HEAVY-MINERAL CONCENTRATIONS ASSOCIATED WITH SOME GAMMA-RAY AERORADIOMETRIC ANOMALIES OVER CRETACEOUS SEDIMENTS IN NORTH CAROLINA: IMPLICATIONS FOR LOCATING PLACER MINERAL DEPOSITS NEAR THE FALL ZONE

by

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U.S. GEOLOGICAL SURVEY OPEN-FILE REPORT OF-92-396

1992

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ABSTRACT

Heavy-mineral concentrations and their mineralogy were characterized for twenty samples from four sites in Cretaceous and younger sediments of the inner Coastal Plain of North Carolina. The sites were near the peaks of individual gamma-ray anomalies (high values) shown by aeroradiometric surveys. Ground vehicle traverses with a gamma-ray scintillometer were used to precisely define the extent of the anomaly. Spectral gamma-ray data were also collected at the sample sites to measure the components of the gamma-ray radiation field before sediment sampling. At each site samples were collected from power auger holes at five-foot intervals; to a maximum depth of 35 feet.

The samples contain an average of 1.30 weight percent heavy minerals with a range of 0.24 to 4.80 weight percent. Two sample sites are in Cretaceous sediments as shown on the 1985 North Carolina State Geologic Map. Two sites are in younger sediments. Economically important heavy minerals (ilmenite (including altered ilmenite), rutile, zircon, monazite, aluminosilicates, and gold) average 71.7 weight percent of the heavy minerals in the samples from the two Cretaceous sites. The average for the two post-Cretaceous sites is lower (35.8 percent) and their assemblages contain greater percentages of the labile heavy minerals (magnetite, epidote, pyroboles, and garnet).

The positive correlation of high thorium and high uranium radioelement concentrations, as determined by gamma-ray spectrometry, with monazite and zircon concentrations, suggests that existing aeroradiometric data may be useful in exploring for heavy-mineral placer deposits in Cretaceous sediments. Supporting evidence for a high placer resource potential in these sediments is provided also by titanium, hafnium and rare-earth element geochemical anomalies in recent alluvial sediments from streams draining the Cretaceous of the Fall Zone. Monazite and zircon concentrations attained maxima of 5.5 and 13.8 weight percent, respectively, of the heavy-mineral assemblage in Cretaceous-derived sediments. Evidently heavy-mineral content is a powerful tool for discriminating between Cretaceous and post-Cretaceous sediments along the Fall Zone of North Carolina.

INTRODUCTION

This report presents the results of a preliminary study of the heavy-mineral assemblages of sediments associated with aeroradiometric anomalies along the Fall Zone of North Carolina. Some anomalies are associated with sediments of Cretaceous age; others are in post-Cretaceous age sediments.

Exploration for heavy-mineral deposits by using gamma-ray aeroradiometric maps is based on the presumption that radioactive heavy minerals (monazite and zircon) are concentrated with the nonradioactive heavy minerals (ilmenite, rutile, leucoxene (altered ilmenite), staurolite, gold, and others). Economic heavy minerals are most common in nearshore marine deposits. Such concentrations in ancient shoreline deposits that are now elevated and

commonly parallel to the present shorelines are the major sources of preferred heavy-mineral assemblages, which contain mature suites of minerals (generally weathered assemblages that have relatively low garnet, epidote, and amphibole group contents, and high TiO_2-content ilmenite). Radiometric contrast caused by monazite and, to a lesser extent, by zircon and sphene is ideally detectable by aerial and ground-radiometric surveys (Force and others, 1982; Grosz, 1983; Grosz and others, 1989; Owens and others, 1989).

PREVIOUS WORK

The presence of monazite (and other heavy minerals) in the southeastern States has been known since 1849 when noted in Rutherford County's gold placers by Shepard (1849, 1852). Monazite placers were mined in 1887-1911 and 1915-1917. A fluvial deposit of monazite, ilmenite, rutile, staurolite, and gravel was mined at Horse Creek near Aiken, SC (Mertie, 1975). This deposit, near the South Carolina-Georgia State line (Figure 1) is both underlain and surrounded by sediments of Cretaceous age. These Cretaceous sediments directly overlie the crystalline rocks of the Piedmont. Mertie (1975) contends that along paleoshoreline deposits the Cretaceous sediments should have higher tenor in heavy minerals than other non-shoreline deposits of the Coastal Plain lying between the Fall Zone and the ocean and, further, that in such deposits, the sediments may contain minable deposits of heavy minerals. The recent alluvial placers on Horse Creek contain heavy minerals reconcentrated from Cretaceous formations. Recent discoveries of heavy-mineral concentrations along the Fall Zone of northern North Carolina and southern Virginia (Berquist, 1987; Carpenter and Carpenter, 1991; Hoffman and Carpenter, 1992), are in sediments younger than Cretaceous, but underscore this Fall-Zone-related placer potential.

Previous work (Mertie, 1975; Overstreet; 1967; Overstreet and others, 1968) shows that some Cretaceous-age sediments in the southeastern United States are monazite enriched. Three belts of monazite-bearing source rocks (not all Cretaceous) are identified in the southeastern United States; all extend into North Carolina (Figure 1). The parts of the Coastal Plain that are most likely to have received monazite and other heavy minerals from the three monazite belts are in Virginia, North Carolina, South Carolina, Georgia, Florida, and eastern Alabama. Monazite was identified in the Cretaceous sediments and in the Tertiary and Quaternary formations in the Coastal Plain of Virginia, (Force and Geraci, 1975; Grosz, 1983), South Carolina (Overstreet, 1968; Force and others, 1982; Owens and others, 1989) and in commercial heavy-mineral deposits in the Coastal Plain of Georgia and Florida (Garnar, 1972; Grosz and others, 1989a). Some of these studies were based on aeroradiometric data. Monazite has also been found in sediments of the Atlantic Continental Shelf offshore of New Jersey (Grosz and others, 1989b), Virginia (Grosz and Escowitz, 1983; Berquist and others, 1990), North Carolina (Grosz and others, 1990),

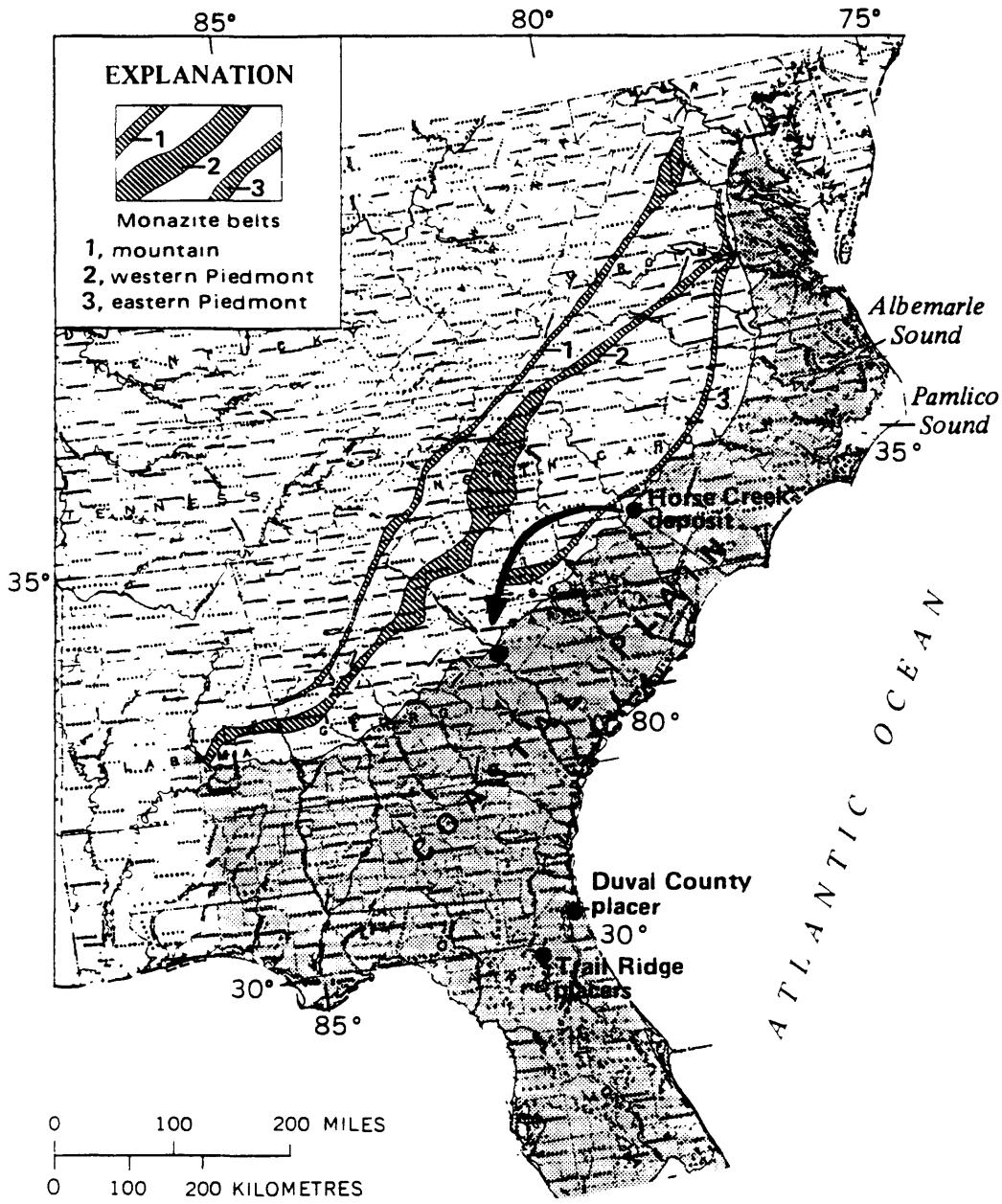

Figure 1.--Map showing the three monazite belts in the southeastern United States. Note that the Horse Creek deposit is at the South Carolina-Georgia State line, not at the North Carolina-South Carolina State line as shown by Mertie. Modified from Mertie (1975).

South Carolina (Grosz and Nelson, 1989), Georgia (Grosz, 1992a), and Florida (Grosz and others, 1989c). Heavy-mineral assemblages in surficial sediments on the continental shelf offshore of North Carolina, for example, contain an average of 25.5 percent labile minerals in a range from 0.0 to 59.5 percent; their ZTR index (Hubert, 1962) (zircon + tourmaline + rutile expressed as a percentage of the non-opaque heavy minerals; an index of textural maturity of sediments) averages 15.5 in a range from 1.9 to 50.

The three monazite belts are drained by the Roanoke River (Virginia), the Pee Dee (North Carolina), the Santee and Savannah rivers (South Carolina), and the Altamaha and Flint rivers (Georgia). The Cretaceous sediments may be important sources for monazite now contained within placer deposits of heavy-minerals in Atlantic Coastal Plain sediments. They may also have been a source for heavy-mineral deposits in the Coastal Plain and Continental Shelf sediments offshore of the eastern United States.

Heavy-mineral deposits are, or have been, investigated in the Carolinas, Georgia, and Florida by State and federal geological surveys and by private companies, onshore and offshore. Results of exploration by companies have not been published, however, considerable exploratory drilling was done in North Carolina north of Albermarle Sound in Chowan, Perquimans, Pasquotank, and Camden Counties. Some drilling was also undertaken between Albemarle and Pamlico Sounds. The sand fraction in the counties north of Albemarle Sound reportedly contains 5-10% kyanite and staurolite plus opaque minerals. The opaque minerals, in decreasing abundance, are: ilmenite, leucoxene, magnetite, and marcasite. Translucent heavy minerals from this size fraction include brown tourmaline, kyanite, staurolite, anatase, zircon, and titanite (Mertie, 1975).

Powers (1951), in his study of the Black Creek Formation in North Carolina along the Cape Fear River, separated heavy minerals from silt and sand fractions of 27 samples. He found, in decreasing abundance, pyrite, staurolite, garnet, kyanite, tourmaline, zircon, ilmenite, rutile, marcasite, hematite, andalusite, titanite, magnetite, epidote, leucoxene amphibole, sillimanite, glaucophane, corundum, pyroxene, clinozoisite(?), limonite, monazite(?), bronzite, spinel(?), hypersthene, and biotite. Of the 27 samples, about one-third contain approximately 5 percent heavy minerals in the silt and sand fractions.

THE STUDY AREA

Cretaceous Deposits in the North Carolina Coastal Plain

The oldest Cretaceous deposits exposed in the Coastal Plain of North Carolina belong to the Late Cretaceous Cape Fear Formation consisting of fluvial sands and muds resting unconformably on the crystalline rocks of the Piedmont Province. Eastward, and at depth, are age-equivalent deposits of marine or marginal marine origin (Hoffman, 1986).

The Middendorf and Black Creek formations, also of Late Cretaceous age overlie the Cape Fear Formation in it's updip and downdip areas, respectively. Some studies (Heron, 1958; North Carolina Geological Survey, 1985) suggest a lateral, intertonguing relationship between the fluvial Middendorf Formation and the deltaic to estuarine Black Creek Formation to the east. The uppermost Cretaceous unit in the North Carolina Coastal Plain is the Peedee Formation. This unit consists of slightly calcareous, locally fossiliferous, fine-grained, marine shelf sands.

More recently, Owens (1989) and Sohl and Owens (1990) have proposed a revised Cretaceous stratigraphy for the Carolinas wherein the Upper Cretaceous sediments are interpreted to comprise a set of stacked deltaic packages separated by regional unconformity surfaces. Each stratigraphic subdivision consists of delta plain, delta front, prodelta, and shelf deposits. These workers retain the Cape Fear, Middendorf, and Peedee as formation names (although with the latter two having revised definitions) and raise the Black Creek name to group status with subdivision into Tar Heel, Bladen, and Donoho Creek formations.

The resolution of these two stratigraphies and the resulting resolution of conflict in geologic mapping of the Cretaceous of the North Carolina Coastal Plain sediments is the object of current on-going studies. For the purposes of this report, the Geologic Map of North Carolina (North Carolina Geological Survey, 1985) is referenced because it is the only consistent mapping at present throughout the study area. One shortcoming of this map that applies to this report is that Quaternary age deposits are not shown at altitudes above 25 feet. Thus, there may be significant areas and thicknesses of Quaternary sediment present at the sample sites, which are not shown on the map.

Rationale For The General Area Of Site Studies

The northeasterly-trending, relatively abrupt, physiographic change at the intersection of the sediments of the Coastal Plain with the crystalline rocks of the Piedmont is termed the Fall Zone. This drop in gradient reduces the relatively high velocity stream-flow associated with he more rugged topography of the Piedmont and Slate Belt rocks and results in the deposition of both the coarse-grained bed load and of some of the higher density finer-grained suspended load along the Fall Zone. The resulting deposits may be reworked and enriched by subsequent stream-flow and channel migration. These zones of hydraulic deposition and reworking can be sites of commercially important deposits of heavy minerals such as the Horse Creek deposit at the South Carolina-Georgia State line (Mertie, 1975). Heavy-mineral resource potential, therefore, may be greater along the western edge of the Coastal Plain than elsewhere within this province.

The Pee Dee River, with headwaters in the Slate Belt, has a heavy-mineral assemblage similar to that of the Cape Fear River although it contains more monazite (Overstreet, 1967;

Mertie, 1975). This similarity probably reflects on the outcrop pattern of the Cretaceous Middendorf and Black Creek formations which contain significant detrital monazite. The high monazite content (Overstreet, 1967; Mertie, 1975; Owens and others, 1989) is reflected by total-count (U.S. Geological Survey, 1975, 1976, 1977, 1978) and spectral airborne gamma-ray radiation surveys of the region (U.S. Department of Energy, 1980a,b,c; Duval and others, 1989, 1990) which show elevated radioactivity and elevated thorium-related radioactivity, respectively, associated with exposures of Cretaceous rocks near the Fall Zone. This relative abundance of monazite in the region near the Fall Zone of North Carolina provides the basis for its inclusion in Staatz and Armbrustmacher's (1982) rare-earth provinces of the conterminous United States map.

Four sites in the vicinity of the Fall Zone coincident with anomalous aeroradioactivity were selected for drill sampling. The surficial extent of the Cretaceous sediments, locations of peak gamma-ray radiation intensity, and drill locations are shown on Figure 2.

HEAVY-MINERAL STUDY

Field Methods

Field investigations began with ground checks of total-count aeroradiometric anomalies. Areas where aeroradiometric values were greater than local background (anomalous) were identified on 7.5-minute quadrangles. There, anomalous areas were traversed with a total-count vehicle-borne scintillometer to validate their existence and extent. Continuous readings of a truck-mounted spectral scintillometer were taken over the sediment of the area to find high values of radioactivity.

Where anomalous high values were found, a four channel, gamma-ray spectral scintillometer with a 113 in^3 sodium iodide detector was used to measure the components of the radiation field. After temperature equilibration and standardization against a Ba^{133} gamma-ray source, the count rate was measured at the following gamma-ray energies: 1.46 megaelectronvolts (MeV) from K^{40}, 1.76 MeV from Bi^{214} in the U^{238} series, and 2.62 MeV from Tl^{208} in the Th^{232} series. The counting time at each locality did not exceed 8 minutes. The field data were reduced to radioelement concentration by Stromswold and Kosanke's (1978) method (Table 1).

Potential drill sites were evaluated by the locations of high aeroradiometric values, good thickness of Cretaceous sediments, truck-mounted auger access, and permission to drill by landowners. Table 2 shows drill hole coordinate locations of the chosen sites. Power auger samples were collected in five-foot intervals to a maximum depth of 35 feet. A shallow water table (commonly at 5 to 15 feet beneath the surface) made difficult the recovery of sediment samples from below those depths.

Laboratory Methods

An average of 8,605 grams of bulk sample (individual sample weights ranged from 372 to 17,205 grams) was

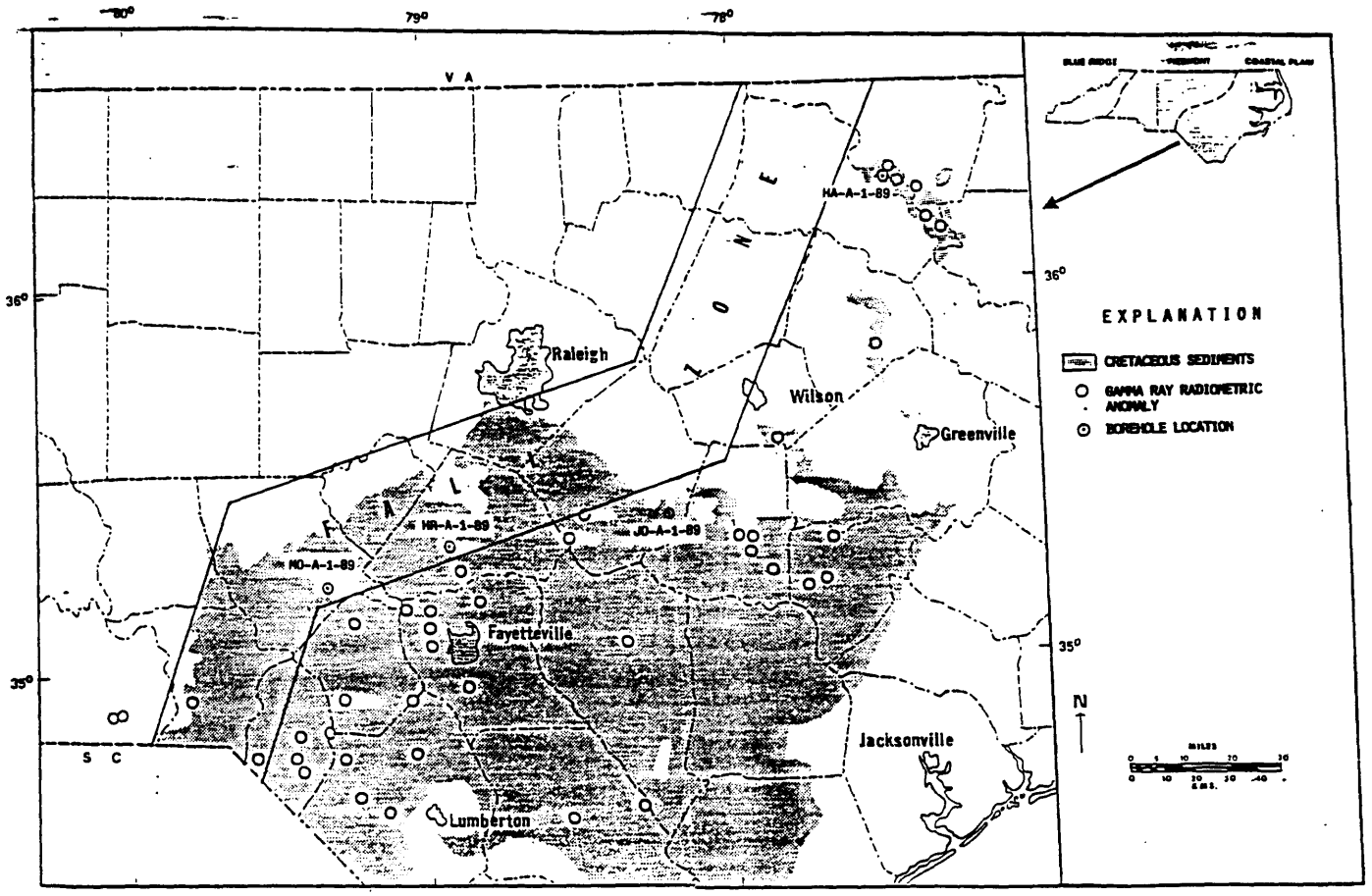

Figure 2.-- Map showing the surficial extent of Cretaceous sediments, locations of peak gamma-ray radiation intensity, and locations of drill holes.

SAMPLE SITE	K CHANNEL COUNTS	U CHANNEL COUNTS	Th CHANNEL COUNTS	COUNTING TIME (sec)	RADIOELEMENT CONCENTRATIONS K %	eU (ppm)	eTh (ppm)
MO-A-1-8	7086	6056	7432	360	0.55 +/- 0.04	7.27 +/- 0.45	31.63 +/- 0.54
MO-A-1-8	7107	6168	7448	360	0.54 +/- 0.04	7.51 +/- 0.45	31.69 +/- 0.54
HR-A-1-8	2339	2088	2180	360	0.19 +/- 0.02	2.72 +/- 0.17	9.24 +/- 0.24
HR-A-1-8	2289	2088	2081	360	0.18 +/- 0.02	2.92 +/- 0.17	8.80 +/- 0.23
JO-A-1-8	597	2283	3399	360	-0.32 +/- 0.02	2.28 +/- 0.19	14.51 +/- 0.29
JO-A-1-8	283	2282	3337	360	-0.39 +/- 0.01	2.33 +/- 0.19	14.23 +/- 0.29
JO-A-1-8	3881	3080	4394	480	0.24 +/- 0.02	2.38 +/- 0.19	14.09 +/- 0.27
HA-A-1-8	9185	2687	2582	360	1.75 +/- 0.04	3.70 +/- 0.28	11.00 +/- 0.37
HA-A-1-8	9997	2588	2594	360	1.94 +/- 0.04	3.45 +/- 0.29	11.01 +/- 0.38

Table 1.--Field spectral gamma-ray data collected at sampling locations and radioelement concentrations. Eu, equivalent Uranium; eTh, equivalent Thorium; negative values caused by insufficient counts in the K channel--data not valid; A,B,C represent replicate measurements at the same locality.

available from each 5-foot section. All of the sample obtained by the auger was used for the separation of heavy minerals because some mineral species, such as monazite and gold, were expected to be present in very small quantities. Smaller samples are less likely to contain rare minerals because of the "particle-sparsity-effect" (Clifton and others, 1969).

After removal of the gravel fraction by wet sieving through a 10 mesh (2.00 mm aperture) U.S. Standard stainless steel sieve, the clay fraction ofthe sediment was decanted. An unknown minor amount of silt-size sediment was lost during this process. The gravel-free and clay-free fractions were then processed through a three-turn spiral concentrator to obtain the heavy-mineral fraction. The concentrates averaged 235 grams but ranged from 37 to 926 grams. A 250- to 360-gram sample of spiral concentrator gangue was also taken to quantify the types of heavy minerals not recovered by the spiral. Two of the samples (HA-A-1-89-6 and JO-A-1-89-5) were not processed through the spiral concentrator because, after removal of their gravel and clay fractions, they were small enough for the next processing step. Sample characteristics are given in Table 2.

Heavy-mineral concentrate and spiral gangue samples were dried and settled through acetylene tetrabromide (SG > 2.96) to extract their heavy-minerals. Magnetic fractionation of each heavy-mineral concentrate was done to reduce the number of mineral species in each magnetic fraction to aid mineral identification and quantification. The heavy-mineral assemblage of spiral concentrates was separated into six magnetic fractions on a Frantz Magnetic Barrier Separator at 0.1, 0.2, 0.4, 0.6, and 1.8 ampere settings. Heavy-mineral concentrates from the spiral gangue which weighed over 2 grams were also separated into six magnetic fractions. Concentrates weighing less than 2 grams were split into three magnetic fractions at 0.4, and 1.8 Amperes.

Each sub-fraction was weighed and studied independently with petrographic and reflected light microscopes. Comparison charts (Terry and Chillingar, 1955) and point-counting were used to estimate mineral volume abundances in each magnetic subfraction. Zircon and monazite identification was aided by the use of long- and short-wave ultraviolet illumination.

Values for individual mineral species were summed and calculated as percentages of the total (combined spiral-recovered and spiral-rejected) heavy-mineral fraction. Densities of individual mineral species were not compensated for by this method. The mineralogic data are given on Table 3.

COMPARISON OF REGIONAL GEOCHEMICAL STREAM SEDIMENT ANOMALIES WITH AERORADIOMETRIC ANOMALIES

The pattern shown by the aeroradiometric data can be compared with patterns shown by selected elements from stream-sediment geochemical data collected under the

SAMPLE NUMBER	LATITUDE NORTH	LONGITUDE WEST	DEPTH INTERVAL (ft)	WET SEDIMENT COLOR	BULK SEDIMENT TEXTURE	BULK WEIGHT (g)	WEIGHT PERCENT GRAVEL	WT% Sp. Gr. >2.96
HA-A-1-89-1	36 17'57"	77 28'35"	0-5	5Y 4/4 MODERATE BROWN	CLAYEY SAND	5831	0.18	2.08
HA-A-1-89-2	36 17'57"	77 28'35"	5-10	10Y 5/4 MODERATE YELLOWISH BROWN	SILTY SAND	6324	0.70	4.42
HA-A-1-89-3	36 17'57"	77 28'35"	10-15	5Y 3/4 MODERATE BROWN	SILTY SAND	10327	0.07	4.80
HA-A-1-89-4	36 17'57"	77 28'35"	15-20	5Y 4/4 MODERATE BROWN	SILTY SAND	5183	2.18	2.56
HA-A-1-89-5	36 17'57"	77 28'35"	20-25	5Y 4/4 MODERATE BROWN	SANDY SILT	5962	16.78	1.74
HA-A-1-89-6	36 17'57"	77 28'35"	25-30	10YR 4/4 MODERATE YELLOWISH BROWN	SILTY SAND	1503	23.19	1.40
HA-A-1-89-7	36 17'57"	77 28'35"	30-35	10YR 4/4 MODERATE YELLOWISH BROWN	SILTY SAND	1686	21.71	1.69
HR-A-1-89-1	35 19'45"	78 56'35"	0-5	10YR 4/4 MODERATE YELLOWISH BROWN	CLAYEY SAND	10958	2.12	0.31
HR-A-1-89-2	35 19'45"	78 56'35"	5-10	5Y 6/1 LIGHT OLIVE GRAY	SANDY CLAY	17205	0.64	0.26
HR-A-1-89-3	35 19'45"	78 56'35"	10-15	5Y 6/1 LIGHT OLIVE GRAY	CLAYEY SAND	16922	1.75	0.36
JO-A-1-89-1	35 22'26"	78 12'26"	0-5	10YR 4/4 MODERATE YELLOWISH BROWN	CLAYEY SILT	9985	3.63	0.76
JO-A-1-89-2	35 22'26"	78 12'26"	5-10	5YR 5/6 LIGHT BROWN	SILTY SAND	15215	20.10	0.56
JO-A-1-89-3	35 22'26"	78 12'26"	10-15	5Y 5/6 LIGHT OLIVE BROWN	SILTY SAND	8770	17.64	0.34
JO-A-1-89-4	35 22'26"	78 12'26"	15-20	5Y 5/6 LIGHT OLIVE BROWN	SILTY SAND	9063	10.60	0.95
JO-A-1-89-5	35 22'26"	78 12'26"	20-25	2 N2 GRAYISH BLACK	SILTY CLAY	372	0.00	0.24
MO-A-1-89-1	35 13'42"	79 20'31"	0-5	5Y 5/6 LIGHT OLIVE BROWN	SILTY SAND	11804	7.55	0.82
MO-A-1-89-2	35 13'42"	79 20'31"	5-10	5Y 6/4 DUSKY YELLOW	SILTY CLAY	4818	1.72	0.92
MO-A-1-89-3	35 13'42"	79 20'31"	10-15	5Y 6/4 DUSKY YELLOW	SILTY CLAY	17038	1.42	0.30
MO-A-1-89-4	35 13'42"	79 20'31"	15-20	5Y 5/4 MODERATE RED	SILTY CLAY	7405	1.25	0.69
MO-A-1-89-5	35 13'42"	79 20'31"	20-25	5Y 5/4 MODERATE RED	SILTY CLAY	5739	0.95	0.73
					COUNT	20	20	20
					MINIMUM	372	0.00	0.24
					AVERAGE	8605	6.71	1.30
					MAXIMUM	17205	23.19	4.80
					STD DEV	5003	8.09	1.28

Table 2.--Sample location coordinates and sediment sample characteristics.

SAMPLE NUMBER	PERCENT GOLD	PERCENT MAGNETITE	PERCENT ILMENITE	PERCENT RUTILE	PERCENT ZIRCON	PERCENT MONAZITE	PERCENT EPIDOTE	PERCENT PYROBOLES	PERCENT GARNET	PERCENT STAUROLITE
HA-A-1-89-1	N	T	20.4	0.8	2.4	N	32.9	12.7	2.2	1.1
HA-A-1-89-2	N	T	19.0	0.6	1.6	N	29.8	16.4	1.0	1.4
HA-A-1-89-3	N	0.1	18.8	0.4	2.1	N	30.5	22.3	1.5	0.6
HA-A-1-89-4	N	T	16.1	0.4	3.0	N	24.2	22.1	1.2	3.3
HA-A-1-89-5	N	0.1	17.7	0.7	2.4	T	27.7	14.8	3.2	2.9
HA-A-1-89-6	N	0.1	31.2	0.2	3.7	N	33.5	9.5	2.0	3.1
HA-A-1-89-7	N	0.1	19.5	0.6	3.0	N	20.3	15.7	4.8	4.0
HR-A-1-89-1	N	T	53.8	3.9	13.8	2.7	0.3	0.3	N	4.6
HR-A-1-89-2	N	T	50.9	3.1	12.1	1.7	N	1.9	T	3.4
HR-A-1-89-3	T	T	48.0	4.2	13.5	2.8	N	1.6	0.1	4.8
JO-A-1-89-1	N	T	23.2	1.0	4.0	0.3	37.0	10.5	0.3	3.5
JO-A-1-89-2	N	N	26.8	6.2	4.3	0.6	16.0	8.8	0.6	5.2
JO-A-1-89-3	N	T	22.0	1.8	1.8	0.5	16.7	10.5	1.5	4.8
JO-A-1-89-4	N	N	11.9	N	0.8	T	4.6	1.7	1.3	1.7
JO-A-1-89-5	N	1.0	19.7	0.6	13.3	0.2	4.1	2.2	5.0	3.6
MO-A-1-89-1	N	T	56.6	3.6	12.5	5.5	0.4	0.4	0.2	1.0
MO-A-1-89-2	N	N	59.4	3.0	8.1	2.7	N	N	N	2.0
MO-A-1-89-3	T	T	61.1	4.2	8.4	1.8	N	N	0.1	1.9
MO-A-1-89-4	N	T	38.1	1.1	4.3	0.9	0.7	N	N	0.7
MO-A-1-89-5	N	T	32.2	1.0	4.4	0.2	N	N	N	T
COUNT	N/A	5	20	19	20	12	15	16	15	19
MINIMUM	N/A	0.1	11.9	0.2	0.8	0.2	0.3	0.3	0.1	0.6
AVERAGE	N/A	0.3	32.3	2.0	6.0	1.7	18.6	9.5	1.7	2.8
MAXIMUM	N/A	1.0	61.1	6.2	13.8	5.5	37.0	22.3	5.0	5.2
STD DEV	N/A	0.4	16.1	1.7	4.5	1.5	13.0	7.3	1.5	1.5

SAMPLE NUMBER	PERCENT TOURMALINE	PERCENT ALUMINO-SILICATES	PERCENT PYRITE	PERCENT Fe-OXIDE	PERCENT OTHERS	PERCENT EHM/C	PERCENT EHM/T	PERCENT LABILES	ZTR INDEX
HA-A-1-89-1	1.4	11.1	N	N	15.0	34.7	0.72	47.8	7.1
HA-A-1-89-2	6.9	8.1	N	0.2	15.0	29.3	1.30	47.4	13.8
HA-A-1-89-3	3.0	9.7	N	0.2	10.8	31.0	1.49	54.6	7.8
HA-A-1-89-4	4.2	9.9	N	0.2	15.4	29.4	0.75	47.7	11.1
HA-A-1-89-5	4.0	11.1	N	0.3	15.1	31.9	0.55	46.1	10.6
HA-A-1-89-6	0.2	9.2	N	0.1	7.2	44.3	0.62	45.2	6.7
HA-A-1-89-7	4.2	10.5	N	0.6	16.7	33.6	0.57	41.5	12.4
HR-A-1-89-1	7.0	7.4	N	0.1	6.1	81.6	0.25	0.7	61.8
HR-A-1-89-2	13.0	5.8	N	T	8.1	73.6	0.19	1.9	68.8
HR-A-1-89-3	9.6	7.8	N	0.3	7.3	76.3	0.27	2.0	61.5
JO-A-1-89-1	5.7	3.2	N	N	11.3	31.7	0.24	47.8	16.3
JO-A-1-89-2	7.2	7.1	N	N	17.2	45.0	0.25	25.4	31.6
JO-A-1-89-3	6.1	11.5	N	T	22.8	37.6	0.13	28.7	17.6
JO-A-1-89-4	5.0	6.9	58.1	N	8.0	19.6	0.19	65.7	26.5
JO-A-1-89-5	5.0	22.8	N	1.0	21.5	56.6	0.14	13.3	33.3
MO-A-1-89-1	6.7	3.8	N	0.1	9.2	82.0	0.67	1.1	66.9
MO-A-1-89-2	7.2	4.2	N	0.1	13.3	77.4	0.71	0.1	67.3
MO-A-1-89-3	9.2	4.7	N	0.1	8.5	80.2	0.24	0.2	71.9
MO-A-1-89-4	4.6	4.6	N	0.1	44.9	49.0	0.34	0.8	59.2
MO-A-1-89-5	7.7	4.6	N	0.3	49.6	42.4	0.31	0.3	73.2
COUNT	20	20	N/A	14	20	20	20	20	20
MINIMUM	0.2	3.2	N/A	0.1	6.1	19.6	0.13	0.1	6.7
AVERAGE	5.9	8.2	N/A	0.3	16.2	49.4	0.50	25.9	36.3
MAXIMUM	13.0	22.8	N/A	1.0	49.6	82.0	1.49	65.7	73.2
STD DEV	2.8	4.2	N/A	0.2	11.4	20.7	0.36	22.9	25.7

Table 3.--Heavy-mineral data for auger samples. Ilmenite includes leucoxene (altered ilmenite); pyroboles include undifferentiated pyroxenes and amphiboles; aluminosilicates may include sillimanite, kyanite, and andalusite; T, trace <0.1%; N, not detected.

NURE program (Arendt and others, 1980; Averett, 1984). For the approximate area of this study (the North Carolina portion of the Greensboro and Norfolk 1^0 X 2^0 quadrangles; the North Carolina portion of the Florence quadrangle; and the Raleigh, Rocky Mount, and Beaufort quadrangles) the analytical data for 5801 stream sediment samples were extracted from the NURE data base. Titanium (Ti), hafnium (Hf), and individual rare-earth element data for these samples were analyzed for patterns of geographic distribution. The rare-earth elements (REE) cerium (Ce), dysprosium (Dy), europium (Eu), lanthanum (La), lutetium (Lu), samarium (Sm), and ytterbium (Yb), are commonly associated with yttrium (Y), thorium (Th), and uranium (U) in heavy minerals such as monazite ($(Ce,La,Y,Th)PO_4$), xenotime (YPO_4), and allanite (epidote group; $(Ca,Ce,Y)_2(Al,Fe)_3(SiO4)_3(OH)$) (other REE were not analyzed in HSSR). Because zirconium and hafnium possess extraordinary geochemical affinity, Hf usually indicates the presence of zircon (Vlasov, 1966). Although other commonly occurring heavy and light mineral species can carry these elements as well (for example Ti in amphiboles; Hf in pyroxenes; REE, U and Th in apatite), they typically contain only trace abundances of those elements.

Cumulative frequency curves were used to select 455 samples with 1.5% (or more) Ti; 243 samples with 150 ppm (or more) Hf, and 300 samples with 500 ppm (or more) REE. The locations of samples with anomalous Ti are shown on Figure 3, those with anomalous Hf on Figure 4, and those with anomalous REE on Figure 5. We believe from these plots that Cretaceous sediments contain anomalously high Ti, Hf, and REE values, with particularly high REE values in the region near auger holes HR-A-1-89 and MO-A-1-89. For the 300 anomalous REE stream sediments, a plot of the REE content as a function of thorium (Th) content (Figure 6) shows a linear relationship which reflects the presence of monazite in the sediments (Grosz, 1992b).

Anomalous southwesterly-trending Ti and Hf values near the 78^0 longitude align with probable Tertiary-age sediments (as shown by the geologic map of the State) where the ilmenite- and zircon-bearing heavy-mineral deposits referred to above were recently discovered. Note the absence of REE anomalies along the region of Tertiary sediments. Other, north-south trending Ti-Hf anomalous zones to the east of the Fall Zone (Figures 5 and 6) are associated with paleoshoreline deposits and may provide additional targets for heavy-mineral exploration.

RESULTS AND DISCUSSION

The average gravel (+10 mesh) content of the twenty samples is 6.71 percent by weight. Individual gravel content ranges from 0.00 to 23.19 weight percent in the samples. The particles in this (gravel-size) fraction are composed of quartz and rock fragments. Quartz is the dominant constituent of the sand-size fraction; feldspar is a minor component except in samples from site HA-A-1-89 (on the Roanoke River floodplain).

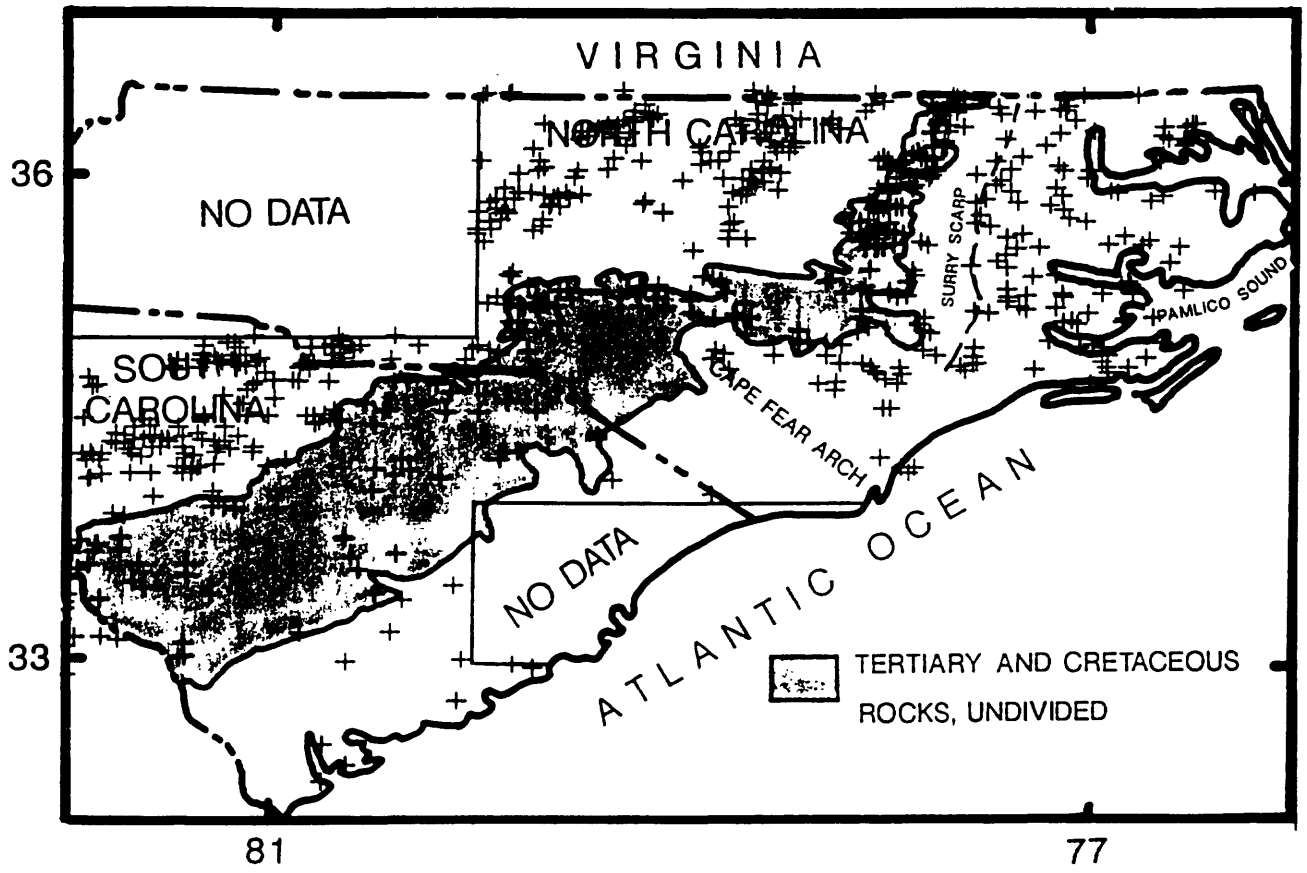

Figure 3.--Plot of NURE stream sediment samples having 1.5 percent (or more) Ti. From Grosz (1992).

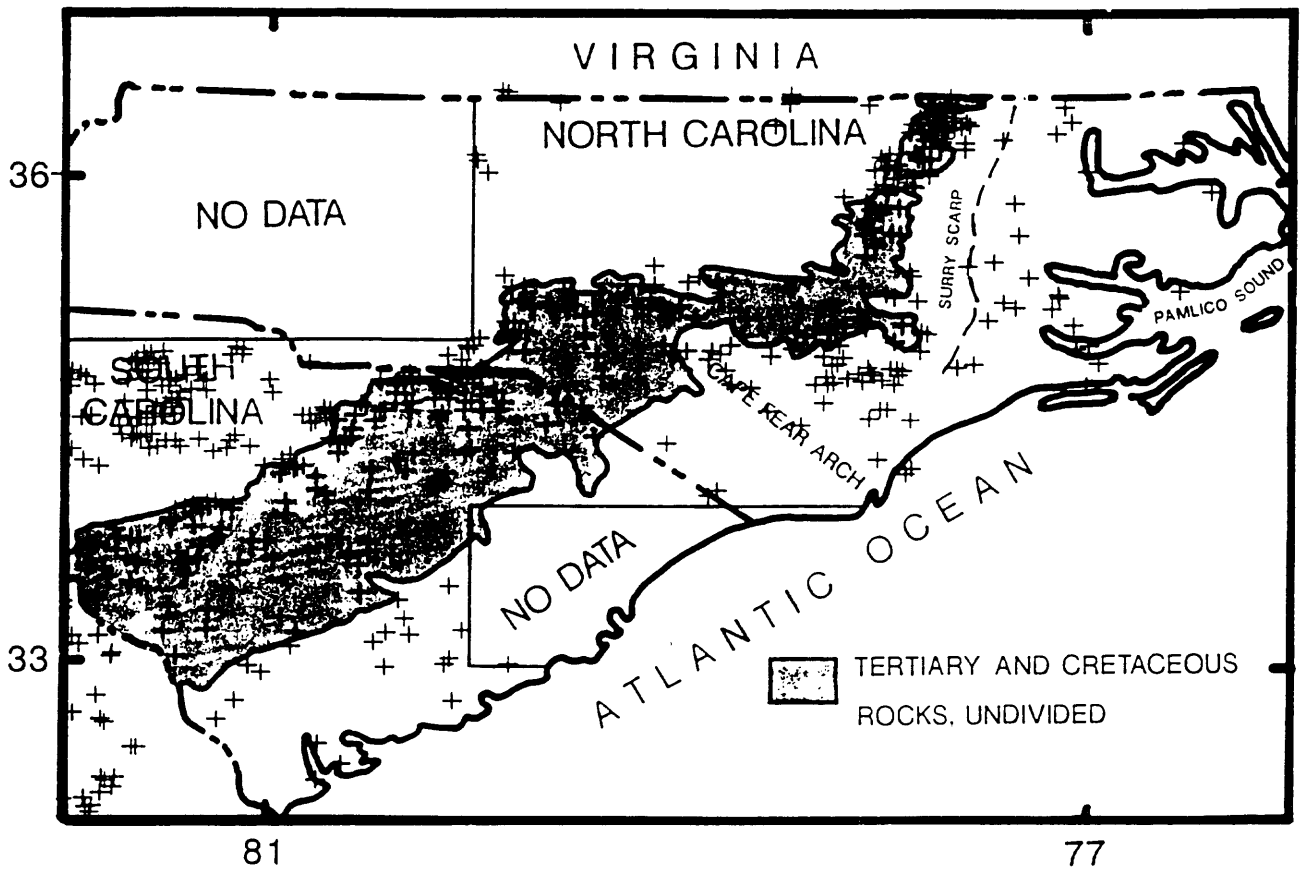

Figure 4.--Plot of NURE stream sediment samples having 150 ppm (or more) Hf. From Grosz (1992).

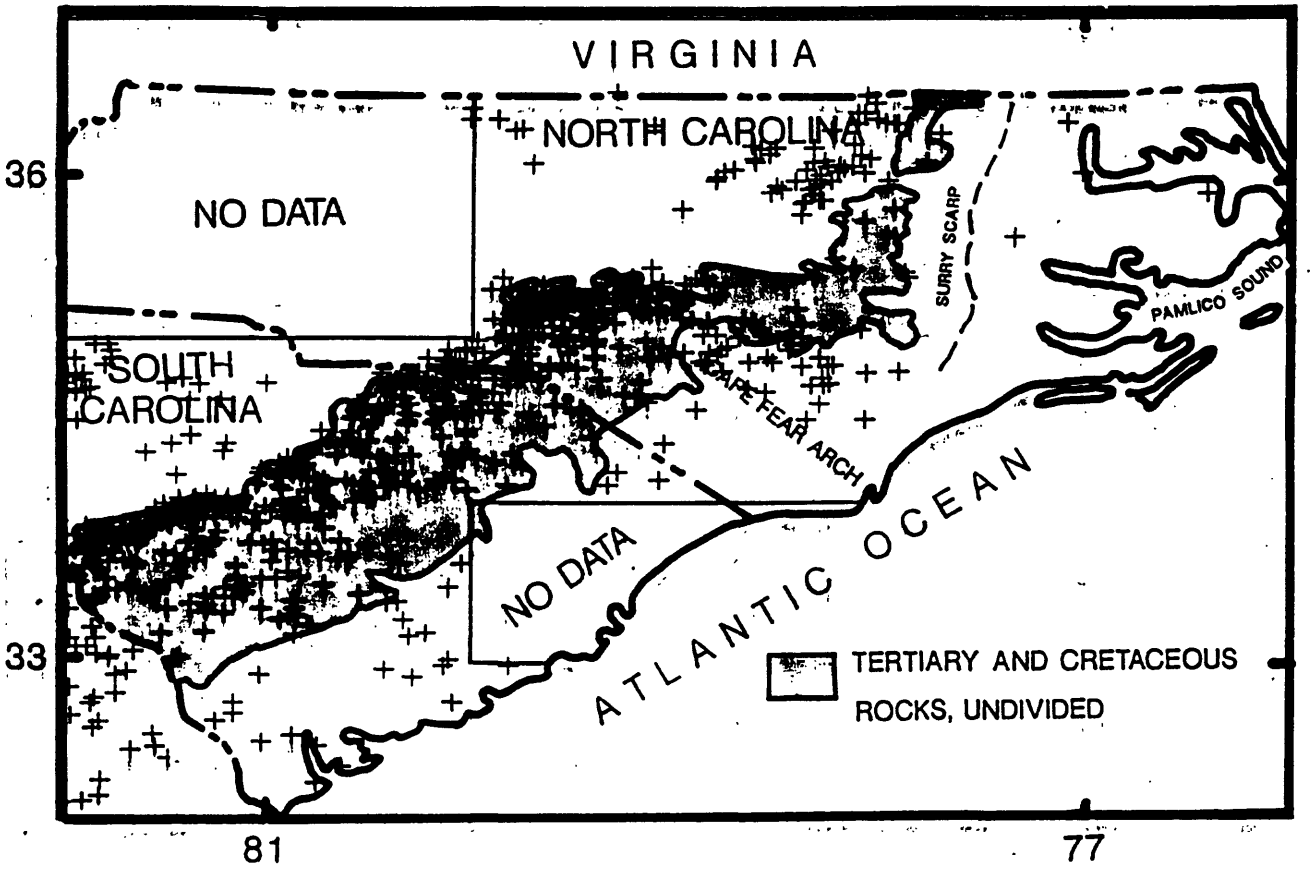

Figure 5.--Plot of NURE stream sediment samples having 500 ppm (or more) REE. From Grosz (1992).

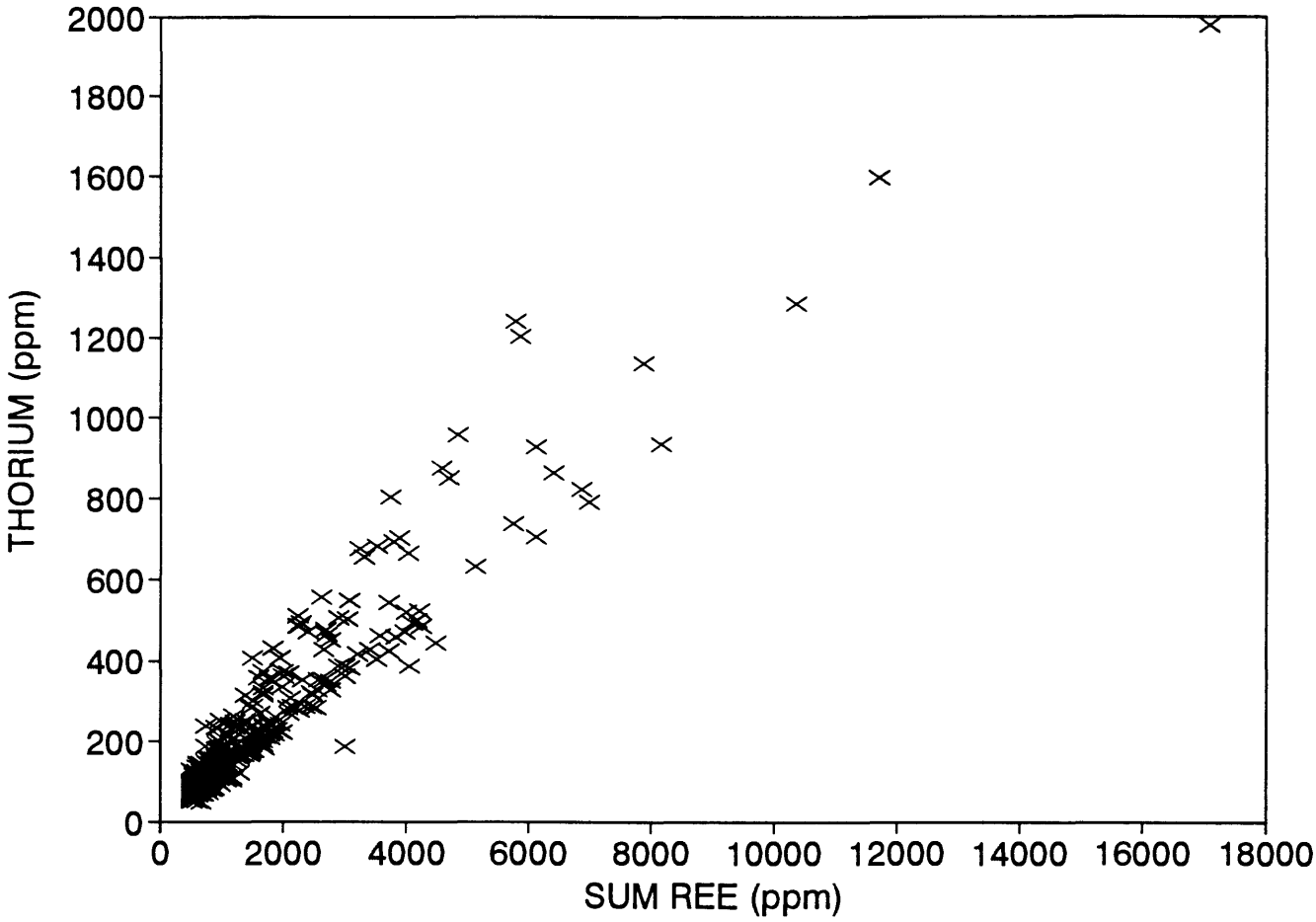

Figure 6.--Plot of REE versus thorium for NURE stream sediment samples having 500 ppm (or more) REE. From Grosz (1992).

The percentage of heavy minerals (calculated as a function of bulk sample on a dry weight basis) ranges from 0.24 to 4.80, but averages 1.30 percent. The heavy-mineral assemblage consists of magnetite, ilmenite (including altered ilmenite), rutile, zircon, monazite, epidote, pyrobole (undifferentiated pyroxenes and amphiboles), garnet, staurolite, tourmaline, aluminosilicates (undifferentiated sillimanite, kyanite, and andalusite), pyrite, and iron oxides (dominantly limonite). An "others" group was also estimated. It includes unidentified opaques and non-opaques, quartz, clay balls, mica, chlorite, spinel(?), and polymineralic grains. For some samples (for example MO-A-1-89 -4 and -5) the "others" group consisted completely of clay-coated mineral grains and clay-cemented grain aggregates.

The economically important heavy minerals (EHM) are ilmenite (including altered ilmenite), rutile, zircon, monazite, and aluminosilicates. Expressed as a weight percentage of the heavy-mineral assemblage (EHM/C, Table 3) they range from 19.6 to 82.0 and average 49.4; expressed as a weight percentage of the bulk sample (EHM/T, Table 3) they range from 0.13 to 1.49 weight percent and average 0.50 weight percent.

Magnetite distribution is erratic and its abundance is low. Most heavy-mineral concentrates contain less than 0.1 weight percent; only a few contain up to the observed maximum of 1 percent. Ilmenite (including altered ilmenite) averages 32.3 percent of the heavy-mineral assemblage in a range of 11.9 to 61.1 percent. The average rutile content ranges from not detected (N; Table 3) to 6.2, and averages 2.0 percent. Zircon, with an average of 6.0 percent is three times more abundant than rutile, and ranges from about 0.8 percent to a maximum of 13.8 percent of the heavy mineral fraction. Monazite, when present in detectable concentrations, ranged in abundance from about 0.1 to 5.5 percent and averaged 1.7 percent of the heavy-mineral assemblage.

Epidote and pyrobole contents are highly variable and range from not detected to 37.0 and 22.2 weight percent of the heavy mineral fraction, respectively. Garnet values range from not detected to 5.0 percent of the heavy-mineral assemblage. The average for fifteen samples in which garnet was quantified is 1.7 percent. The average staurolite content is 2.8 percent in a range of less than 0.1 to 5.2 weight percent of the heavy minerals. Tourmaline content averages 5.9 percent and ranges from 0.2 to 13.0 weight percent of the heavy-mineral assemblage. Pyrite was noted only in one sample. Iron oxides (predominantly limonite) ranged from not detected to a maximum of 1.0 percent. For the fifteen samples in which limonite was noted the average was 0.3 weight percent of the heavy-mineral assemblage.

Fine-grained detrital gold was identified in two samples from Cretaceous sediments (HR-A-1-89-3 and MO-A-1-89-4). Its commercial importance is difficult to evaluate because our sample processing scheme was not directed at the recovery of fine-grained gold.

Halifax County Site

The Halifax County site (HA-A-1-89) is located on a fluvial meander on the flood plain of the Roanoke River. The borehole was 35 feet-deep. The geologic map of North Carolina (North Carolina Geological Survey, 1985) shows this site to be underlain at an undetermined depth by the Cretaceous Cape Fear Formation. Spectral gamma-ray data (Table 1) show the highest potassium values (K %) measured in this study, about 1.8 percent and low uranium and thorium values. Gravel content of the sediment samples increases with depth (Table 2), and the heavy-mineral content is inversely proportional to the gravel content.

The economically important heavy minerals average 33.5 and 0.86 percent of the heavy-mineral concentrates and bulk samples, respectively. The concentrations of radioactive heavy minerals (monazite and zircon) are low which explains the low uranium and thorium spectral gamma-ray data. Labile heavy minerals (magnetite, epidote, pyroboles, and garnet) comprise an average of 47.2 weight percent of the heavy mineral suite. The average is slightly less for the lower three five-foot samples where gravel is more abundant. The ZTR index for these sediments averages 9.9. The high labile mineral (species subject to dissolution by weathering) content and the low ZTR index is not similar to the deeply weathered and texturally mature sediments associated with Cretaceous-age sediments elsewhere on the eastern seaboard and within the area of this study. Heavy-mineral data suggest that these sediments are younger than Cretaceous in age and may be either Quaternary or Tertiary age.

Harnett County Site

The Harnett County site (HR-A-1-89) is located on Cretaceous Middendorf Formation (North Carolina Geologic Survey, 1985) sediments. Spectral gamma-ray data (Table 1) show low potassium, uranium, and thorium. The gravel content is low, averaging 1.5 percent over the 15-foot drill hole. The heavy-mineral content averages 0.31 percent (Table 2). The economically important mineral species comprise an average of 77.2 and 0.24 weight percentage of the heavy-mineral suites and bulk samples, respectively. The high content of radioactive minerals zircon and monazite appear contrary to low thorium and uranium radioelement concentrations determined by the gamma-ray spectrometry. However, mineralogic data represents a five-foot section whereas the radioelement data is restricted to the upper few centimeters. Most likely the radioactive minerals are more concentrated below the surface where their abundance triples with depth over a fifteen-foot interval. The labile mineral content is low and averages 1.5 percent (table 3). The ZTR index is large and averages 64.0. The deeply weathered and texturally mature character of these sediments is consistent with their Cretaceous age.

Johnston County Site

The Johnston County site (JO-A-1-89) is associated with an aeroradiometrically anomalous site

underlain by Cretaceous-age Cape Fear Formation (North Carolina Geological Survey, 1985) sediments. The drill hole was 25 feet deep. Spectral gamma-ray radiometric data show low potassium and uranium values; however, thorium values are considerably above that of the previously discussed sites. Although highly variable, gravel content averages 12.5 percent. The heavy-mineral content is 0.57 percent. The economically important heavy minerals average 38.1 and 0.2 weight percent of the heavy-mineral concentrates and bulk samples, respectively. The low concentration of the radioactive heavy minerals zircon and monazite in the upper five-foot section is in contrast to the relatively high radioelement concentrations determined by gamma-ray spectrometry. It is probable that in this instance the radiometric effects of higher concentrations of these minerals in the upper few centimeters of sediment were diluted by the lower concentrations in the lower part of the upper five--foot section. The percentage of labile heavy minerals averages 36.2 percent (comparable to the percentage in the sediments in the Halifax County site). The ZTR index averages 25.1 for the 25-foot section. These sediments do not contain a deeply weathered heavy-mineral assemblage, nor are they mature texturally: they are younger than Cretaceous, probably of Quaternary or Tertiary age.

Moore County Site

The Moore County site (MO-A-1 -89) is located on an aeroradiometric anomaly over Cretaceous-age Middendorf Formation (North Carolina Geological Survey, 1985) sediments. The hole was 25 feet deep. Spectral gamma-ray radiometric data from this locality show low potassium, high uranium, and very high thorium values (Table 1). Gravel content averages 2.6 percent. Most of the gravel is restricted to the upper five-foot section (Table 2). The heavy-mineral content averages 0.69 percent. The economically important heavy minerals average 66.2 and 0.45 percent of the heavy-mineral assemblages and bulk samples, respectively. The concentration of the radioactive minerals zircon and monazite (Table 3) in the upper five-foot section is consistent with the highest concentrations of uranium and thorium determined radiometrically. As at the Harnett County Site, the percentage of labile heavy minerals is low, averaging 0.5 percent (table 3), and the ZTR index averages 67.7 percent. These sediments contain a deeply weathered heavy-mineral assemblage in a texturally mature matrix indicative of Cretaceous sediments.

CONCLUSIONS

Sediments of Cretaceous age associated with the North Carolina Fall Zone contain a texturally and mineralogically mature heavy-mineral assemblage characterized by a high ZTR index, low labile mineral content, and a high proportion of economically valuable minerals in the heavy-mineral assemblage. Here, and as shown elsewhere on the eastern seaboard, the gamma-ray aeroradiometric anomalies associated with these sediments are controlled by the relative abundance of the radioactive heavy minerals zircon and monazite.

This interpretation is supported by high uranium and thorium radioelement concentrations determined by field gamma-ray spectrometry, and by Ti-Hf-REE distribution patterns in NURE stream sediment geochemical data.

This study shows that Cretaceous heavy-mineral assemblages near the North Carolina Fall Zone are mature and are enriched in monazite, zircon, and titanium minerals relative to younger Coastal Plain and Continental Shelf sediments. The high proportion of these economically important minerals in the heavy-mineral assemblage indicate a potential for larger absolute concentrations in the Cretaceous (and sediments reworked from the Cretaceous) in this region. Heavy-mineral studies provide an effective ancillary technique to distinguish Cretaceous sediments from younger sediments.

Acknowledgments

This study was funded in part by the U.S. Geological Survey's Historically Black Colleges and Universities (HBCU) Program under Cooperative Agreement Number 14-08-0001-A0580 to Elizabeth City State University (ECSU), Elizabeth City, North Carolina. We thank R.P. Sinha, Chairman, Department of Geology, ECSU, and P. Hanshaw, U.S. Geological Survey HCBU program coordinator for their help in setting up this study. The North Carolina Geological Survey (NCGS) drilled the holes. Edward R. Burt, III, of the NCGS assisted with the drilling and P. Gallagher of the NCGS's Coastal Plain Office provided depth to basement information. We are indebted to Charles W. Hoffman of the NCGS, and John D. Peper of the USGS for their critical reviews and their suggestions for the improvement of this manuscript.

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