Aeroradioactivity Maps in Heavy-Mineral Exploration—Charleston, South Carolina, Area

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1218

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By ERIC R. FORCE, ANDREW E. GROSZ, PATRICIA J. LOFERSKI, *and* ARTHUR H. MAYBIN

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When used with other data to differentiate anomalies, aeroradioactivity maps are useful tools in exploring for placer heavy-mineral deposits

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By ERIC R. FORCE, ANDREW E. GROSZ, PATRICIA J. LOFERSKI, and ARTHUR H. MAYBIN[1]

ABSTRACT

The vicinity of Charleston, S.C., was designated as the area in which to design and test a method for using aeroradioactivity maps in heavy-mineral exploration. Such maps have recently become available for much of the Atlantic Coastal Plain.

The modes of occurrence of anomalies are heavy-mineral-bearing sands (old beach-complex deposits), heavy-mineral-bearing muds (old bay-complex deposits), sands and muds in the Santee River flood plain and its former flood plains, outcrops of phosphatic Tertiary formations, road networks made with phosphorite or granite aggregate, and former phosphate strip mines and related sites. The minerals contributing the most radioactivity are monazite, apatite, potassium feldspar, mica-group minerals, and possibly goethite.

Heavy-mineral-bearing lithologic units can be detected in aeroradioactivity surveys where monazite makes surficial concentrations radioactive. Only such concentrations in old beach-complex sands appear to be of economic importance in the study area. Other anomalously radioactive material, especially uraniferous phosphorite, can have economic value but must be separated from heavy-mineral anomalies for efficient exploration.

A method of correlation of anomalies with geology is presented; spectral radioactivity data, county soils maps, culture maps, and regional mineralogic trends were used as components. The absence of detailed regional mapping was assumed, but the method was checked in quadrangles already mapped.

We discovered 14 heavy-mineral accumulations in sands of old beach complexes by checking total-count anomalies, and another accumulation by checking a spectral anomaly. Of these, five together contain about 2 million metric tons of economic heavy minerals at grades of 2 percent or greater. Several difficulties in exploration for heavy-mineral-bearing sands by means of aeroradioactivity became apparent; those difficulties due to other types of anomalies over lithologies containing few heavy minerals are presumably resolved by our method. Other difficulties remain unresolved; several heavy-mineral deposits found by means of their radioactivity were valueless because of fine grain size, thinness, or unstable mineral suite.

Young, immature beach-complex sands contain abundant potassium feldspar, hornblende, and epidote. In older, more mature sands, these minerals are progressively depleted, and stable minerals are residually enriched. The composition of ilmenite varies in a similar way. These changes alter the economic value of deposits and the radioactivity signatures over heavy-mineral anomalies by their effect on potassium feldspar and possibly monazite.

Our methods could easily be adapted to regional geologic mapping or to other types of mineral exploration; a byproduct of this study was evaluation of uraniferous phosphate resources of the region.

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CONTEXT OF THIS STUDY

PURPOSE

The Coastal Plains Regional Commission (CPRC) has financed and the U.S. Geological Survey (USGS) has contracted for extensive aeroradioactivity mapping of the Atlantic Coastal Plain. Most of those maps are now available. The maps were made specifically to faciliate exploration for economic minerals. Existing literature provides relatively little guidance on how best to use aeroradioactivity data from the Coastal Plain; we therefore tried to design a method for using such data and to cover an area as an example. This report emphasizes the heavy-mineral-exploration aspect of the overall program. Previous studies that are also part of this effort are by Stockman and others (1976), Neiheisel (1976), Perlman and others (1976), Force and Bose (1977), and Force and others (1978). Other studies in adjacent States are planned. Isidore Zietz of the USGS initiated this program, and we acknowledge his aid in acquiring the aeroradioactivity data, suggesting this study, and arranging financial support.

PAST WORK

The reports cited have been published since the CPRC–USGS aeroradioactivity maps became available. Before that time, the only published works on aeroradioactivity in the Atlantic Coastal Plain were those by Meuschke (1955) in South Carolina, Schmidt (1962) in South Carolina and Georgia, and Moxham (1954) in Florida. Mahdavi (1964) directed a study of heavy minerals in the Coastal Plain, a topic of special interest in this report. We found, however, that inconsistency of the analytical data within that report limited its use.

EXPLORATION FOR HEAVY MINERALS BY MEANS OF AERORADIOACTIVITY

Aeroradioactivity surveys have a known but sketchy application in heavy-mineral prospecting. Although little has been published, private firms have reportedly conducted many surveys designed for heavy-mineral exploration. Heavy-mineral accumulations elsewhere have been found by uranium prospectors carrying portable scintillometers (Carpenter and others, 1966; Houston and Murphy, 1962); the valuable heavy-mineral deposits near Folkston, Ga., were delineated in Moxham's (1954) radioactivity information. The existence of a deposit near Green Cove Springs, Fla., was confirmed by an aeroradioactivity survey. Stockman and others (1976) using CPRC–USGS aeroradioactivity surveys, found a possibly economic heavy-mineral placer near Brunswick, Ga.

Prospecting for heavy minerals by means of radioactivity is based on the presumption that the thorium- and uranium-bearing heavy-mineral monazite and other radioactive heavy minerals (zircon and possibly xenotime, glauconite, sphene, allanite, and apatite) are hydraulically concentrated with nonradioactive economic heavy minerals (weathered ilmenite and lesser rutile, kyanite, and sillimanite), mostly in beach-complex sands. In some other areas, monazite is not present in sufficient quantity to make heavy-mineral concentrations radioactive (see Force and Bose, 1977), and in such places, the assumption is not valid.

The gamma radioactivity of a heavy-mineral deposit should depend roughly on the thorium and uranium contents of its heavy minerals. Radioactive elements are present mostly in the crystal lattices of stable heavy minerals. Because no element can readily escape, parent elements should be in equilibrium with daughter products. If so, gamma radioactivity is proportional to some combination of uranium, thorium, and potassium contents. The relative specific radioactivity strengths, if uranium is assigned a value of 1.0, are thorium, 0.5, and potassium, 2.5×10^{-4} (International Atomic Energy Agency, 1976). In this report, however, we have not assumed a true proportional relation.

CHOICE OF STUDY AREA

The region around Charleston, S.C., (fig. 1) was chosen for this study for the following reasons:

1. Heavy mineral concentrations, which include monazite, are present in the sands of modern beach complexes (Martens, 1935; Neiheisel, 1958a, b; McCauley, 1960). Several old beach-complex sand bodies also contain the appropriate heavy minerals (Beck, 1973; Cazeau, 1974). The possibility of finding sizable concentrations in the old sands seemed good.
2. Useful information of two types supplement the CPRC–USGS aeroradioactivity maps in that area:
   a. In South Carolina, additional sources of aeroradioactivity information are spectral surveys that have 5-mile spacing between lines. Surveys were conducted by U.S. Energy Research and Development Administration (1975a–c; calibrated by Duval and others, 1977); in those surveys, gamma radioactivity was plotted separately for daughter products of parent elements potassium, uranium, and thorium.
   b. In the three-county area around Charleston, S.C., geologic information was being collected for another USGS project. The two studies were of mutual benefit.

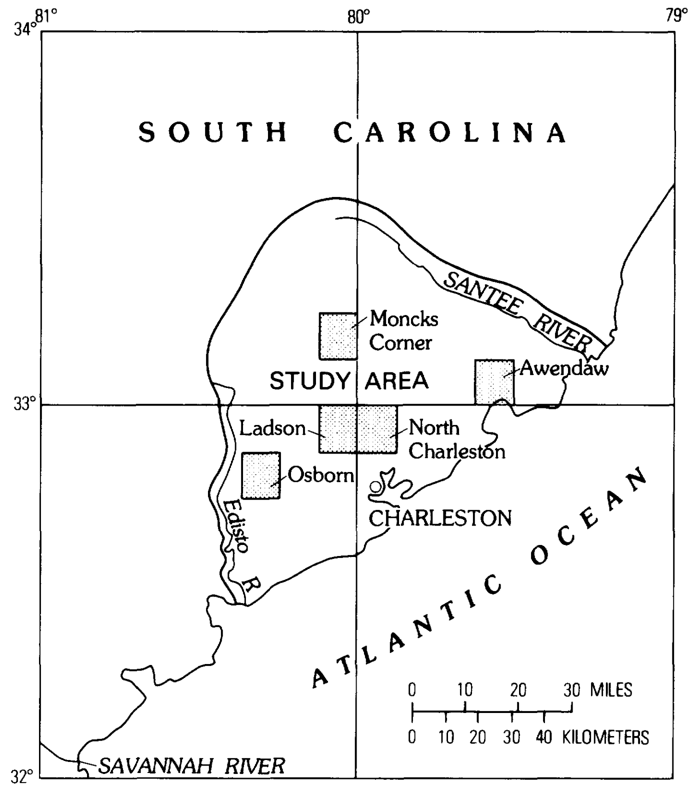

FIGURE 1. – Index map of part of South Carolina showing area of this study and 7.5-minute quadrangles (shaded) for which U.S. Geological Survey geologic maps have been published.

GEOLOGY OF THE STUDY AREA

Published literature on the geology of the Charleston region consists mostly of older generalized work (Cooke, 1936; Colquhoun, 1965) and spotty modern coverage (Malde, 1959; Colquhoun and others, 1972; Inden, 1976). The progress of recent USGS work has been summarized by Gohn and others (1977), Gohn, Bybell, and others (1978), Gohn, Christopher, and others (1978), Gohn, Gottfried, and others (1978), Higgins and Gohn (1978), Force and others (1978), and Cameron and others (1979). This published work does not include a lithostratigraphic nomenclature for most surficial units; therefore, in the following discussion, we consider mainly sediment facies.

Pre-Pleistocene "bedrock" is exposed only in streambanks and artificial excavations. It consists of the Santee Limestone of Eocene age to the north and east and overlying foraminiferal impure limestone of the Cooper Formation of Eocene and Oligocene age in the central, southern, and western parts of the area. Thin upper Tertiary marine deposits locally are present between the Cooper Formation and the Pleistocene deposits.

Pleistocene fluvial and nearshore marine deposits control the geomorphology of the area and are the dominant surficial units. Several abandoned shorelines are present, each still marked by relict morphology suggestive of transitions from offshore shelf to steep shoreface to barrier island and commonly to tidal flats or lagoons. At least one part of the succession of sedimentary facies corresponds to the physiography; the barrier-island morphology is found on mostly well-sorted fine to medium sand, such as one finds on beaches and dunes. In this report, these sands are called beach-complex deposits. The term is meant to include beach, dune, inlet, and washover-fan environments; in most places, we could not further distinguish the environments because of the few available exposures. The beach-complex sands are of greatest importance in this study because heavy minerals are concentrated here and are mined from beach-complex sands elsewhere.

In surrounding areas, the surficial units consist in large part of sandy muds that are blue or gray and shelly where fresh but mottled orange and gray where weathered. These and associated deposits are called bay-complex deposits in this report. This term probably includes bay, lagoon, estuary, tidal-flat, and shallow offshores facies. On the South Carolina coast, the discontinuity of the barrier system makes the differentiation of even modern muds into lagoon and offshore facies difficult. Bay-complex deposits grade from very fine sands (washover deposits?) to beach-complex sands. Each old shoreline is represented by deposits that include the above-named facies, so that the facies recur.

Stranded river deposits of several ages are also present in the area. We were especially interested in an old Santee River deposit, now occupying an area that is higher than and southwest of the present Santee River banks. Like the modern Santee River deposits, the old deposit is typified by crossbedded feldspathic granular coarse sand, and interbedded muddy sand and granular clay.

MECHANICS OF THIS STUDY

AERORADIOACTIVITY-MAP CHARACTERISTICS

The main sources of aeroradioactivity data for this study were contour maps (pls. 1,2) of total-count gamma radioactivity (CPRC–USGS, 1975). The data were acquired by GeoMetrics Co. in a single survey. Flight lines were oriented north-south 150 m above ground surface and 1.6 km apart. A computer was used in the contouring.

This survey was abnormally "noisy"; anomalies[2] of about 300 counts[3] are common over the open sea, where values should be low and constant. Nevertheless, we found that most anomalies shown on the contour map can be found on the ground. Comparison with ERDA (1975a–c) surveys and overlapping CPRC–USGS surveys suggest consistency of the data sets. Where the contouring was questionable, we inspected the strip charts from which the contour map was made. Correlation of our ground measurements with the aeroradioactivity maps suggest that 100 counts equals about 1 ur[4]. A north-south break in radioactivity values at about long 80°05′ W. proved not to be real.

FIELD METHODS

The first major type of field investigation was the determination, on the ground, of the radioactive character of the geologic units in five previously mapped quadrangles in the Charleston region. A portable scintillometer recording total-count gamma radioactivity was held against a flat surface of freshly excavated subsoil. Where possible, we rode in a vehicle over roads made of local material and read the scintillometer continuously to determine the extent to which the unit is radioactively homogeneous.

The other type of fieldwork was the checking of individual total-count anomalies and spectral anomalies. We traversed an anomalous area first on dirt roads by vehicle to determine the areal extent of the anomaly; this also provided a check on the reality of the anomaly recorded by airborne instruments. Scintillometer measurements were made over several localities where subsoil was excavated; the scintillometer was read over a flat surface where possible. For most anomalies

[2]For purposes of this study, an anomaly is defined as any point or area where radioactivity is greater than that of the local background.

[3]The time unit in which the contractor recorded counts does not appear on the maps. These counts have significance only within the contracted area, as they depend on the crystal used by the contractor.

[4]The International Atomic Energy Agency (1976) has replaced previous measures of crustal gamma radiation intensity with the term "radio-element unit" (ur), defined as the radiation measured from a source containing 1 part per million (ppm) uranium in equilibrium and equivalent to 0.6 μR/hr.

checked, material capable of producing the anomaly was found. Where possible, this material was sampled at several places. Most samples consisted of a 1-m channel sample taken from the base of the soil downward so that it should represent all materials contributing radioactivity. Samples were taken from soil-auger borings, roadcuts, streambanks, and so forth–all from weathered material.

Where deposits in the anomalous area seemed to have possible economic value, more extensive work was done. Samples were collected from auger borings, and the extent of the anomaly was determined more precisely by means of ground scintillometer traverses and examination of the original aeroradioactivity strip charts.

LABORATORY METHODS

We collected samples to study lithologies having anomalous radioactivities and to analyze the samples for economic minerals. Therefore, some of the analysis techniques are somewhat unusual and should be described. Samples in which phosphate was determined by chemical analysis have been discussed in another paper (Force and others, 1978).

Well-sorted sands.–Samples of well-sorted sands were divided into three fractions–coarser than 18 mesh (1.0 mm), finer than about 62 μm, and an intermediate sand fraction–by screening and washing, and the percentage of each fraction was established. We separated heavy minerals from the intermediate sand fraction by using both bromoform (sp gr, 2.85) and methylene iodide (sp gr 3.3). These two liquids were used to separate the generally heavier economic heavy minerals from the generally lighter noneconomic minerals. The methlylene iodide sink fraction was further separated into magnetic fractions by means of a hand magnet and an isodynamic separator set at 0.4 and 1.0 amperes. We estimated mineral abundance using a binocular microscope for each of the five resulting fractions. Because only a few mineral species were present in each fraction, estimation was easy. The relative mineral abundance in the whole heavy-mineral suite was the sum of the five fraction compositions, adjusted for the weight of each fraction. Identifications were checked by means of a petrographic microscope and X-ray diffractions of one sample in each group of closely related samples.

The light fraction of each sand fraction was stained to test for potassium feldspar. About 500 grains of loose sand in a plastic cup were immersed in hydrofluoric acid for about 20 seconds, rinsed, and immersed in saturated sodium cobaltinitrite solution for about 60 seconds, then rinsed again. Potassium feldspar turned yellow, and its abundance was estimated under a binocular microscope. The abundance of phosphate grains was also estimated in this fraction.

Muddy sands and sandy muds.–We divided samples of muddy sands and sandy muds into fractions coarser than 60 mesh (0.25 mm), between 60 and 230 mesh (0.25 to 0.062 mm), 230 mesh to about 20 mm, and finer than about 20 mm by sieving and decantation of slowest settling grains. Sand and silt fractions were each processed in bromoform. Silt fractions were separated in a centrifuge and removed by local freezing of the bromoform and heavy minerals in an acetone-dry-ice mixture. Using a binocular microscope, we made estimates of the relative abundance of heavy minerals for both sand and silt fractions. Potassium feldspar was estimated in the light fractions of sand and silt by means of the method described above.

X-ray diffraction patterns of the <2 μm clay-minerals of these deposits were made to determine the relative abundance of the potassium-bearing clay illite. We separated clay- and silt-size fractions by dispersing the particles in water, using an ultrasonic vibrator; then a size-cut of less than 2 μm was separated from each sample in a centrifuge. We prepared the clays for X-ray analysis by making two oriented mounts of each sample. To make the mounts, we placed drops of the clay slurry onto glass slides and allowed the clay to settle. One mount of each sample was used for ethylene glycol treatment, and the other for heat treatments of 350°C and 550°C; these treatments cause known and characteristic changes in various clay minerals and therefore are used in standard clay identification. After each treatment, X-ray diffraction traces were made for each sample.

BACKGROUND RADIOACTIVITY RESPONSE OF SOME LITHOLOGIC UNITS

The level and the meaning of background radioactivity in the study area are essential to the study of radioactivity anomalies, as anomalies are defined as local values greater than regional background values. For our purpose, normal radioactivity was established for areally extensive geologic units in five areas.

In order to determine what radioactivity responses are typical of the more common lithologies of the Charleston area, we read a handheld scintillometer at random locations within each lithologic unit of five previously mapped or partially mapped quadrangles (see fig. 1). The results (tables 1–6) established background levels for lithologies and for areas against which anomalies could be evaluated. These data are summarized for the entire study area in table 7.

Ladson Quadrangle (Malde, 1959).–Aeroradioactivity maps show that the area of the Ladson Quadrangle has a high background level and several large individual

TABLE 1.—*Ground radioactivity response of some lithologic units in Ladson Quadrangle*

[Radioelement unit measured by means of hand-held scintillometer]

Units[1]	Radioelement units (ur)
1. Mine-dump spoil	17–130
2. Sand on Tenmile Hill[2]	13– 17
3. Ladson Formation[1]:	
a. Medium-sand member[2]	13– 17
b. Fine-sand member[2]	13– 27
c. Phosphate member	13– 67
4. Cooper Formation (weathered)	33–170

[1]From Malde (1959).
[2]Beach-complex sands of this report.

anomalies. Table 1 shows the results of ground measurements. The large anomalies result from strip-mine exposures of phosphate and from outcrops of phosphatic material. High background level results in part from incorporations of varying amounts of phosphatic material in several Pleistocene(?) units that form large parts of the land surface, such as the fine-sand member of the Ladson Formation.

Heavy minerals are also abundant locally in the fine-sand member of the Ladson Formation. Table 2 shows the mineralogy of the only sample (EF 45C) for which an analysis was made; note the maturity of the heavy-mineral suite in addition to the high heavy-mineral content. The hand-held scintillometer read 27 ur over the sample site. The area is not an anomaly on the aeroradioactivity map, presumably because the effect of heavy minerals was drowned out by the effect of nearby and admixed phosphorite material. Monazite contents are low. Thus, this is a heavy-mineral accumulation found virtually by accident. Its size is not known.

Monck's Corner Quadrangle (Inden, 1976).—The highest aeroradioactivity values in the Monck's Corner Quadrangle were found over the Cooper Formation. Contrast is low over the rest of the quadrangle (a north-south contrast at about long 80°05′ W. proved not be real). Table 3 shows the range of radioactivity responses of Inden's lithologies. The alluvial–tidal channel–fan delta deposits (a combination of beach-complex, bay-complex, and river deposits of this report) are commonly covered by swamp, which decreases their radioactivity; thus, these deposits are only locally aeroradioactivity highs. The relatively high radioactivity of dry sediment of this type is not explained. Phosphate and potassium feldspar (both less than 1 percent) produce some of the radioactivity in Inden's tidal flat-subtidal deposits (table 2).

Awendaw Quadrangle.—Geologic map information in the Awendaw Quadrangle is from Cameron and others (1979). Aeroradioactivity maps show little contrast over this quadrangle, and we found little contrast among lithologic types when we used the hand-held scintillometer (table 4). A difference in strength of potassium radiation on ERDA (1975a–c) maps appears to correspond to a contact between Holocene(?) and Pleistocene beach sands about 500 m northwest of the Intracoastal Waterway. Radioactivity values measured on the ground were 20 ur over a small heavy-mineral accumulation (table 2, EF 29A).

Analyses of surficial sand units collected by means of a power auger by Cameron and others appear in table 2. Note the immaturity of heavy-mineral suites.

Cottageville S.E. (Osborn) Quadrangle.—Aeroradioactivity maps of the Cottageville S.E. (Osborn) Quadrangle show little contrast, and field checking showed that the lithologic units do indeed have similar radioactivities (table 5). ERDA (1975 a–c) maps show a slight total-count anomaly and an unusually high ratio of thorium to the other radioactive elements over sand between Ravenel (in Ravenel Quadrangle) and Capwell's Crossroads; this proved to be a heavy-mineral accumulation, which is discussed more fully in a following section.

Distribution of lithologic units is based on unpublished work (1978) by G. S. Gohn; table 5 generalizes his units. Gohn contributed three power-auger samples of surface sands, analyses for which are shown in table 2.

North Charleston Quadrangle.—The most intense anomalies in the North Charleston Quadrangle proved to be manmade; the least intense are those in marshes along the Cooper River. The highest natural values are over old alluvial deposits. Table 6 shows the radioactivity responses of some lithologic units, which are based on unpublished mapping by L. M. Force (1979). The results from ground measurement and aeroradioactivity agree. Analyses of power-auger samples of surface units (table 2) show that the distribution of heavy minerals and that of high radioactivity are not the same, though concentration of heavy minerals is apparently not great in any lithologic unit.

Table 7 shows radioactivity ranges of lithologic units in mapped quadrangles. Values from anomalies are also included. Outcrops of phosphatic material are the most radioactive in the study area. Beach-complex sands are, on the average, the least radioactive; heavy-mineral concentrations within these sands would be anomalies within a region of low values. The most extensive surficial unit in the area, the bay-complex deposits, has fairly consistent and moderately high values; variations over these deposits are largely due to the distribution of covering swamps, which absorb radiation.

Areal differences in background level are due in some areas to local incorporation of phosphorite grains into extensive Pleistocene units (such as in the Ladson Quadrangle) and in other areas to man's activities (such as in the Ladson and the North Charleston Quadrangles).

TABLE 2.–*Mineralogy of surficial sand units in five mapped quadrangles*

[P, <0.5 percent. --, no analysis]

					Weight percent							Weight percent of specific gravity < 2.85 fraction									
Sample No.	Radioactivity (ur)	Thickness sampled (m)	Latitude Longitude	Lithology (from tables 1, 3–6)	Gravel	Sand	Mud	Potassium feldspar	Phosphate	Monazite	Specific gravity >2.85	Altered ilmenite	Epidote	Amphibole[1]	Garnet	Tourmaline	Staurolite	Sillimanite[1]	Leucoxene	Rutile	Zircon
Ladson Quadrangle (surface sample)																					
EF 45C	27	0.5	32°54′15″ N. 80°04′55″ W.	3B	0	84	16	1	1	0.00	3.3	45	17	2	P	4	6	7	3	4	3
Moncks Corner Quadrangle (surface samples)																					
AG 77–6	17	0.25	33°11′40″ N. 80°06′45″ W.	1	1	42	58	1	0.2	--	0.3	37	2.0	0	0.2	7.0	3.0	19.0	2.0	4.0	5.0
AG 77–14	17	0.25	33°12′30″ N. 80°06′20″ W.	1	2	74	25	1	.3	--	.5	25	3.0	0.4	0	8.0	3.0	24.0	.9	5.0	3.5
AG 77–16	15	1.0	33°09′00″ N. 80°03′35″ W.	2	[2]3	80	17	1	.4	0.003	.8	34	.2	0	0	3.0	1.5	11.0	2.0	10.0	5.0
AG 77–24	15	0.25	33°11′25″ N. 80°03′10″ W.	3	3	67	30	1	.1	.01	.7	28	.06	0	0	8.0	7.0	17.5	3.0	5.0	8.0
AG 77–26	17	0.25	33°14′00″ N. 80°02′20″ W.	3	4	82	14	1	.1	.01	.9	26	1.0	0	0	10.0	8.0	16.0	3.0	7.0	8.5
AG 77–27	22	5.0	33°09′40″ N. 80°00′45″ W.	4	2	72	25	1	.2	.004	.3	27	6.0	0	.5	8.0	4.5	9.0	5.0	6.5	7.0
Awendaw Quadrangle (power auger samples)																					
Ca1	--	1.6	33°03′00″ N. 79°35′45″ W.	5	1	80	19	5	0	0.005	2.7	15	25	30	2	2	4	10	2		P
Ca3	--	5.5	33°05′15″ N. 79°36′00″ W.	6	1	89	10	<1	0	.00	.8	7	30	30	P	3	8	8	3		2
EF29A	20	0.5	33°05′10″ N. 79°34′20″ W.	6	0	91	9	1	0	--	2.2	--	--	--	--	--	--	--	--		--
Cottageville SE (Osborn) Quadrangle (power auger samples) [Collected by G. S. Gohn; see also table 9, EF52D, 52E]																					
GF1	--	15.2	32°49′18″ N. 80°15′04″ W.	5	0	52	48	2	0.2	<0.005	1.6	17	25	25	5	4	5	13	1		1
GF7	--	16.5	32°45′31″ N. 80°16′33″ W.	3	0	87	13	?	0	.005	1.0	23	28	19	0	5	4	13	2		1
GF9	--	16.8	32°46′52″ N. 80°15′59″ W.	3	0	91	9	<1	.2	<.005	2.0	20	30	25	1	2	2	10	1		P
North Charleston Quadrangle (power auger samples) [Collected by L.M. Force; see also table 9, EF35B]																					
CNC 2	--	3.1	32°59′15″ N. 79°58′15″ W.	4	0	68	32	1	0.7	0.00	1.6	30	10	2	3	4	4	10	2		1
CNC 5	--	6.4	32°58′30″ N. 79°58′30″ W.	6	0	81	19	<1	0	<.01	.8	35	10	2	P	6	3	20	4		1
CNC 7	--	5.2	32°56′30″ N. 79°57′30″ W.	6	0	69	31	<1	<.1	<.01	.5	30	8	P	P	4	4	20	7		1
CNC 8	--	4.6	32°56′30″ N. 79°57′30″ W.	6	0	69	31	1	0	<.01	1.0	55	5	1	P	5	3	10	7		1
CNC 12	--	6.7	32°55′00″ N. 79°58′45″ W.	5	0	88	11	<1	0	.00	1.7	30	25	5	P	5	3	20	3		P
CNC 15	--	8.8	32°56′00″ N. 79°53′30″ W.	5	2	82	16	1	2.5	.00	1.3	20	20	10	1	P	2	15	2		P
CNC 18	--	11.0	32°55′00″ N. 79°54′30″ W.	5	1	92	8	<1	.2	.004	1.8	30	20	10	3	5	5	10	1		P

[1]In this table, "amphibole" includes subordinate pyroxene, and "sillimanite" includes subordinate kyanite.
[2]Includes gibbsite nodules.

TABLE 3.—*Ground radioactivity response of some lithologic units in Moncks Corner Quadrangle*

[Radioelement units measured by means of hand-held scintillometer]

Units[1]	Radioelement units (ur)
1. Braided alluvial–tidal channel–fan delta	17–20
2. Tidal flat and high subtidal (bay-complex deposits of this report)	13–17
3. "Dune Beach(?)"(beach-complex sands of this report)	
Western part	10–13
Eastern part	7–10
4. "Cooper Marl"	22–50

[1]From Inden (1976).

ANOMALY CLASSIFICATION

Hundreds of anomalies are shown on the radioactivity map (pl. 2). We found that they range in significance from economically interesting deposits of heavy minerals or uraniferous phosphorite to isolated outcrops of extensive bay-complex deposits surrounded by swamps. Thus, a method of separating anomalies into different types is essential for efficient use of the maps. We attempted such a classification before the fieldwork was begun, but we also examined almost all larger anomalies and thereby checked the classification.

Using ERDA (1975 a–c) aeroradioactivity data, we could classify almost half the total-count anomalies shown on CPRC–USGS (1975) aeroradioactivity maps according to spectral characteristics. The classifications are listed and defined in table 8*A*.

Soil survey information was used in conjunction with this classification. In this area, soils in which the C horizon is described as well-sorted, clean, or loose sand are formed most commonly on old beach-complex deposits. A list of such soils was compiled from the Charleston County soils map and text (Miller, 1971); those units were plotted together on our maps to show old beach-complex deposits (pl. 1). A similar procedure was useful for adjacent counties, where older soil maps were used. Available geologic information was also used.

ThU anomalies shown on table 8 (that is, those consisting of strong uranium and thorium components without an appreciable potassium component) which are over beach-complex sands as outlined from soils maps, were predicted to be heavy-mineral deposits. Field study showed that this was generally true.

Similarly, high uranium contents (Altschuler and others, 1958) in phosphorite from the Charleston area led to a prediction that U anomalies listed in table 8*A* (that is, where uranium is the only anomalous component) would be phosphatic material. This also proved to be true.

GEOLOGIC SETTINGS OF AERORADIOACTIVITY ANOMALIES

Table 7 shows the range in radioactivity of various types of deposits. We found that all the lithologies produced local anomalies (points or areas where radioactivity values are above the local background), though the anomalies over beach-complex sands are of most interest in this study.

OLD BEACH-COMPLEX SANDS CONTAINING HEAVY-MINERAL CONCENTRATIONS

All the aeroradioactivity anomalies associated with beach-complex sands correspond to heavy-mineral concentrations. Aeroradioactivity anomalies guided us to 15 concentrations of heavy minerals in old (Pleistocene?) beach-sand deposits. These concentrations are discussed individually in a following section.

RADIOACTIVITY

Radioactivity over the old Pleistocene? beach sands is shown as high as 1,755 counts per second on the aeroradioactivity maps, and as high as 58 ur on a hand-held scintillometer; one body that contains phosphate grains as well as heavy minerals read 67 ur. Values of about 17–25 ur are more typical (table 9). The anomalies over heavy-mineral deposits are neither the highest nor the most extensive in the area; we checked some of the anomalies only because we had evidence from soils maps and spectral surveys that they might be caused by heavy minerals.

Most beach-complex sands do not contain heavy-mineral concentrations, and the barren sands are among the least radioactive deposits in the area (table 7). The heavy-mineral concentrations are radioactivity highs within belts of low values.

Most of the anomalies caused by heavy minerals are the ThU type (table 8*A*,*B*). A few are A type, owing to a higher potassium content. One deposit that has no associated total-count aeroradioactivity anomaly was found from an appropriate anomaly in the spectra alone.

TABLE 4.—*Ground radioactivity response of some lithologic units in Awendaw Quadrangle*

[Radioelement units measured by means of hand-held scintillometer]

Units	Radioelement units (ur)
1. Holocene beach sand	12
2. Holocene salt marsh	8
3. Holocene swamp	3– 5
4. Pleistocene bay-complex deposits (very fine sand and silt)	7–10
5. Younger Pleistocene beach-complex sands	7–10
6. Older Pleistocene beach-complex sands	3–20

TABLE 5.–*Ground radioactivity response of some lithologic units in Cottageville SE (Osborn) Quadrangle*

[Radioelement units measured by means of hand-held scintillometer]

Units	Radioelement units (ur)
1. Holocene swamp deposits	10–13
2. Pleistocene fluvial-estuary deposits	20
3. Younger Pleistocene beach-complex sands	8–18
4. Muddy sand (bay complex deposits of this report) overlying older Pleistocene beach-complex sands	10–20
5. Older Pleistocene beach-complex sands	8–20

Equivalent thorium content is about five times as high as equivalent uranium content over the beach deposits containing heavy-mineral concentrations (from the calibrations of Duval and others, 1976). Typical equivalent values are 10–25 ppm of thorium and 2–5 ppm of uranium. Indicated potassium contents range from about 0.25 to 1.0 percent.

HEAVY-MINERAL CONTENT

Minerals that have >2.85 sp gr reached average concentrations in channel samples as high as 26 percent, and minerals that have >3.3 sp gr as high as 18 percent (table 9). They generally were found disseminated in loose, medium to very fine sand.

Heavy-mineral concentrations commonly occupy a restricted stratigraphic zone in the beach-complex deposits. They also appear to grade laterally into sands that have insignificant heavy-mineral concentrations and that are not radioactivity anomalies.

The heavy-mineral concentration is closely related to the radioactivity of the deposit (fig. 2). Monazite is apparently the major contributor to the radioactivity of the heavy-mineral deposits because it was present in roughly the right amounts (mostly 0.0x percent of the total sample) and has the proper average composition (6 percent thorium, 0.5 percent uranium; Mertie, 1975) to produce the observed anomalies. Monazite was detected by means of X-ray and (or) optical techniques in most of the samples investigated. Zircon was present in all the samples, but its abundance was insufficient and its typical ratio of thorium to uranium was too low to explain much of the radioactivity of the deposits. If we assume an average uranium content of 1,000 ppm for zircon, the point counts shown in table 9 indicate that monazite contributed 4 to 100 times as much radioactivity as zircon. Monazite would represent 10–20 ppm thorium and 1–2 ppm uranium in the composition of a typical sand containing about 3 percent heavy minerals; zircon would represent about 1 ppm uranium.

VARIATIONS IN MINERALOGY

The potassium component of anomalies in beach-complex sands is explained by the potassium feldspar content. Potassium feldspar varied in abundance from less than 1 to about 5 percent in the old beach sands (table 9). The variation is orderly, the potassium feldspar content being greater in the youngest deposits (seaward and at low altitute) and less in the older deposits (landward and at high altitude).

The heavy-mineral assemblage shows a variation similar to that of potassium feldspar (table 9; fig. 3). The youngest beach sands contain an immature (or unstable) heavy-mineral assemblage dominated by hornblende and epidote, whereas the more mature (or stable) suites of older deposits are dominated by altered ilmenite, staurolite, sillimanite, and other minerals more resistant to weathering and intrastratal solution (table 10).

Much of this change probably took place at the depositional site because the source material must have been roughly the same for all the deposits. This interpretation is supported by the highly irregular shapes observed in some hornblende grains (fig. 4); their present shapes indicate that these grains could not have been transported far. The fact that the samples above the water table, which constitute the bulk of samples reported here, are more mature than those below it suggests postdepositional alteration (table 10). Many workers have also documented the in-place weathering of heavy-mineral assemblages in old beach deposits elsewhere in the Coastal Plain (Thom and others, 1972; Beck, 1973; Cazeau, 1974, in South Carolina; others in Georgia and Virginia).

Monazite itself may have been altered in place, as the total-count aeroradioactivity maps indicated no heavy-mineral deposits in the oldest shorelines in the area, even though two such deposits were found. In the older sands, monazite is present but in reduced quantity (table 9).

The TiO_2 content of altered ilmenite parallels the other mineralogic trends. Sample EF 56A, from one of the youngest shorelines in the area, contains altered ilmenite, 52.1 percent of which is TiO_2. Sample EF 54C,

TABLE 6.–*Ground radioactivity responses of some lithologic units in North Charleston Quadrangle*

[Radioelement units measured by means of hand-held scintillometer]

Units	Radioelement units (ur)
1. Roads made with phosphate aggregate	42–100
2. Roads made with granite aggregate	17– 33
3. Holocene salt marsh	7– 13
4. Pleistocene river deposits	17– 20
5. Pleistocene beach-complex sands	8– 15
6. Pleistocene bay-complex deposits	10– 15

TABLE 7.—*Summary of ranges of total-count gamma radioactivity of some lithologies*

[ur, radioelement units, measured by means of handheld scintillometer]

Lithology	Range (ur)	Typical values (ur)
Old beach-complex sands	3– 67	7–13 for bodies low in heavy minerals; 17–25 for bodies containing 2–3 percent heavy minerals.
Old bay-complex deposits (muddy sands, sandy muds)	13– 33	20
River deposits:		
Old river sands	13– 25	17
Old river muds	17– 25	20
Modern river sands	13– 42	17
Modern river muds	17– 25	20
Cooper Formation:		
Weathered	22–200	100
Unweathered	17– 33	25
Manmade phosphorite concentrations:		
Strip mines and similar sites	17–200	20 where recovery of phosphorite and (or) covering is nearly complete; 80 where recovery and (or) covering is poor.
Phosphate-aggregate roads	42–100	70

from a shoreline of intermediate age, contains altered ilmenite, 54.6 percent of which is TiO_2. EF 52E, from the oldest of the three shorelines and having the most mature of the three heavy-mineral suites, contains altered ilmenite, 56.5 percent of which is TiO_2 (X-ray fluorescence analyses by Susan Wargo and James Lindsay, USGS, corrected by modal analyses for minor impurities). X-ray diffraction shows that all three samples are mostly ilmenite containing minor (probably secondary) rutile. Force and Geraci (1975) showed a similar correlation of ilmenite composition with shoreline age and heavy-mineral suite in Virginia.

OLD BAY-COMPLEX DEPOSITS

Probably the largest number of anomalies are over old (?Pleistocene) bay-complex deposits consisting of muddy sands and sandy muds. Radioactivity over these bodies is 13–33 ur on the ground and 1,500–1,730 counts on aeroradioactivity maps. The anomalies are A and ThU types (table 8).

Bay-complex deposits underlie more than half the study area. The edges of anomalies shown on maps reflect primarily not the extent of the deposit but the distribution of swamp, river deposits, and even dense vegetation covering bay-complex deposits. In areas near phosphate strip mines, bay-complex deposits are present and have high radiometric values, but their radioactivity is overwhelmed by phosphorite radioactivity.

The composition of "bay-complex" deposits is variable, as the term is used in the previously discussed generalized manner. Typically, mottled orange and gray weathered muddy sands and sandy muds are visible on the surface and produce the anomalies. Drilling through these weathered deposits has shown that the parent materials are commonly blue gray and locally contain large macrofaunas and microfaunas indicative of shallow water and normal marine salinity. These deposits grade from mud through loose very fine sands to beach-complex sands, and a few anomalies were difficult to classify for this reason.

Heavy-mineral contents of bay-complex deposits are as highly variable as the lithologies. Minerals that have a specific gravity of more than 2.85 constitute 0.6–2.5 percent of the whole sample (table 11). In some samples, most of the heavy minerals are sand size; in others, most are silt-size. No detailed mineralogic study was made of silt-size heavy minerals, but sillimanite was a consistently conspicuous component (fig. 5).

The mineralogy of bay-complex sand-size heavy minerals reflects a variation in intensity of weathering, as does the mineralogy of heavy minerals in beach-complex sands.

Bay-complex deposits contain potassium in feldspar and in mica. X-ray diffraction studies showed that the $<2\mu m$ fraction contains small amounts, probably 5 percent or less, of the potassium-bearing clay mineral muscovite (table 11). Coarse mica was abundant in many samples, but we had difficulty estimating its amount. Potassium feldspar contents of the whole sample range from less than 1 to about 3 percent; potassium-feldspar

TABLE 8.—*Classification of aeroradioactivity anomalies*

A, **Relative strength of spectra**

Abbreviation	Definition	Correlative Lithologies
K	K anomalous, U and Th normal	None.[1]
U	U anomalous, K and Th normal	Phosphorite.
Th	Th anomalous, U and K normal	Heavy-mineral concentration.
ThU	Th and U anomalous, K normal	Heavy-mineral concentration.
ThK	Th and K anomalous, U normal	None.
UK	U and K anomalous, Th normal	None.[2]
A	All spectra anomalous	Feldspathic and (or) micaceous heavy-mineral concentration.

B, **Spectral classification of anomalies over different deposit types**

Lithology	Anomaly type (from *A*)
Old beach-complex sands with heavy-mineral concentrations	ThU, A
Old bay-complex deposits	ThU, A
River deposits	A
Phosphatic deposits	U

[1]Could be produced by feldspathic or micaceous sand but was not observed.
[2]Could be produced by glauconitic phosphorite but was not observed.

TABLE 9.–*Analyses of old beach-complex sands*

[See also table 2: --, no data; P, < 0.5 percent

						Weight percent								Weight percent of specific gravity > 2.85 fraction										
Sample Number	Radioactivity (ur)	Thickness sampled (m)	Anomaly symbol (fig. 2)	Quadrangle	Latitude; longitude	Gravel	Sand	Mud	Potassium feldspar	Phosphate	Monazite	Specific gravity > 2.85	Specific gravity > 3.3	Magnetite	Altered ilmenite	Epidote	Amphibole[1]	Garnet	Tourmaline	Staurolite	Sillimanite[1]	Leucoxene	Rutile	Zircon
EF 27B1	35	1.5	A	Santee	33°10'10" N. 79°24'55" W.	0	88	11	5	0	--	3.7	--	--	--	--	--	--	--	--	--	--	--	--
EF 27D	23	1.0	A	do	33°09'50" N. 79°24'35" W.	0	96	4	0	0	--	3.6	1.8	P	10	22	44	P	P	2	8	P	1	2
EF 27E	38	.5	A	do	33°09'40" N. 79°25'15" W.	0	91	9	2	0	0.07	11.0	7.7	P	31	32	16	P	3	3	6	1	2	2
EF 28D	25	1.0	B	do	33°12'50" N. 79°28'50" W.	1	94	5	1	0	.02	4.8	4.3	2	33	15	14	2	3	3	13	2	3	2
EF 29A	20	.5	None	Awendaw	33°05'10" N. 79°34'20" W.	0	91	9	1	0	--	2.2	--	--	--	--	--	--	--	--	--	--	--	--
EF 30A	15	3	None	Sewee Bay	32°59'00" N. 79°39'20" W.	6	90	3	10	0	--	2.8	--	--	--	--	--	--	--	--	--	--	--	--
EF 32C	28	1.5	C	Fort Moultrie	32°49'15" N. 79°51'25" W.	0	98	2	1	0	.09	4.3	4.0	1	31	24	20	1	5	5	8	1	2	2
EF 32F	23	1.0	D	Sewee Bay	32°55'15" N. 79°41'40" W.	5	91	4	3	0	.01	4.6	3.1	1	23	24	29	P	3	4	8	2	2	2
EF 35B	15	1.5	None	North Charleston	32°53'25" N. 79°56'00" W.	0	97	3	1	0	--	2.1	--	--	--	--	--	--	--	--	--	--	--	--
EF 37B	17	.5	D	Sewee Bay	32°56'40" N. 79°39'20" W.	1	94	5	3	0	.05	4.7	3.9	1	25	27	20	2	3	5	6	2	1	2
EF 37C	17	1.0	E	Bull Island	32°59'55" N. 79°36'45" W.	0	97	3	5	0	--	3.2	--	--	--	--	--	--	--	--	--	--	--	--
EF 37D	15	.5	E	do	32°59'55" N. 79°37'10" W.	1	95	3	3	0	.04	5.9	3.7	1	19	28	20	P	4	4	11	1	2	2
EF 37E	17	1.0	F	Sewee Bay	32°58'00" N. 79°38'35" W.	0	95	5	3	0	--	2.2	--	--	--	--	--	--	--	--	--	--	--	--
EF 38E	42	1.0	G	James Island	32°43'00" N. 79°57'50" W.	0	94	6	1	0	.18	9.2	--	?	25	10	10	5	5	10	5	2	1	3
EF 45C	27	.5	None	Ladson	32°54'15" N. 80°04'55" W.	0	84	16	1	1	.00	3.3	2.7	P	45	17	2	P	4	6	7	3	4	3
EF 49B	20	.7	H	Legareville	32°41'50" N. 80°07'15" W.	2	90	8	<1	0	.07	4.0	2.7	?	29	24	17	1	P	4	15	2	1	1
EF 49D	33	1.0	H	do	32°42'10" N. 80°07'15" W.	0	88	12	<1	0	.00	4.4	3.2	2	34	18	11	1	P	3	13	2	5	2
EF 50B	33	2.1	I	Wadmallaw Island	32°41'45" N. 80°11'05" W.	0	99	1	<1	P	.005	5.2	4.4	P	36	18	7	1	1	4	7	3	5	2
EF 51B	17	.5	J	do	32°39'20" N. 80°09'35" W.	1	87	12	2	0	.02	3.7	2.1	1	19	32	20	1	2	3	15	1	2	1
EF 52C	17	1.0	K	Revenel	32°46'30" N. 80°14'45" W.	0	84	16	<1	0	.003	1.9	1.5	5	31	19	3	P	6	7	12	3	6	2
EF 52D	18	1.0	K	Cottageville SE (Osborn).	32°47'00" N. 80°15'45" W.	0	88	12	?	0	.00	2.3	1.9	6	33	14	2	P	4	6	10	4	6	2
EF 52E	15	.9	K	Cottageville SE (Osborne).	32°47'10" N. 80°15'55" W.	0	95	5	<1	0	.00	1.5	1.2	4	35	12	2	P	4	5	10	3	4	2
EF 54A	23	1.0	L	Legareville	32°41'55" N. 80°01'00" W.	0	98	2	2	0	.00	4.3	2.5	1	20	25	18	1	7	3	9	2	2	1
EF 54C	58	1.3	L	do	32°41'40" N. 80°02'00" W.	0	97	3	1	0	.05	10.6	8.2	1	32	21	13	1	2	6	5	1	3	4
EF 55B	20	1.0	M	do	32°40'40" N. 80°02'30" W.	0	95	5	2	0	.00	3.3	2.2	1	24	23	21	1	3	4	8	2	2	1
EF 55C	33	1.5	L	do	32°41'05" N. 80°04'10" W.	0	89	11	<1	0	.002	6.6	4.9	1	23	21	11	2	5	7	9	1	3	2
EF 55D	17	1.1	None	do	32°40'50" N. 80°05'50" W.	0	94	6	3	0	?	1.7	0.7	--	--	--	--	--	--	--	--	--	--	--
EF 56A	67	1.0	N	do	32°39'10" N. 80°03'35" W.	0	97	3	?	2	.23	26.2	18.4	P	35	12	12	2	1	6	7	1	5	4
EF 58D	18	1.5	O	Fenwick	32°41'25" N. 80°24'25" W.	0	93	7	<1	0	.008	3.0	2.2	2	42	12	5	P	5	6	6	2	4	2
EF 59B	22	1.1	B	Honey Hill	33°11'40" N. 79°31'55" W.	0	92	8	1	0	.005	3.2	2.4	2	32	20	8	P	5	3	7	2	2	2
EF 59C	?	.9	B	do	33°12'00" N. 79°30'50" W.	0	88	12	1	0	.003	3.2	2.0	2	31	16	8	P	10	4	12	2	2	2

[1]In this table and tables 12–14 "amphibole" includes subordinate pyroxene, and "sillimanite" includes subordinate kyanite.

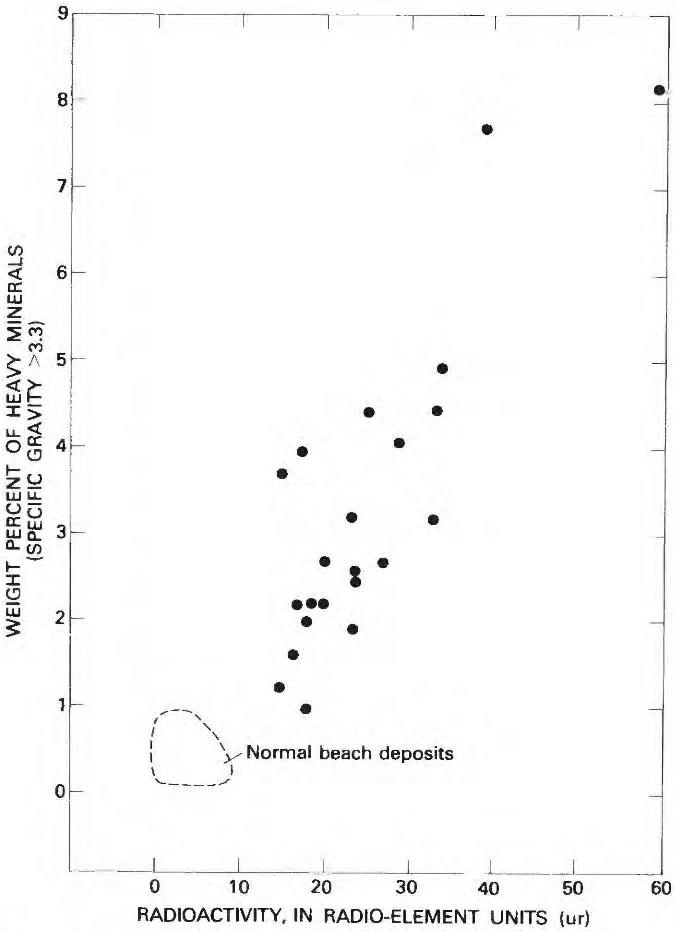

FIGURE 2.–Relation between heavy-mineral content and radioactivity of beach-complex sands.

content decreases somewhat as the age of the sample increases, as it does in beach-complex deposits. Little preferential enrichment of potassium feldspar into the sand or silt fractions was noted. Spectral aeroradioactivity surveys indicate that total potassium contents of bay-complex deposits range from about 0.2 to 1.5 percent, the higher values being in A-type anomalies.

Heavy minerals apparently are a major source of radioactivity in some bay-complex deposits. Surprisingly, avFrage heavy-mineral content of bay-complex deposits (about 1.5 percent; table 11) is about the same as the local average in beach-complex deposits. Monazite probably constitutes roughly the same percentage of the heavy minerals in bay-complex deposits as it does in adjacent beach-complex deposits. Where monazite is supplied as fine grains, it may even be preferentially winnowed out of beach sands and deposited in bay complexes. If so, heavy minerals would contribute at least an average of 12 ppm thorium and 1 ppm uranium to the composition of bay-complex deposits. This would be 40 percent of the observed average radioactivity of bay-complex deposits (about 18 ur), assuming equilibrium. A large contribution by heavy minerals is also consistent with the A and ThU spectral characteristics of the radioactivity.

Owing to their fine grain size, heavy minerals in bay-complex deposits have little economic value; nevertheless, they seem to be a major factor in the appearance of aeroradioactivity maps of the area, as they are important components of the radioactivity of the most extensive surficial unit.

Some of the muddier bay-complex deposits, however, have far too few visible heavy minerals to explain their radioactivity (for example, EF 31C, table 11). Perhaps finer silt- or clay-size heavy minerals are present. Other sources of radioactivity in weathered deposits of this type are thorium and uranium present in hydroxides of iron and aluminum. Laterites and bauxite commonly are enriched in uranium and thorium, and the average ratios of thorium to uranium in these enrichments (30/1 to 1/1; Adams and Weaver, 1958, p. 397) are such that they could produce anomalies similar to those produced by monazite. However, we were not able to check the contribution of hydroxides or of extremely fine grained heavy minerals to radioactivity.

RIVER DEPOSITS

The Santee River flood plain shows an almost continuous radioactivity high from Lake Marion downstream to the area marked by the first influences of the tide. The old Santee River deposits that occupy a level above the present flood plain show anomalies in several areas also (pls. 1,2). Radiometric values are as high as 1,700 counts on the maps and 42 ur on the ground over young river deposits, 1,650 counts and 25

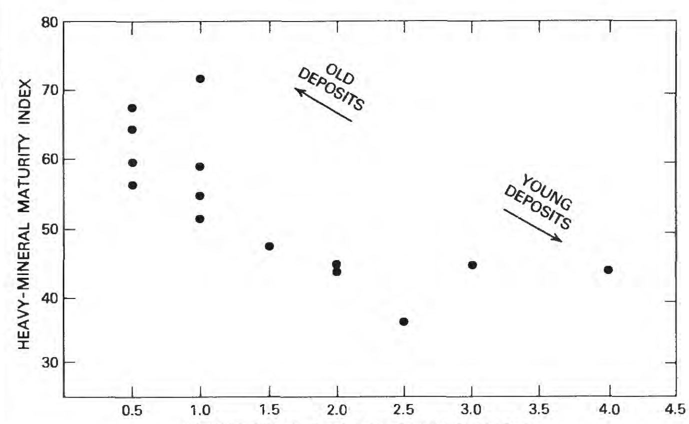

FIGURE 3.–Relation between potassium-feldspar content and heavy-mineral maturity index of beach-complex sands. Heavy-mineral maturity index=(weight percents of (ilmenite+tourmaline+staurolite+sillimanite+leucoxene+rutile+zircon) × 100)/(weight percent of all heavy minerals of specific gravity greater than 2.85).

TABLE 10.–*Summary comparison of heavy-mineral fractions of beach-complex sands*

[Taken from tables 2 and 9. Figures are weight percentages of heavy-mineral (sp gr >2.85) fraction; P, <0.5 percent]

	Altered ilmenite	Epidote	Amphibole	Sillimanite	Leucoxene + rutile	Zircon
Sands of different ages, but from same source (Santee River) [Both samples taken from above water table]						
EF 27D (younger)	10	22	44	8	1	2
EF 28D (older)	33	15	14	13	5	2
Sands of same age and general location [Positions of samples relative to water table differed]						
EF 52D (above water table)	33	14	2	10	10	2
GF 9 (mostly below water table)	20	30	25	10	1	P

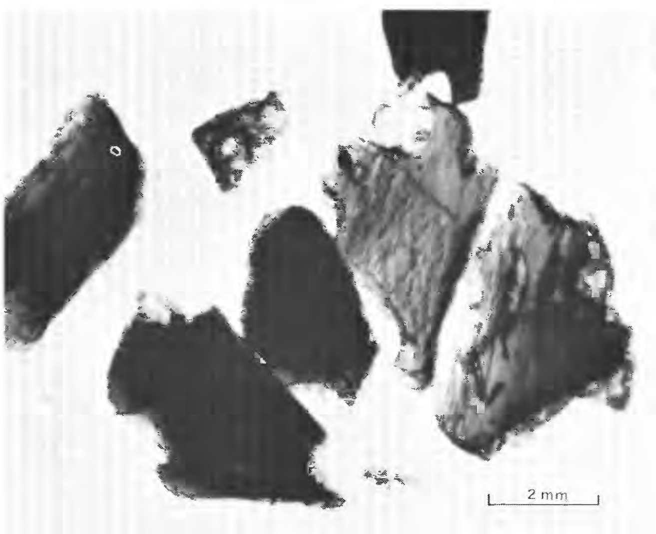

FIGURE 4.–Irregular terminations and shapes of hornblende grains in beach-complex sand sample EF 28D. These grains probably acquired their shapes from etching after deposition because their shapes could not have survived transport.

ur over old river deposits. Anomalies are of the A type (table 8), and indicated potassium contents are as high as 1.5 percent.

The modern flood plain is best described as a forested braided river. Deposits there are feldspathic granular coarse sand, muddy sand, and granular clay, all more or less unweathered.

Old river deposits are similar to the modern deposits, and the facies are commonly superimposed in vertical sequence. The sands are cross bedded. The deposits are mottled orange and gray owing to weathering. Colquhoun and others (1972) have given a history of successive courses of the Santee River.

The most radioactive river sands are rich in heavy minerals. Minerals that have >2.85 sp gr constitute as much as 4.2 percent of channel samples, and minerals

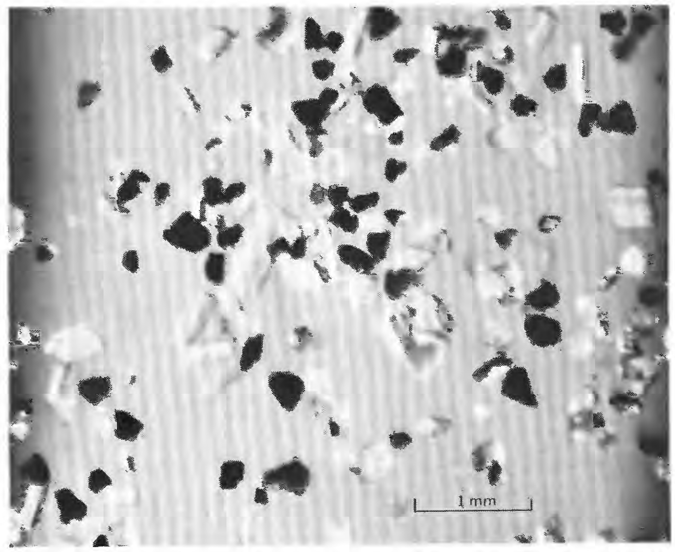

FIGURE 5.–Assemblage of silt-size heavy minerals in sample EF 31C, dominated by sillimanite but also containing zircon, ilmenite, rutile, and monazite. This material, which we call "pixie dust," is apparently a major contributor to the radioactivity of muddy samples and as such to the overall appearance of aeroradiometric maps of the area.

that have >3.3 sp gr, as much as 1.4 percent (table 12).

The heavy-mineral assemblages are dominated by amphiboles and epidote-group minerals, which in the modern river deposits form 70 percent or more of the minerals that have >2.85 sp gr (table 12).

Potassium feldspar content of the modern flood-plain deposits is commonly more than 10 percent and locally as much as 20 percent (table 12). This fact certainly explains the strong potassium component of radioactivity anomalies, but the potassium content itself does not cause the sands to show strong anomalies; Big Hill in the Santee Valley consists of river sand containing typically high potassium feldspar contents but unusually low heavy-mineral contents, and does not show any anomalies.

Mica is also present in the river deposits and contributes to the potassium component of anomalies. Its abundance was not established because of counting difficulties. Illite forms only a minor part of the clay minerals; thus, potassium-bearing clay could not possibly cause the anomalies over the river deposits.

The remarkable immaturity (prevalence of minerals unstable in a weathering environment) of both the light and heavy fractions of Santee River deposits has been discussed by other authors (Neiheisel, 1976; Colquhoun and others, 1972) and has led Neiheisel (oral commun., 1979) to refer to the Santee River as "a pipe to the Piedmont." The Savannah River, the next Piedmont-draining river to the south, has somewhat similar deposits (Neiheisel, 1976).

TABLE 11.—*Analyses of old bay-complex deposits*

Sample number	Radioactivity (ur)	Anomaly symbol (fig. 2)	Quadrangle	Latitude; longitude	Weight percent					Clay minerals (<2 μm)	Weight percent, Sp gr >2.85			Predominant heavy minerals	
					+60 mesh sand	−60 mesh sand	Silt	Clay	Potassium feldspar (approximate)		Sand	Silt	Total	In sand	In silt
EF 20D	25	P	Kilsock Bay	33°16′50″ N. 79°28′05″ W.	0	22	28	49	0.5	Kaolinite, vermiculite.	0.3	2.0	2.3	Epidote, sillimanite, amphibole, ilmenite.	Epidote, sillimanite.
EF 22C	28	Q	Jamestown	33°21′15″ N. 79°38′00″ W.	2	35	8	54	.5	Kaolinite, vermiculite, muscovite.	.7	.7	1.4	Sillimanite, goethite, ilmenite, tourmaline.	Goethite.
EF 31C	22	R	Bethera	33°07′40″ N. 79°45′40″ W.	1	8	16	74	.1	Kaolinite, vermiculite.	0	.6	.6		Sillimanite, goethite, ilmenite.
EF 38B	20	S	Charleston	32°45′35″ N. 79°58′55″ W.	7	70	5	19	3	Vermiculite, montmorillonite, kaolinite.	1.5	1.0	2.5	Amphibole, sillimanite, epidote, ilmenite.	?
EF 39A	23	T	Sewee Bay	32°56′20″ N. 79°44′20″ W.	0	24	19	56	.3	Kaolinite, chlorite, mixed chlorite and smectite.	.4	2.0	2.4	Epidote, sillimanite.	Epidote, sillimanite.
EF 48C	27	None	Ravenel	32°48′40″ N. 80°09′35″ W.	1	30	14	54	.3	Kaolinite, montmorillonite.	.2	1.0	1.2	Sillimanite, limonite, ilmenite.	Sillimanite, ilmenite, zircon, goethite.
EF 52A	27	None	Johns Island	32°46′35″ N. 80°05′25″ W.	1	41	16	43	.3	Kaolinite, montmorillonite, muscovite.	.2	1.1	1.3	Sillimanite, ilmenite, amphibole.	Sillimanite, ilmenite.
EF 53B	27	U	Wadmallaw Island	32°43′25″ N. 80°13′35″ W.	1	45	25	29	.3	Kaolinite, montmorillonite.	.4	1.4	1.8	Sillimanite, ilmenite.	Sillimanite, ilmenite.

Older Santee River deposits have potassium feldspar contents from less than 1 to about 10 percent, and heavy-mineral assemblages range from limonite-dominated mature suites to immature suites.

Modern river sediment is mostly unweathered; we could expect uranium and thorium to be present (adsorbed?), but not in aluminum and iron hydroxides. However, the older river deposits are heavily weathered and may contain thorium and uranium in hydroxides. The muddiest deposits do not contain enough visible heavy minerals to produce the observed radioactivity. Thus, the radioactivity of some old river deposits, as well as of some old bay deposits, may come from iron and aluminum hydroxides formed during weathering.

PHOSPHATIC DEPOSITS AND MAN'S ENRICHMENT OF THEM

The largest anomalies in the area are over former strip mines and associated manmade deposits of the Charleston phosphate district. Maximum radioactivity is 200 ur on the ground and 2,800 counts on the maps. Values over outcrops of phosphatic material are also as much as 200 ur on the ground but are commonly not anomalous on total-count aeroradioactivity maps owing to their small size (most are steep streambank exposures).

The anomalies are U type (table 8) and can be confidently assigned to a phosphorite source in this area. The aeroradioactivity anomalies indicate equivalent U/Th ratios of 2:1–10:1, and equivalent uranium contents of as much as 15 ppm.

The phosphatic materials occur naturally as weathering and detrital enrichments over Cooper Formation, a slightly phosphatic foraminiferal limestone of Eocene and Oligocene age. Phosphate rock becomes enriched in uranium during weathering, and uraniun in nodular phosphatic material reaches concentrations as high as 1,200 ppm. The uranium content of phosphorite in place is as high as about 150 ppm and averages 60 ppm. Details are given in Altschuler and others (1958) and Force and others (1978), but more recent work has shown that stratigraphy at the top of the Cooper Formation is more complex than that discussed by those authors.

During the period 1867–1938, strip mining of phosphate, coupled with locally poor recovery, left large areas (Force and others, 1978, fig. 1) littered with phosphatic material, which produced some anomalies. In some areas, especially south of Ashley River, recovery of the phosphatic material was better or covering was more thorough, and radioactivity is barely anomalous. Other anomalies are present at phosphate washing and drying plants, where phosphate was loaded onto barges, or at fertilizer factories. Phosphate granules were used as road aggregate at many places near the washing plants, and at the old military-port complex, such roads form a network dense enough to cause a substantial radioactivity anomaly. A specimen of asphalt from such a road contained 78 ppm uranium. Some small anomalies are caused by spoil from tunneling in unweathered Cooper Formation.

OTHER ANOMALOUS MANMADE DEPOSITS

Granite from Cayce, S.C., near Columbia, is the most commonly used aggregate in roads of the Charleston area. Radioactivity measurements over such roads are as much as 30 ur on the ground. Where road networks are dense, as over North Charleston, they cause radioactivity anomalies. Cayce granite at the quarry measures about 38 ur.

Other manmade anomalies are believed to be minor in the study area. Radioactivity is locally enhanced over cleared and fertilized agricultural land, presumably because of the potassium and uranium contents of the fertilizer. However, most of the study area is forested, and the distribution of farmland is apparently not a major factor in the distribution of radioactivity as shown on the maps.

THE HEAVY-MINERAL CONCENTRATIONS

The 15 aeroradioactivity anomalies (including spectral anomalies) over heavy-mineral concentrations in old beach-complex deposits are discussed individually in this section (See figs. 2 and 3). We conclude that five of the deposits together contain about 2×10^6 metric tons of economic heavy minerals at approximately economic grade. Other deposits, some that have more attractive mineralogy and probably larger size, contain less than 2 percent economic heavy minerals (altered ilmenite, sillimanite, leucoxene, rutile, zircon, and monazite).

Letter names of anomalies refer to figures 2 and 3 and to table 9, which also contains location data. Raw data from aeroradioactivity strip charts and other information were used to determine the areal extent of heavy mineral concentrations.

Anomaly A.—Ground and aeroradioactivity measurements outlined an anomalous area of about 6 km² extending from near South Santee and Collins Creek southwestward to Route 45. The land is mostly forested. In this area, heavy-mineral contents of short channel samples were consistently high (EF 27B1, 27D, 27E, table 9). We sampled the heavy-mineral deposit with a power auger, and drilled at the intersection of the South Santee-Collins Creek road and the Harrieta Road. Results (table 13) show that the greatest concentration is present in a surface layer 1.5 m thick or less. The heavy-mineral assemblage is dominated by amphibole and epidote (table 10) in all samples except 27E (a rich

TABLE 12.—*Analyses of river deposits*

[P, <0.5 percent]

A, Coarse-grained deposits

Sample no.	Radioactivity (ur)	Anomaly symbol (fig. 2)	Quadrangle	Latitude; longitude	Weight percent: Gravel	Sand	Mud	Potassium feldspar	Phosphate	Monazite	Specific gravity >2.85	Specific gravity >3.3	Weight percent of specific gravity >2.85 fraction: Magnetite	Altered(?) ilmenite	Epidote	Amphibole	Garnet	Tourmaline	Staurolite	Sillimanite	Leucoxene	Rutile	Zircon
Deposits of the present geomorphic cycle:																							
EF 24C	17	V	Jamestown	33°18′50″ N. 79°40′30″ W.	0	94	6	20	0	0.00	2.8	0.5	P	3	15	56	P	3	1	7	P	P	P
EF 25B	15	V	do	33°18′10″ N. 79°41′00″ W.	32	61	8	15	0	.00	<.2	--	--	--	--	--	--	--	--	--	--	--	--
EF 41A	18	V	Bonneau	33°29′30″ N. 79°57′25″ W.	26	73	1	10	.1	.01	1.1	.2	P	4	5	27	1	P	1	10	P	P	P
EF 41B	17	V	do	33°27′40″ N. 79°58′50″ W.	15	84	1	10	0	.00	2.1	.6	P	6	7	38	P	3	P	8	P	P	P
Deposits of a previous geomorphic cycle:																							
EF 43C2	18	W	Bonneau	33°23′15″ N. 79°48′45″ W.	3	75	22	10	0	.00	[1]1.7	.4	--	--	--	--	--	--	--	--	--	--	--

B, Fine-grained deposits

[?, no data]

Sample number	Radioactivity (ur)	Anomaly symbol (fig. 2)	Quadrangle	Latitude; longitude	Weight percent: +60 mesh sand	−60 mesh sand	Silt	Clay	Potassium feldspar	Clay minerals (<2 μm)	Weight percent, Sp gr >2.85: Sand	Silt	Total	Predominant heavy minerals: In sand	In silt
Deposits of the present geomorphic cycle:															
EF 24D	20	V	Jamestown	33°18′30″ N. 79°40′35″ W.	4	14	6	76	2	Kaolinite, chlorite, montmorillonite.	0.5	0.7	1.2	?	Epidote, hornblende, sillimanite.
EF 42E	22	V	Bonneau	33°27′40″ N. 79°59′20″ W.	12	33	11	43	10	Kaolinite, vermiculite.	1.3	.7	2.0	Hornblende, epidote, sillimanite.	Hornblende, epidote, sillimanite, ilmenite.
AG 28	19	V	Chicora	33°26′25″ N. 80°05′20″ W.	3	56	41		8	?	4.2	?	?	Ilmenite, phosphate, sillimanite, epidote, amphibole, muscovite.	?
AG 30	19	V	Manning	33°24′50″ N. 80°07′50″ W.	1	26	73		2	?	1.5	?	?	Amphibole, epidote, muscovite, ilmenite, sillimanite, leucoxene.	?
Deposits of a previous geomorphic cycle:															
EF 26A	25	W	Jamestown	33°15′30″ N. 79°38′40″ W.	2	2	1	95	<.1	Kaolinite, vermiculite, montmorillonite.	0	0	0		
EF 43B	23	W	Bonneau	33°18′55″ N. 79°49′50″ W.	12	12	5	70	<.5	Kaolinite, vermiculite, muscovite.	?	.4	--		Goethite, sillimanite.
EF 43C1	23	W	do	33°20′35″ N. 79°48′45″ W.	17	16	14	53	<.5	Kaolinite, montmorillonite.	?	.3	--		Sillimanite, goethite, ilmenite.
EF 43D	23	W	do	33°23′15″ N. 79°51′25″ W.	1	28	10	61	.5	Kaolinite, montmorillonite.	.3	.5	.8	Sillimanite, ilmenite, leucoxene.	Sillimanite, ilmenite, zircon, goethite.
EF 43E	23	W	do	33°22′55″ N. 79°51′00″ W.	1	15	8	76	<.5	Kaolinite, montmorillonite.	?	.5	--		Goethite, sillimanite, ilmenite.
EF 43G	25	W	do	33°19′00″ N. 79°48′15″ W.	3	49	12	36	.5	Kaolinite, montmorillonite, muscovite, goethite.	.5	.7	1.2	Sillimanite, ilmenite, leucoxene.	Sillimanite, ilmenite.

[1]Mostly goethite.

TABLE 13.–*Heavy-mineral contents of sands from power-auger cuttings in anomaly A*

Depth (m)	Heavy minerals[1] (percentage)
0–1.5	3.7
1.5–3.0	2.0
3.0–4.6	.9
4.6–6.1	2.7

[1]Specific gravity >2.85.

concentrate in which the heaviest heavy minerals are concentrated relative to the lighter ones). Below the water table, the silicate component of heavy minerals is even greater than it is above it, and economic heavy minerals constitute only about 10 percent of the heavy fraction. The body thus averages much less than 2 percent economic heavy minerals, and its size was not calculated.

Anomaly B.–A chain of aeroradioactivity anomalies and correlative ground radioactivity values of as much as 27 ur are present over sand of an old barrier island in the Cedar Hill-Morgan Branch area. The area is mostly forested. Heavy-mineral contents are high in the same area, and the mineralogy of the heavy-mineral concentrate is sufficiently mature to be of economic interest (EF 28D, 59B, 59C, tables 9 and 10). We believe that only the part of this deposit toward the river contains as much as 2 percent economic heavy minerals, and on the basis of ERDA (U.S. Energy Research and Development Administration, 1975 a–c) and total-count aeroradioactivity and on ground radioactivity, we estimate the size of this area in which material of this grade occurs to be 8 km^2, mostly in the Santee Quadrangle. Modern erosion into the south edge of the deposit in the Morgan Branch area shows its thickness to be about 3 m. The richest layer is at an altitude of about 4–5 m, and the surface layer on Cedar Hill is relatively lean. Erosion and sinkhole formation have decreased the extent of the deposit. We estimate that about 5×10^5 metric tons of economic heavy minerals is present in concentrations of more than 2 percent.

Anomaly C.–A poorly defined aeroradioactivity anomaly along Mathis Road, north of Mt. Pleasant, seems to be caused by heavy minerals in very fine sand. The area is now mostly residential. Only one channel sample was taken and analyzed (EF 32C, table 9). Using radioactivity itself to outline the area of concentration, and assuming an average thickness of 2 m, we estimate that $6 \times 10^6 m^3$ of sand contains heavy-mineral concentrations. Our sample and the radioactivity data indicate that the body probably does not average as much as 2 percent economic heavy minerals.

Anomaly D.–Two small aeroradioactivity anomalies in the area of Moore's Landing and the Drew farm (which is fertilized) are on adjacent flight lines and should have been contoured as one anomaly. They are in the same body of very fine sand. The heavy-mineral suite is immature, and grade of economic heavy minerals is less than 2 percent (EF 32F and 37B, table 9).

Anomaly E.–A small anomaly near Sewee Camp is present over heavy-mineral-bearing sand. The area is forested. The heavy-mineral suite is immature, and less than 2 percent economic heavy minerals is present (EF 37C and 37D, table 9).

Anomaly F.–A small anomaly is present over a slight heavy-mineral concentration in very fine sand, about 2 km southwest of anomaly E (EF 37E, table 9). The area is forested.

Anomaly G.–An aeroradioactivity anomaly and correlative ground radiation as high as 50 ur is present along Kings Road in Riverland under housing developments. Heavy minerals are concentrated in very fine sand. Only one sample was analyzed (EF 38E, table 9) owing to the difficulty in working with the fine grain size. The distribution of anomalous radioactivity suggests that the sand body occupies 2 km^2. Creek-bank and hand-auger samples show that thickness is greater than 1 m; the body thus probably contains more than 2×10^5 tons of economic heavy minerals at grades of more than 2 percent. The fine grain size and the immaturity of the heavy-mineral suite, however, are great detriments to the recovery of the minerals.

Anomaly H.–Aeroradioactivity anomalies on both ERDA and total-count surveys are present over the Maybank Highway across the boundary between Legareville and Wadmallaw Island Quadrangles on Wadmallaw Island. The area is farmed. Heavy minerals are present in fine to very fine sand over an area of about 2.5 km^2. They are concentrated primarily at altitudes of 4.5–8 m; therefore, we believe that the deposit is as much as 3 m thick. On the basis of the two analyzed channel samples (EF 49B and 49D, table 9) the deposit probably does not average 2 percent heavy minerals.

Anomaly I.–About 3 km west of anomaly H along the Bears Bluff road is another anomaly that is probably closely related. It is a sand body, perhaps a sand dune, forming a gentle rise, and overlies clayey sand. The maximum thickness is 2.1 m. Its area, taken in part from the distribution of radioactivity, is about 1.5 km^2. We believe that the body contains only about 5×10^4 tons of economic heavy minerals at concentrations of 2 percent (EF 50B, table 9).

Anomaly J.–A body of very fine sand near Bethlehem Church causes a small anomaly apparently produced by heavy minerals (EF 51B, table 9). The area is farmed. The grade of economic heavy minerals is much less than 2 percent, and the grain size of the matrix makes separation difficult.

Anomaly K.—A Th anomaly (table 8) and slight total-count anomaly in ERDA (1975a, flight ML10) data is present in the Ravenel area; no corresponding anomaly is shown on CPRC-USGS (1975) aeroradioactivity maps. The area was checked for the previously described calibration of Cottageville SE (Osborn) Quadrangle. The lithology producing the anomaly is well-sorted to moderately sorted medium sand. The heavy-mineral assemblage is moderately mature above the water table but less mature below it (EF 52C, 52D, and 52E, table 9; see also GF 9, tables 2 and 10). Although economic heavy-mineral contents average only about 1 percent, the considerable volume of this body (at least 10^2 km in area, about 10 m thick) and the high proportion of the more valuable heavy minerals suggest that it should be considered a resource.

Anomaly L.—A string of aeroradiometric anomalies and correlative anomalies measured on the ground extends 9 km from Johns Island Airport past Blessed Sacrament Church. The area is mostly forested. Beach-complex sands seem to cover much of the area, both inside and outside the anomaly, but the body producing the anomaly is that outlined roughly by the 20-foot contour. Near Stono Stables (EF 54C, table 9), the width of the body that produces radioactivity of more than 15 ur is about 300 m, but the width that produces more than 35 ur is only 20 m. Heavy minerals are readily apparent in medium sand at all three sampled localities (EF 54A, 54C, and 55C, table 9). At EF 54C, medium sand 1.3 m thick containing 10.6 percent minerals of >2.85 sp gr is underlain by fine sand from 1.3 to 2.0 m beneath the surface containing 3.4 percent minerals of >2.85 sp gr. The same stratigraphy is present at locality EF 55C. Power augering between Mt. Zion School and Calvary Church shows that heavy-mineral concentrations are present through a thickness of as much as 4 m. We estimate that the body averages 2.5 m in thickness, that average content of economic heavy minerals is about 2 percent, and that it contains approximately 7×10^6 tons of economic heavy minerals. The suite of heavy minerals is not mature, and difficulty in separation is therefore a limitation on the value of the deposit.

Anomaly M.—Just south of anomaly L, a small anomaly is present near Mt. Zion School. The area is mostly farmed. Heavy minerals are present in well-sorted sand. The single channel sample contained much less than 2 percent economic heavy minerals (EF 55B, table 9). Dimensions of the deposit were not determined.

Anomaly N.—Near Legareville, in an area of fertilized market-garden farms, a long narrow anomaly on the aeroradioactivity maps corresponds to radioactivity readings as high as 65 ur on the ground. The width of readings of 35 ur or more is 150 m near locality EF 56A (table 9). Heavy-mineral contents in the sand are the highest observed in this study. Beneath the 0.5–1.5-m interval reported in table 9 is a 1.5–1.95-m interval containing 20.3 percent material >2.85 sp gr. and 13.3 percent material >3.3 sp gr. This sample contains abundant phosphorite, both in the lighter heavy-mineral fraction and in the light fraction. Phosphate is present mostly as slightly to completely phosphatized tests of Foraminifera, and is estimated to constitute 3.3 percent of the sample. The water table at 1.95 m prevented further penetration. Two flight lines east of EF 56A show anomalous radioactivity where they cross the sand body, and heavy-mineral concentration continues along strike to the west; on this basis, the body is thought to be 5 km long. A volume of $2.2 \times 10^6 m^3$ for the deposit is a minimum as it is limited by the thickness we were able to penetrate. The body contains about 6×10^5 tons of economic heavy minerals, including about 1×10^5 tons of phosphate.

Anomaly O.—An impressive anomaly over the road to Willtown Bluff corresponds to ground readings of as much as 27 ur. The area is forested. Heavy minerals are present in well-sorted medium sand; economic heavy-mineral contents, however, are well under 2 percent (EF 58D, table 9). The volume of the deposit was not determined.

THE ROLE OF AERORADIOACTIVITY IN HEAVY-MINERAL PROSPECTING

Results of this study show, as do several other studies, that aeroradioactivity surveys can be used to find deposits of detrital heavy minerals where the heavy-mineral suite contains radioactive minerals. However, this study also shows that most radioactivity anomalies are caused by other types of deposits and that the radioactivity of the heavy-mineral deposit has little relation to its economic value.

The first difficulty was that of predicting which of the anomalies shown on an aeroradioactivity map might be caused by heavy minerals; it was solved in the study area by intensive use of spectral radioactivity information, available geologic information, and county soils maps. Heavy-mineral deposits have a range in relative strength of spectra that eliminates anomalies caused by phosphate, clay, mica, potassium feldspar, or glauconite. Geologic and soils maps can be used to delineate the well-sorted sands (mostly old beach-complex sands) in which heavy-mineral accumulations occur and to elminate the anomalies caused by muddy bay-complex and other deposits. Presumably, in other areas and in other circumstances, other techniques could be used to narrow the number of anomalies to those that might be caused by heavy minerals. Aeroradioactivity alone is not a good prospecting tool, and the best information available should be used with radioactivity in searching for heavy minerals.

The second difficulty is that the heavy-mineral deposit found by means of aeroradioactivity may have little value owing to any or all of the following factors: (1) thin deposit; (2) unstable heavy-mineral assemblage containing low-TiO_2 ilmenite, and silicate minerals that are hard to separate from ilmenite; (3) fine grain size or muddy matrix, which makes mineral separation difficult. None of these unfavorable factors decreases the radioactivity of a deposit. Knowledge of regional mineralogy may enable a heavy-mineral prospector to eliminate the anomalies caused by unstable mineral assemblages (in some places, the strength of the potassium component could be used to screen out unstable potassium-feldspar-bearing sands). However, the prospector must resign himself to looking at many thin or fine-grained deposits.

The most efficient method for prospecting for heavy minerals in the Charleston area using aeroradioactivity maps is probably as follows:

1. Using culture maps, eliminate those aeroradioactivity anomalies over densely populated areas. Dense population produces anomalies and makes mineral exploitation difficult.
2. Using soils maps and geologic maps, eliminate all lithologies other than well-sorted sands.
3. Eliminate all aeroradiometric anomalies that are not dominated by uranium and thorium in appropriate proportions (ThU anomalies of table 1).
4. Eliminate all deposits known to have unstable heavy-mineral suites, such as the Santee River deposits.
5. Examine the remaining anomalous areas. Heavy-mineral anomalies typically form isolated anomalies or chains of anomalies in a fairway having low background. Low background represents beach-complex sands that are not enriched in heavy minerals.

OTHER APPLICATIONS OF THE AERORADIOACTIVITY DATA

Our method, with little modification, has proved useful in regional geologic mapping in the Charleston region. For that purpose, emphasis is on differences in background levels between lithologies rather than on anomalies, except where anomalies represent the only outcrops of the material being mapped. The greatest regional contrast in total-count gamma radioactivity is between most beach-complex sands and virtually all other deposits (table 7). The greatest spectral contrasts are among phosphorite, river deposits, and most other deposits (table 8).

Our method also lends itself to exploration for other types of mineral deposits in the area. For example, a byproduct of this study was another study by Force and others (1978) documenting uranium-bearing phosphorite resources of the region. We can also see aeroradioactivity applications in the same area for other types of uranium deposits and for feldspar or silica sand deposits.

In other areas of the Coastal Plain, our method would have to be modified to allow for differences in regional mineralogy (see Force and Bose, 1977). A method similar to ours, based on spectral and total aeroradioactivity values coinciding with geologic and cultural criteria, would probably be useful in many areas.

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