lithologic equivalents are considered Plio-Pleistocene in southeastern Louisiana (Campbell, 1971; Cullinan, 1969; Self, 1983,84), and Southern Mississippi (Smith and Meylan, 1983). McFarlan and LeRoy (1988) traced High Terrace deposits (Citronelle Formation) downdip on to the Louisiana continental shelf, using electric log, well samples and seismic correlations and found that the sand and gravels were underlain by an ash bed dated at 3.1 ± 0.43 m.y. (Pliocene) and by the extinction horizon of Globoquadrina altispria dated 2.9 m.y. which would date the basal units no older than Late Pliocene. Gravels in West Tennessee (Blythe, McCutchen and Stearns, 1975) are also considered Plio-Pleistocene.

The age of the Late Tertiary-Early Quaternary gravels may vary from place to place but range from Pliocene or Plio-Pleistocene in age.

Inland deposits, such as the Lafayette Formation and the Crowley's Ridge gravels tend to be considered Pliocene while the Citronelle is thought to be Late Pliocene to Plio-Pleistocene in Louisiana, Mississippi and Alabama, and Early Pleistocene in the Florida Panhandle, which seems to confirm the concept of younger deposits tending to be located nearer the coast and away from the sedimentary Appalachians (Brown, 1967).

LITHOLOGY

Composition and Source

Citronelle and Lafayette gravel fractions are dominated by rounded, iron-stained, honey-colored cherts (Potter, 1955; Autin, 1977; Self, 1983; Smith and Meylan, 1983). Casts of Middle Paleozoic fossils are common. Chert content decreases with decreasing grain size. Sand fractions are quartz arenites with minor amounts of chert and muscovite. Metamorphic quartz is usually present. Heavy mineral suites are dominated by metamorphic minerals (Potter, 1955; Rosen, 1968; Smith and Meylan, 1983). Iron oxides and red interstitial clays are common.

Potter (1955) believes the Lafayette cherts were derived from sources less than 100 miles from the outcrop area in the Mississippi Valley which is confirmed by Olive (1980) who further suggests a southeastern source indicated by: 1) increase in dip of bedrock to the southeast; 2) increase in grain size to the southeast; 3) increase in modal class to the southeast. Smith and Maylan (1983) point to the Fort Payne formation (Mississippi) of the Appalachian as a source of Citronelle gravels in southern Mississippi. Quartzose sand and heavy minerals were derived from the Blue Ridge and Piedmont with secondary amounts originally derived from the Canadian Shield in the Upper Mississippi Valley (Potter, 1955).

Therefore, the Plio-Pleistocene units were believed to have two original sources: the sedimentary Appalachians for the gravel fraction and the crystalline Appalachians for the finer fractions.

The overall composition of maturity and rounding of the Citronelle-Lafayette suggests recycling with Cretaceous through Miocene of the Gulf Coast-Mississippi Embayment being intermediate sources (Potter, 1955; Maxwell, 1971; Isphording, 1983). Much of Citronelle along the Gulf Coast has been recycled from the underlying Miocene units (Isphording, personal communication). Small isolated outliers of gravels mapped as Cretaceous Tuscaloosa Formation are scattered across the Western Highland Rim of Tennessee, suggesting that they covered a more extensive area and that they could be an intermediate source for both chert and metaquartzitic components.

Plio-Pleistocene gravels have been recycled into Pleistocene and younger deposits and may have covered more extensive areas.

Texture

Coarse-grained Plio-Pleistocene deposits of the Gulf Coast and Mississippi Embayment can be described as an immature trimodal mix of sand, gravel and clay. Typical lithologies include sandy gravels, muddy sandy gravels, silty sands, and muddy gravelly sand.

Gravel is the dominant mode in graveliferous beds of the Lafayette Formation (Potter, 1955) and the Citronelle of southern Louisiana (Self, 1984) and southern Mississippi (Smith and Meylan, 1983). Gravels are well-rounded with mean grain sizes in the coarse granule (-1.57ø) in southern Mississippi to medium pebbles (-4.0ø) in southeast Louisiana (Smith and Meylan, 1983, Self, 1984). Rare cobbles and boulders are found in the Lafayette (Potter, 1955) and in Southeastern Louisiana (Mossa and Self, 1986) Gravels usually are found in a fine to coarse sand matrix. Crowley's Ridge deposits were thought to be derived from mid-continent Paleozoic and the Appalachian source rocks (Guccione, Pryor and Rutledge, 1990). The lack of igneous material indicative of glacial and/or Mississippi River sources were noted.

Sands are described as coarse-grained and poorly sorted, but in southeastern Louisiana, the sand fraction is typically well- rounded to subangular, moderately-sorted, medium sand, although considerable variability exists (Self, 1984). Sands tend to have reddish interstitial clay, due to diagenetic oxidation of unstable iron-rich minerals.

Clay beds are uncommon, although a few red or green clay lenses less than 1 meter thick are present in southeastern Louisiana (Self, 1984) and some extensive clay beds are present in Baldwin County, Alabama (Isphording, personal communication).

Thickness is highly variable, ranging from 10 to 100 ft. over most of the region, but thickening to 600 ft. in the subsurface of Southeast Louisiana (Self, 1986). Individual beds are highly lenticular and discontinuous, with thicknesses seldom exceeding 5-6 ft (2 m), especially in sands, although 20 ft (6 m) beds are present. Both trough and tabular crossbeds are common, and Potter (1955) reports sets up to 20 ft (6 m) thick in the Lafayette Formation Cut and fill structures, scoured surfaces, and channels are also common. A few of the gravel beds are graded.

Paleocurrent directions range from west-southwest to south in the Upper Mississippi Valley (Potter, 1955) to south-southeast in southern Mississippi (Smith and Meylan, 1983).

In southeast Louisiana, the Citronelle grades upward in a very red, sandy-clayey soil zone with mottled light greenish-grey (10 YR 7/1) silt stringers and iron concretions. Weakly developed paleosols are found within the lower portions of gravels and Crowley's Ridge with a well-developed soil in the upper part (Guccione and Rutledge, 1990).

Depositional Environments

Potter (1955) considers the Lafayette gravels to be channel fill, lag or lateral accretion sediments deposited by braided, high-energy, laterally migrating streams associated with three coalescing alluvial fans: the ancestral Mississippi, Tennessee and Ohio-Cumberland fans. Olive's (1980) older graveliferous unit was deposited by the ancestral Tennessee River which built up a large low gradient alluvial fan (the Jackson Fan) that covered most of the Jackson Purchase area (Kentucky west of the Tennessee River) which is compared to the Kosi River fan of Northern India (Gole and Chitale, 1967).

Guccione and others (1990) propose that the coarse sands and gravels on Crowley's Ridge were deposited in braided streams and possibly coarse-grained meandering stream environments. They interpret gently dipping (<20°) interbedded sand and gravel with epsilon bedding as coarse-grained point bars. They did not recognize finer-grained overbank deposits.

In the Lower Mississippi Valley and Gulf Coast, the Citronelle is thought to be a braided stream deposit (Autin, 1977; Self, 1984;, Smith and Maylan, 1983) and may be associated with small alluvial fans forming along valley walls, fault scarps and structural high such as the Wiggins Uplift of southern Mississippi (Figure 1). Campbell (1971) considers some of the gravel point bar deposits. The Citronelle also contains some pointbar and overbank deposits in Alabama (Isphording, personal communication).

Plio-Pleistocene gravels appear to be an apron of braided stream deposits associated with alluvial fans that surround the Appalachian Province to the northwest, west and south.

Age, petrology, sedimentary structures, sources, and depositional environments are summarized in Tables 1 and 2.

Discussion

The Plio-Pleistocene Citronelle-Lafayette gravels and their lithologic equivalents represent coalescing, braided-stream, alluvial fan deposits that formed an apron or pediment around the Appalachian province as suggested by Doering (1956, 60) and Self (1984).

The coarse-grained nature of these deposits contrasts with typical fine-grained Quaternary sediments such as fine sands, silts, clays and marls deposited in swamps, marshes, lagoons low- energy, shallow marine, deltaic and fluvial environments in the Gulf Coastal Plain-Mississippi Embayment. Plio-Pleistocene streams had higher competencies than modern streams and thus operated under different hydrological conditions. Coarse-grained material was available in the Appalachians and adjacent coastal plain and were transported by high-energy, braided streams. These conditions may be accounted for by: 1) Plio-Pleistocene paleoclimates; 2) sea level changes; 3) uplift of source areas.

Paleoclimate

Potter (1955) indicates that fauna and flora in the Citronelle (Berry, 1916) are similar to those living today in the southeast, suggesting a similar Plio-Pleistocene climate -a humid, temperate climate.

Guccione and Rutledge (1990) propose a humid climate for the Crowley's Ridge deposits based on the following: 1) logs are found in the deposits; 2) paleosol with the deposits contain rootlets; 3) the absence of carbonate gravel even though Paleozoic carbonates were abundant and available in the source areas; 4) the lack of abundant cut and fill structures and the lateral continuity of the deposits suggest a more constant stream flow found in humid climates.

Alluvial fan formation is well-documented in humid climates. Smith (1981) reports on small alluvial fans forming in the warm humid Yazoo Valley of Mississippi, and Reinhardt and others (1984) believes that the same processes that formed Pliocene alluvial fans in the Warm Springs area of the Georgia Piedmont still operate today. The Kosi River fan of northern India is a large fan developing in a humid climate (Gole and Chitale, 1967).

Sedimentary structures, such as 20 ft (6 m) thick sets of crossbeds (Potter 1955) and channels of 6-9 ft (2-3 m) deep with cobble to boulder-sized purple to white mudstone clasts (Mossa and Self 1986), probably ripped up from underlying Tertiary units indicate high magnitude sediment-laden flood flows.

Such large-scale features and cobble-boulder sized clasts are relatively rare in the deposits and seem to indicate local flooding events. Olive (1980) suggests increased Miocene (?)-Pliocene runoff due to increased spring melts. Although increased spring runoff would contribute to the reworking and transport of sedi-

Table 1. Summary of age, composition and sources of important late Cenozoic graveliferous deposits – Gulf-Atlantic Coastal Plain.

Area & Authors	Age	Composition	Sources
Upper Mississippi Valley (Potter, 1955)	Pliocene	Chert-dominated gravel fraction, secondary qtz. granules. Sands are qtz. arenites with minor chert, micas, feldspar. Meta, qtz. present. Meta. heavy mineral suite. Iron oxides present.	Blue Ridge with minor contribution from Canadian Shelf. May have been re-cycled through Eocene deposits.
Southeastern-Louisiana (Self, 1983, 84)	Plio-Pleistocene	Chert-dominated gravel fraction with qtz. granules. Sand is qtz. arenite with minor chert. Red interstitial clay & iron oxides. Meta. qtz. present. Meta. heavy mineral suite.	Sedimentary Appalachians for chert, crystalline Appalachians for qtz. Recycling through Tertiary units.
Southern Mississippi (Smith & Meylan,1983)	Plio-Pleistocene	Chert gravels, 2 sands with meta. heavy mineral suite	Ft. Payne chert (Miss.) of Highland Rim for Chert. Crystalline Appalachian for quartz.
Alabama (Springfield & LaMoreaux, 1957; Isphording & Lamb, 1971)	Plio-Pleistocene	Qtz. sand with occasional chert gravels and qtz. granules. Sand is micaceous; clays are present. Ironstones present. Meta. heavy mineral suite	Southern Appalachians recycled through Tertiary units
Crowley's Ridge (Guccione, Pryor, & Rutledge, 1990)	Pliocene	Gravel-chert dominate Sdst, quartz and Tertiary clay pebbles present sand-quartz with minor chert. Hm-Zircon, Rulite, tourmaline and high ranked metamorphic.	Mid-continent Paleozoics Appalachian

ments, it is doubtful that this could initiate widespread gravel deposition from the Mississippi Valley to the Gulf Coast.

Sea Level Fluctuations

A relative lowering of sealevel might be expected to lower base level, increase the stream gradient, competence, load and erosions and lead to fluvial sedimentation prograding seaward (Posamentier and Vail, 1988). However, the affect of sealevel change on streams draining into coastal areas is influenced by the rate and magnitude of sealevel change, the width and slope if the Continental Shelf and the increase in drainage area (Miall, 1991). In addition, Gulf Coast subsidence and sediment influx must be considered.

Table 2. Summary of texture, sedimentary structures, paleo-current directions and depositional environment of important Late Cenozoic gravel deposits in the Atlantic-Gulf Coastal Plain

Area & Authors	Texture And Sedimentary Structures	Paleo-current Directions	Depositional Environment
Upper Mississippi Valley (Potter, 1955)	Open work gravels with interstitial sds. poorly sorted. Gravel rounded with broken rounds. X-beds with sets up to 20 ft. thick, cut & fill structures	190-250° Azimuth (south to west-southwest)	Braided stream assoc. with three large alluvial fans (Mississippi, Tennessee, and Ohio Cumberland fan
Southeast Louisiana & Southwest Mississippi (Self, 83,84; Smith and Meylan 1983)	Poorly sorted gravelly sands to muddy sandy gravels. Gravels are rounded trough and tabular x-beds, cut and fill structures, scoured surfaces and channels (some large). A few gravel beds graded. Bedding lenticular.	South to southeast at Red Bluff, Miss. (Smith & Meylan 1982)	Braided streams associated with small alluvial fans
Alabama (Springfield & LaMoreaux, 1957; Isphording & Lamb, 1971)	Coarse to medium sands, poorly sorted with scattered granules. Secondary gravel beds. Bed lenticular and highly x-bedded in places. Some thick clay lenses or beds.	?	Fluvial
Crowley's Ridge (Guccione, Pryor, and Rutledge, 1990)	Gravel-granule-pebble with coarse sd. matrix. Bedding gravels indistinct-weakly horiz. Sands high x- bedded - planar and trough.	Southwest to west (Channel direction)	Combination of coarse- grained braided and meandering stream deposition

Miall (1991) argues that fluvial deposition, as well as coastal onlap and coastal plain progradation occurs during rising sealevel due to the infilling of incised valleys by fluvial sediments as demonstrated by Sutter, and others (1987) for Quaternary sealevel shifts on the Louisiana Continental Shelf.

Seismic stratigraphic studies (Vail and others, 1977), Atlantic deep sea cores (Loubre and Moss, 1986), and studies of the Louisiana Continental Shelf (Lowrie, 1986, Shideler, 1987, Geitgey, 1988) show the Plio-Pleistocene sealevels were lower than at present, were falling, and that a Plio-Pleistocene lowstand occurred on the Louisiana Continental Shelf. The magnitude of the lowstand on the eastern Gulf and its effect on coastal fluvial systems is difficult to ascertain due to the factors listed above.

The vast majority of Late Tertiary-Early Quaternary coarse- grained deposits, including

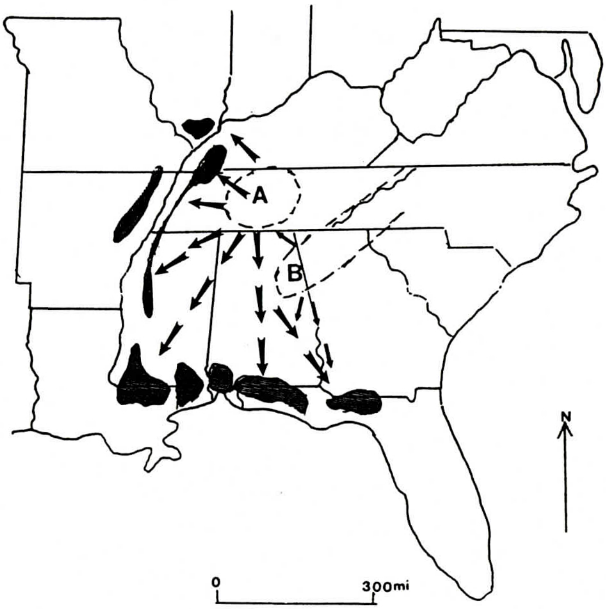

Figure 2. Source and dispersion of Late Tertiary-Early Quaternary graveliferous deposits. Large arrows show dispersion of chert and reworked Appalachian materials from the Nashville Dome. Small arrows show secondary components from Blue Ridge and Piedmont. A = Nashville Dome; B = Crystalline Appalachians.

all of the Lafayette, Crowley's Ridge, Tennessee Plio-Pleistocene and the majority of the Citronelle Formation are considered "hinterland deposits" (Vail and others, 1977) that are too far inland to be noticeably affected by sea level (Vail and others, 1977; Saucier, 1974). In Mobile and Baldwin Counties, Alabama, the Citronelle outcrops within 2 to 4 miles of the present shoreline at elevations of approximately 50 ft (15 m) (Reed, 1971a, 1971b). But they would be much further inland from a Plio-Pleistocene shoreline on the outer edge of the shelf (Shideler, 1987; Geitgey, 1988) and might not be affected.

The distance from a Plio-Pleistocene shore, plus possible factors suggested by Miall (1991) and Sutter (1987) suggest that relative sealevel change played little or no part in the deposition of Late Tertiary-Early Quaternary coarse-grain clastics, although it is uncertain whether it had some effect on the Citronelle in the lower Gulf Coast.

Vertical Uplift

Cenozoic uplift and topographic rejuvenation are well-documented in the Appalachians where superimposed streams have exhumed older landscapes and cut wind and water gaps as well as anomalously narrow valleys (Dott and Batten, 1971, p. 421). Many authors use the coarse clastics to infer Late Cenozoic uplift and rejuvenation (Dott and Batten, 1971; Doering, 1956, 60).

Late Cenozoic tectonism has occurred in the Atlantic Coastal Plain (Winkler and Howard, 1977; Markewich, 1987; McCartan, 1987; Newell, 1987; Prowell and Owens, 1987; Soller, 1987). The southeastern United States has been subjected to East-West to NW- SE compressional forces that have resulted in regional uplift and reverse faulting, with maximum uplift taking place in the Blue Ridge and Piedmont (Prowell and Owners, 1987; Rader and others, 1986; Soller, 1987).

"No load" structure maps and differential erosion rates of units exposed in the Central Basin and Highland Rim of the Nashville Dome were used by Reesman and Stearns (1989) to show that the Nashville Dome has been uplifted from Late Tertiary through quaternary time due to isostatic adjustment resulting from the stripping of 7000-8000 ft of overlying rocks. The Ft. Payne chert, which covered the Dome, was breached over the Central Basin 5 million years ago (Early Pliocene?) (Reesman and Stearns, 1989). Smith and Meylan (1983) show that the Ft. Payne is the source of chert in the Citronelle gravels of Southern Mississippi while Potter (1955) and Olive (180) point to the Highland Rim-Nashville Dome area as the source for the Lafayette gravels. The uplift of the Dome and associated Highland Rim would not only provide large amounts of cherts, but would result in the recycling of the Tuscaloosa gravel and other clastic units (Pennsylvanian?) no longer present, thereby providing a source for quartzose (Appalachian) components of the deposits. Some components may have been contributed from uplift of Blue Ridge and Piedmont, especially as one goes eastward along the Gulf Coast toward the Florida Panhandle. Thus, the breaching and stripping away of the Ft. Payne chert, Tuscaloosa and perhaps other units during rejuvenation and uplift of the Nashville Dome could be the triggering mechanism for widespread Late Tertiary- Early Quaternary cherty graveliferous deposits in the Lower Mississippi Valley and Gulf Coast, as shown in Figure 2.

Reworking of the gravel sheet by rivers as well as continued erosion of the Ft. Payne and local uplifts such as the Wiggins Uplift (Burnett and Schumm, 1983) may have redistributed gravels and resulted in age variations from Pliocene to Early Pleistocene for individual deposits and the general decrease in age towards the coast and away from the Nashville Dome. Brown (1967) and Isphording (1983) have proposed that the Tertiary ancestral Tennessee River flowed directly through Mississippi or eastern Alabama to the Gulf of Mexico and has transported the Citronelle and older sediments into the Gulf Coast region. Late Tertiary- Early Quaternary graveliferous deposits were recycled into Pleistocene graveliferous deposits and recent alluvium (Olive, 1980; Cullinan, 1969; Self, 1983;).

CONCLUSIONS

Plio-Pleistocene coarse sand or gravels were deposited as a coalescing system of braided stream and alluvial fan deposits with secondary meandering stream deposits that surrounds the Appalachian-Allegheny provinces.

It is proposed that the removal of the Ft. Payne chert, Tuscaloosa Formation and possibly other units that covered the Nashville Dome during Late Tertiary rejuvenation an uplift is the triggering mechanism for the deposition of Late Tertiary-Early Quaternary chert gravels such as the Lafayette and Citronelle formations in the Lower Mississippi Valley and Gulf Coast. This hypothesis could account for the following:

1. a mechanism for production of the large volume of chert found in gravels;
2. an apron of braided/alluvial fan deposits distributed in an arcuate pattern around the Dome;
3. the presence of quartzose components derived from the Crystalline Appalachians through recycling of the Tuscaloosa Formation and perhaps other (Pennsylvanian?) clastic units no longer present on the Dome;
4. location variations in age from Pliocene to Early Pleistocene due to reworking by streams' continued erosion of the Ft. Payne and the influence of local uplifts. These processes are continuing today;
5. the general decrease in age towards the coast and away from the Dome.

It appears that climatic and/or relative sea level controls, although important locally, were minor contributors on the regional scale and did not trigger widespread Late Tertiary-Early Quaternary gravel deposition in the Lower Mississippi Valley and Gulf Coast.

Continued detailed studies of Late Tertiary-Early Quaternary non-glacially derived gravels on a regional scale, including the upland/Citronelle gravels in the Atlantic Coastal Plain (Schlee, 1957; Doering, 1960; Rader, Newell and Mixon, 1987) will lead to a more complete understanding of the Late Tertiary preglacial history of the southeastern United States.

ACKNOWLEDGMENTS

This report is an outgrowth of a project on gravel resources funded by the Louisiana Geologic Survey under the direction of Dr. Charles Groat. Discussion with Whitney Autin, Charles Givens, Russell Bender, Michael Gibson, and Thomas McCutchen were beneficial. Angeline Sanders typed the manuscript.

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