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With a section on Field-Spectrometer-Data Reduction

By KENNETH L. KOSANKE

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A method of exploration for nearshore marine placer heavy-mineral deposits by the use of gamma-ray ground-radiometric and aeroradiometric techniques

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APPLICATION OF TOTAL-COUNT AERORADIOMETRIC MAPS TO THE EXPLORATION FOR HEAVY-MINERAL DEPOSITS IN THE COASTAL PLAIN OF VIRGINIA

By ANDREW E. GROSZ

ABSTRACT

Total-count contoured aeroradiometric maps for the Coastal Plain of Virginia were used in an effort to locate economic heavy-mineral placer deposits. The principle behind this approach is that heavy-mineral suites commonly contain radioactive minerals that, if the concentration of heavy minerals is exposed at or within inches of the surface, enable the deposit to be located by use of airborne instruments because of its radiometric contrast with the host sediment.

Detailed and regional geologic maps, soil maps, land-use and land-cover maps, information on fertilizer use, and ground-spectrometer data were used to study aeroradiometric anomalies for efficient exploration. Aeroradiometric anomalies in the Coastal Plain of Virginia have three general causes. First, the most intense anomalies are associated with cultural features, such as roads made of granitic material. Second, most anomalies of high to intermediate intensity are associated with land used for agricultural purposes and evidently are caused by applications of radioactive fertilizer. Third, anomalies of intermediate to low intensity are associated with heavy-mineral deposits.

Results of this study show that aeroradiometric anomalies associated with heavy-mineral accumulations in the Coastal Plain of Virginia have ground radiometric spectra in which thorium is the strongest component and uranium and potassium are lesser components.

Heavy-mineral accumulations found in this study by use of the aeroradiometric data are not considered to be of economic importance, mostly because of the low percentage of economic minerals in the heavy-mineral suites and also because of other factors such as the very fine grained nature of the host sediments and competing land use.

INTRODUCTION

Economically valuable heavy-mineral placer deposits in nearshore marine sediments on the Atlantic Coastal Plain are sources for a significant fraction of much-needed titanium dioxide minerals in the United States. Currently, most of the demand for such minerals is supplied by foreign imports, particularly from Africa, Brazil, and Australia. This investigation is primarily concerned with locating such deposits on the Outer Coastal Plain of Virginia by the use of aeroradiometric maps, but it also documents a method of approach to efficient exploration and to the interpretation and evaluation of such maps for other purposes in coastal areas.

Valuable heavy-mineral accumulations in sand ore bodies on the Atlantic Coast have been discovered by a variety of techniques. Deposits have been discovered by geologic reasoning and shallow augering (Spencer, 1948; Markewicz and others, 1958). Aeroradiometric surveys have played, or in hindsight could have played, a part in the discovery of several deposits, such as those at Folkston, Ga. (Moxham, 1954), Green Cove Springs, Fla. (James Hetherington, oral communication, December 18, 1974), and Brunswick, Ga. (Stockman and others, 1976). Surface sampling and shallow drilling have been relied on in exploration efforts; the high costs associated with such programs, however, warrant new exploration techniques, such as the application of aeroradiometric data, so that large areas can be scanned at lower cost.

Extensive aeroradiometric surveys for the southeastern Atlantic Coastal Plain States have been contracted for by the United States Geological Survey (USGS). Funding for the surveys and subsequent field investigations was supplied by the Coastal Plains Regional Commission. The objective behind these surveys was to detect concentrations of radioactive minerals exposed at the surface.

Exploration for heavy minerals by the use of aeroradiometric surveys is based on the assumption that radioactive heavy minerals such as monazite, sphene, and zircon are concentrated with nonradioactive heavy minerals such as ilmenite, rutile, and sillimanite to form placer deposits. Wave, tidal, and wind actions are the mechanisms by which the heavy minerals are concentrated on present-day shorelines in beach sand. Concentrations are also present in former shoreline deposits now found inland, commonly parallel to present shorelines. Placer deposits thus formed will exhibit radiometric contrast to their host sediment if radioactive minerals are present in the heavy-mineral suite. Such radiometric contrast is, in principle, detectable by airborne scintillation counters.

The study area is Virginia's Outer Coastal Plain and includes approximately 2,500 square miles (6,475 square kilometers), including the Delmarva Peninsula (fig. 1). Parts of this area have been settled since colonial days and are focal points of commercial, industrial, and military activities on the Atlantic coast. With the exception of two broad clusters of urbanized areas (the tip of the James-York Peninsula and the Norfolk-Portsmouth-Chesapeake-Virginia Beach complex), the bulk of the study area is used for agricultural purposes and is sparsely populated.

Inasmuch as the James River drains an ilmenite-rich terrane (Minard and others, 1976), the probability of heavy-mineral concentrations on the Coastal Plain is good. Because shoreline sands elsewhere are commercial sources of heavy minerals, Force and Geraci (1975) undertook a study to evaluate the possibility of heavy-mineral deposits in the Pleistocene(?) shoreline sands in eastern Virginia. A suite of 53 samples (pl. 1) was collected and processed for heavy minerals in methylene iodide (s.g. (specific gravity) 3.3), but the heavy-mineral contents were much lower than those of deposits presently being mined. Of particular interest to this study is that the radioactive-mineral content of the heavy-mineral suites is very low to absent. The implications behind this are that, if the most promising lithology for heavy-mineral deposits in the area is low in radioactive heavy minerals, other less favorable lithologies are not likely to contain much monazite and zircon; as a consequence, aeroradiometric contrasts of heavy-mineral accumulations with respect to barren host sediments were expected to be low.

PREVIOUS WORK

A large amount of literature on the theory and use of airborne radiometric surveys exists (for example, Moxham, 1954, 1960; Gregory, 1960; Schmidt, 1962; Mahdavi, 1964; Pitkin and others, 1964; Neuschel, 1970; Neuschel and others, 1971; Neiheisel, 1976; Perlman and others, 1976; Stockman and others, 1976; Force and Bose, 1977). Until recently, however, little has been published on the application of such data to the exploration for placer heavy minerals in coastal areas. A study of the applicability of aeroradiometric maps to placer prospecting in South Carolina's Coastal Plain (Force and others, 1978) was recently published; it presents a method of classifying aeroradiometric anomalies into different types. That study uses airborne total-count and airborne spectral radiometric data in conjunction with county soils maps, regional mineralogic trends, and regional geologic information. Results of that study show that aeroradiometric surveys can be used to find detrital heavy-mineral accumulations containing radioactive heavy minerals. The study, however, also shows that most aeroradiometric anomalies are caused by deposits other than heavy minerals and that the intensity of aeroradiometric signature of a heavy-mineral deposit does not reflect its economic value. Another recent study (Robson and Sampath, 1977) tested the effect of heavy-mineral sand deposits at Jerusalem Creek, New South Wales, Australia, on a variety of geophysical instruments. That study shows aeroradiometry to be among the more promising geophysical techniques for locating heavy-mineral deposits that crop out. Furthermore, the study shows that, although the ore is highly radioactive (presumably because of monazite), 10 feet (3 meters) of overburden completely attenuated the response. However, in general, the thickness of overburden needed to mask gamma radiation is about an order of magnitude less (Beck, 1975).

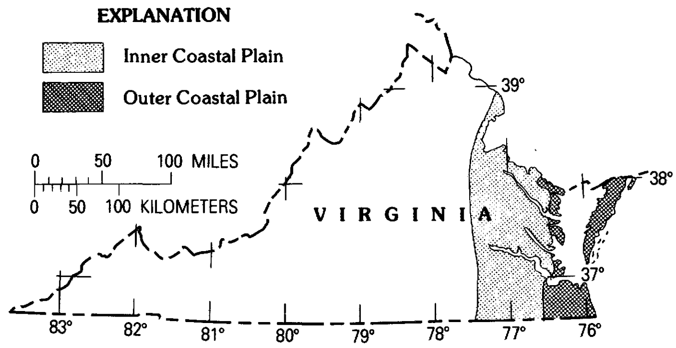

FIGURE 1.—Index map showing the relation of the Coastal Plain of Virginia to the State, the Outer Coastal Plain (the study area), and the Inner Coastal Plain. Modified from Wentworth (1930, p. 2).

PRESENT WORK

Field investigations of aeroradiometric anomalies in the study area were conducted in the summer of 1978. During this time, sediment and ground-radiometric samples were collected for analyses, and several anomalies west of the study area were sampled. All the samples were analyzed in USGS laboratories at Reston, Va. Ground-radiometric data were analyzed and corrected by the Bendix Field Engineering Corporation, Grand Junction, Colo. (see the section on "Field-Spectrometer-Data Reduction").

The method of approach in this study was partially based on methods and results from previous studies on the uses of aeroradiometric maps. The use of geologic, land-use and land-cover, and fertilizer-use maps, in conjunction with ground-spectrometer data, as "filters" over the aeroradiometric maps is presented. This method is part of an effort to identify anomalies caused by materials other than heavy-mineral accumulations.

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Property owners throughout the study area were both friendly and helpful. I am grateful to all of these people and many others for their generous help and consideration.

THE STUDY AREA

MORPHOLOGY

The study area has little relief. The most prominent geomorphologic feature in the coastal area is the east-facing Suffolk scarp and correlative scarps, which trend north through Virginia's Coastal Plain. This scarp is an old shore face that forms a natural stratigraphic boundary separating post-Pliocene units into an older group to the west (the Inner Coastal Plain) and a younger group to the east (the Outer Coastal Plain) (Oaks and Coch, 1973, p. 4). Altitudes on the Inner Coastal Plain range from 20 to 175 feet (6 to 53 meters) above sea level, and relief is 20 to 50 feet (6 to 15 meters) near major streams. The Outer Coastal Plain, in contrast, is characterized by altitudes generally below 25 feet (8 meters) above sea level, and relief is as much as 20 feet (6 meters) locally along the James and Nansemond Rivers only. Wide and flat undissected tracts form poorly drained areas between major streams in both parts of the Coastal Plain.

Depositional morphology predominates east of the Suffolk scarp and correlative scarps, but fluvial erosion has altered large parts of the original depositional surfaces west of the scarps. Linear morphologic features have a north-south trend that is closely related to the depositional morphology of ancient barrier-and-lagoon environments (Oaks and others, 1974, p. 62).

GEOLOGY

Published literature on the geology of Virginia's Coastal Plain spans more than 350 years and ranges from the first known published reference to the generalized geology of the Coastal Plain (John Smith, 1624, cited *in* Wentworth, 1930) to more detailed studies in recent years (Coch, 1968, 1971; Oaks and Coch, 1973; Oaks and others, 1974; Johnson, 1972, 1976; Onuschak, 1973; Force and Geraci, 1975). Current USGS work on the geology of the Delmarva Peninsula south of the Maryland-Virginia State line (Robert B. Mixon, written communication, 1979) provided additional information on the character and composition of surficial lithologies in the coastal area.

Recent workers have studied post-Pliocene sediments east of the Suffolk scarp and correlative scarps to determine their origin, relation to sea level, geologic history, and mineral composition. On the basis of these studies, lithostratigraphic nomenclature for most surficial units and pre-Pleistocene units has been suggested; major groupings of sediments are thought to have been deposited during submergent phases of emergent-submergent cycles attributed fot the most part to glacial eustatic effects. A generalized geologic map (pl. 1) shows surface distributions of the units mapped in southeastern Virginia and on the Delmarva Peninsula.

The oldest sediment in the study area is the Yorktown Formation of early Pliocene age, exposures of which, in southeastern Virginia, are generally limited to river bluffs and artificial excavations. The Yorktown Formation consists of marine clay, sand, silt, and coquinite. Postdepositional fluvial erosion has created severe relief locally in the top of this unit (Oaks and others, 1974, p. 62).

Widespread, flat-lying units above the Yorktown record a complex history of relative sea-level changes through time. Oaks and Coch (1973, p. 108) recognized six important periods of sea-level fluctuation, during the submergent phases of which the following formations[1] were deposited, from oldest to youngest: the Sedley Formation, the Bacons Castle Formation, the "Moorings" unit, the Windsor Formation, the Great Bridge Formation, the Norfolk Formation, the Kempsville Formation, and Holocene units. Some of these formations (for example, the Windsor Formation) are found only west of the Suffolk scarp and correlative scarps.

The post-Yorktown formations are predominantly marginal marine clastic sediments, ranging in depositional environment from beach barrier to offshore deposits and in grain size from clay to coarse sand. The materials are predominantly quartz sand, silt, and feldspar; clay, mica, chert, and rock fragments are locally important but generally are minor constituents. Oxidation of exposed facies is generally 1 to 5 feet (0.3 to 1.5 meters) deep, whereas in older facies, oxidation penetrates more than 10 feet (3 meters).

With the exception of Holocene facies, which are virtually unweathered, most units show limonitic or mottled hematitic (Coch's Windsor Formation, upper member) color in the weathered zone. Alteration of quartz-grain surface features and of soluble heavy minerals is very slight to moderate with the exception of the "Moorings" unit, where alteration is heavy. Soil is well developed to a depth of approximately 3 to 4 feet (0.9 to 1.2 meters) on older units and is virtually absent on Holocene units. Clay enrichment is significant (0.25 to 8 feet; 0.08 to 2.4 meters) in lithologies having well-developed soil zones and minor in lithologies without soil zones (Oaks and others, 1974, table 2, p. 66).

Facies exposed at present on the Delmarva Peninsula (units A through F, pl. 1) are of late Pleistocene and Holocene age (Robert B. Mixon, written communication, 1979) and range in composition from the medium- to coarse-grained sand, gravelly in part, interbedded with lesser amounts of fine-grained sand, of barrier island or barrier spit complexes to fine-grained sand deposits on the bottom of an ancestral Chesapeake Bay.

EVALUATION OF THE AERORADIOMETRIC DATA

The total-count gamma-ray-intensity survey for Virginia was flown and compiled for the USGS by Geodata International, Incorporated, in late 1976 and early 1977. Part of the survey covering southeastern Virginia was flown and compiled in 1975–76 by LKB Resources, Incorporated (Force and Bose, 1977). The mismatch of aeroradiometric contour lines at the border between the two surveys is a phenomenon common to overlapping airborne surveys. The instruments for such surveys are generally not calibrated over pads of known radioelement concentrations, and as a result, different instrument packages and, more importantly, different detector sizes will yield different results (in count-rate magnitude) over the same sediments; these results can be correlated only with difficulty.

The fundamental principle behind airborne radiometric surveys is that radioactive materials exposed at the surface emit a spectrum of radioactivity that can be measured by airborne scintillometers. Instruments of this type commonly consist of a large-volume (400 to 500 cubic inches, 6,600 to 8,200 cubic centimeters) NaI (sodium iodide) crystal coupled to an electronic system that records the activity detected by the crystal. An airborne system registers radioactivity from three basic sources, terrestrial, atmospheric, and cosmic. The strongest component is the terrestrial source. Atmospheric and cosmic sources generally account for a small part of the total count rate observed but are highly variable with time, altitude, and prevailing atmospheric conditions; as a result, some airborne surveys register substantial and variable radiometric count rates over open bodies of water where values should be low and constant. Airborne surveys are generally flown at an altitude of 500 feet (150 meters), and flight lines are oriented to cross the strike of geologic contacts. Spacing between flight lines is commonly 1 to 1 ½ miles (1.6 to 2.4 kilometers). Total-count contoured aeroradiometric maps are the end products of such surveys; they are commonly hand contoured, but recently computer programs have been written to do the contouring. Aeroradiometric surveys, although more limited in resolution and accuracy than surface methods, can best show regional variations in radiation, from which some estimates may be made of terrestrial radioelement content and of surface radiation intensities.

The aeroradiometric map (pl. 2) outlines major water bodies in the study area, indicating that location accuracy and instrument calibration are good. Large parts of the survey, however, particularly west of the study area, show major contrasts in radiometric signatures that are inconsistent with other parts of the survey. This inconsistency is due to switching from one type of navigational system over the Outer Coastal Plain to another over the Inner Coastal Plain and Piedmont regions (Robert S. Foote, President, Geodata International, Incorporated, oral communication, 1978) and is esentially a geographic location problem. Because the areas of high contrast were well west of the study area, the part of the survey covering the Outer Coastal Plain is considered acceptable with the following stipulations.

Large parts of the survey, particularly near the

[1]These formations have not been adopted for U.S. Geological Survey usage; their usage herein is based on the mapping of Oaks and Coch (1963, 1973) and Coch (1965, 1968).

Virginia-Maryland border and near the mouth of Chesapeake Bay, registered significant count rates over open bodies of water where signatures should be very close to zero. Because count rates of 30 to 60 counts per second were registered over open water, radiometric values over land are subject to an error equaling the count rate observed over water for those flight lines that registered greater than zero counts per second over water.

Further complications arise from the computer contouring technique. The total-count aeroradiometric map of the Portsmouth area (pl. 3) is used as an example of the computer contouring technique and its results. By use of a matrix of measured values from adjacent east-west oriented flight lines, "hybrid" numbers were first extrapolated and then contoured. Such "hybrid" numbers appear between flight lines and represent averaged values that do not correspond to actual measured values, either in their numerical value or in geographic location. Plate 3 also shows how a point source of radiation is treated by the plotter. The "dipole-like" anomaly southeast of the Elizabeth River consists of a radiometric high (362 counts per second) and a proximal radiometric low (48 counts per second). The high value corresponds to radioactive source(s) within the main building of the Portsmouth Naval Hospital—a point source for all practical consideration—exaggerated by contouring to more than a mile (1.6 kilometers) long and to ⅓ of a mile (0.5 kilometer wide); the low is associated with a major drainage that is truncated at the north by the distended high. Such distortion is increased by flight-line spacing greater than 1 mile (1.6 kilometers) and is typical of areas where the count rate exceeds 200 counts per second.

In a preliminary reconnaissance study of natural radiometric contrasts between surficially exposed lithologic units in the study area, the lower member of Coch's Windsor Formation (where exposed near the Suffolk scarp) was found to be anomalously radioactive with respect to adjoining lithologic units. This radiometric contrast cannot be found on the aeroradiometric map, indicating that the resolution of the map with respect to spatial extent is marginal in places.

Because of complicated cultural patterns in parts of the study area, and because previous work has shown that most anomalies in coastal plain areas are caused by materials other than heavy minerals (Force and others, 1978), anomalies were classified prior to field investigation. For this purpose, land-use and land-cover maps (USGS, 1977a–c) provided an excellent first approximation of which anomalies would likely be caused by heavy-mineral deposits and which would be caused by cultural activities. The results of this approach are illustrated in plate 4. Land-use and land-cover maps are constructed from remote-sensor data, mostly U-2 photographs and satellite imagery. The resolution of these maps is such that 10-acre (4-hectare) plots of land are the smallest mappable units. Plate 4 represents the intersection of the sets of radiometric signatures and land-use and land-cover data for anomalous areas. Analyses of numerical codes within anomalous areas show that clusters of anomalies can be related to one or more of eight types of land-use and land-cover settings. The types are residential, commercial, industrial, agricultural, forest, wetland, barren, and beach.

The area south of the James River can be characterized by two broad zones of different types of anomalies; zone 1 includes residential, commercial, and industrial types for the most part near urbanized areas, and zone 2 is agricultural, forest, wetland, and beach types for the most part near the North Carolina border. Similarly, the tip of the James-York Peninsula is characterized by predominantly residential and commercial types. A cluster of anomalies near the southern bank of the Rappahannock River is characterized as predominantly agricultural and forested land. Anomalies on the Delmarva Peninsula are almost exclusively of the agricultural type; beach-type anomalies (not accessible in this study) are on the Atlantic shore. The land-use map is more than 6 years old, and, in some areas, major changes were noted during field investigation.

Field investigation of the anomalous areas just described proved the land-use and land-cover categorization scheme applicable. Anomalies associated with residential, commercial, industrial, and military sites are invariably caused by radioactive material brought in from outside the Coastal Plain by man. Such materials are generally granitic road metal, facing stone, and other hard rock. On the other hand, anomalies associated with agricultural, forest, wetland, barren, and beach areas are in some instances explainable by concentrations of radioactive heavy minerals exposed at the surface.

FIELD METHODS

Field investigation consisted of ground checks of total-count aeroradiometric anomalies by two methods and of sampling anomalous materials for laboratory analyses. Geographic areas where the aeroradiometric signature is greater than local background are outlined on plate 4 and were also outlined on 7½-minute-quadrangle topographic maps for the purposes of field investigation.

First, an anomalous area was traversed by vehicle to determine the geographic extent of the anomaly; this approach also verified that the anomaly registered by the airborne system was real. During the vehicle traverse, readings were taken over sediment at 0.1-mile (0.16-kilometer) intervals by use of a total-count portable scintillometer to find the anomalous material. Second, where this material was found, a four-channel spectral scintillometer containing a large-volume (110 cubic inches, 1,900 cubic centimeters) NaI detector was used to measure the components of the gamma-radiation field. To achieve constant geometry at each locality, the detector unit of the instrument was suspended about 1.5 feet (0.5 meter) above the surface from a tripod. After temperature equilibration and standardization against a barium-133 gamma-ray source, the count rate was measured at the following gamma-ray energies: (1) 2.62 MeV (million electron volts) from thallium-208 in the thorium-232 series; (2) 1.76 MeV from bismuth-214 in the uranium-238 series; and (3) 1.46 MeV from potassium-40. The counting time at each locality did not exceed 6 minutes. The data are given in table 1. Sediment samples were taken immediately below the detector crystal by a soil auger to a depth of 3.3 feet (1 meter). In the auger sample where dark minerals were observed in quantities of 1 to 3 percent, more extensive sampling was done.

Of 164 anomalous sites investigated (pl. 1), 75 were sampled for laboratory analyses; the remainder were not confirmed by field inspection or did not contain visible dark minerals. All aeroradiometrically anomalous localities on the Delmarva Peninsula were estimated to contain considerably less than 1 percent total heavy minerals in the top 3.3 feet (1 meter) of sediment, and consequently none was sampled for laboratory analyses. The sample collected at loc. 20E was from 15 to 20 feet (4.6 to 6.1 meters) depth.

EFFECTS OF FERTILIZER USE ON AERORADIOMETRIC MEASUREMENTS

The most acute problem encountered during field investigation was related to land used for agricultural purposes. Typical of this problem is an area north of the North Carolina-Virginia line, where aeroradiometric anomalies exceeding 250 counts per second could not be located on the ground. The dominant lithology in this area is a silty clay of the Sand Bridge Formation.[2] Ground-radiometric characterization of this area (see A, pl. 2) shows no consistently high values associated with the aeroradiometric high. This lack of ground-radiometric anomalies is typical of most agricultural fields associated with aeroradiometric anomalies. In these areas, corn, cash crops (for example, tomatoes, strawberries), and "double crops" (for example, corn followed by grain) are the main products. The common denominator of these crops is that they all need very large amounts of mixed fertilizer frequently applied. Mixtures commonly consist of variable amounts of nitrate, potash, and phosphate either in liquid or granular form. Potash and phosphate are radioactive. Because both aeroradiometric surveys conducted near the North Carolina-Virginia border registered high count rates over these silty-clay deposits, we can assume that, at the time of the surveys, anomalously radioactive material was present. The inability of ground surveys to prove these anomalies real poses a problem for which no clear-cut explanation exists. Examination of flight recovery sheets and analog charts of the northern part of the aeroradiometric survey shows that the survey was conducted between October 1976 and February 1977, coinciding with fertilizer application times. The most reasonable explanation involves the temporal and geographic coincidence of fertilizer application and of survey flights.

To test the assumption that fertilizer was responsible for causing anomalies, gross fertilizer consumption by counties (index map pl. 4) was compared with radiometrically anomalous areas in each county. As a result, strong correlation was found to exist between the types and quantities of fertilizer used in counties with anomalies falling on agricultural fields, so that, for Accomack County, Northampton County, Virginia Beach City (formerly Princess Anne County), and Chesapeake City, aeroradiometric anomalies on agricultural lands were suspected to be caused by fertilizer. Subsequent field and laboratory investigations strongly indicate the fertilizer to be the cause of these anomalies. A possible alternate explanation is that clayey material normally contains potassium-40 in clay minerals such as muscovite, biotite, and illite and contains uranium-series nuclides adsorbed on clay minerals; hence, areas where clay is common should be anomalous with respect to sandy terranes.

LABORATORY ANALYSES

Laboratory procedures were directed toward two goals. First, I wanted to find the amount of economic minerals in each sample. Second, because mined heavy minerals are normally separated as coarse- to fine-grained sand, by splitting the very fine grained sand- and silt-size fraction away from the coarser sand and examining both size fractions independently for their heavy-mineral content, insight would be provided as to partitioning tendencies according to size of different heavy minerals.

[2]As mapped by Oaks and Coch (1963, 1973).

TABLE 1.—*Ground-radiometric and aeroradiometric signatures of sample localities in the Coastal Plain of Virginia*

[Dash (—) means no data were collected. Sample localities are labeled on plate 1 by the sample numbers minus the prefix "AG"]

Sample number	Ground radiometric signature µR/hr.	Ur[1]	Aeroradiometric signature (CPS)[2]	Total count	K^{40} count	Bi^{214} count	Tl^{208} count	T (min)	K (%)	eU (ppm)	eTh (ppm)	eTh (ppm)/K(%)	eTh (ppm)/eU (ppm)	eU (ppm)/K(%)
Norfolk Formation[3], shelf fine-sand facies														
AG 12N	10-12	17-20	220	23,780	1500	482	371	2	1.73	1.40	4.73	2.73	3.38	0.81
AG 14N	4-5	7-8	250	20,500	1470	461	377	2	1.75	1.25	4.85	2.77	3.88	.71
AG 62N	—	—	200	76,720	6289	2228	1864	6	1.68	2.32	8.48	5.05	3.66	1.38
AG 76N	—	—	250	—	—	—	—	—	—	—	—	—	—	—
AG 77N	7	12	250	—	—	—	—	—	—	—	—	—	—	—
AG 78N	6	10	340	—	—	—	—	—	—	—	—	—	—	—
Pleistocene and Holocene shoreline sands														
AG 13N	10	17	250	19,600	1290	366	247	2	1.59	1.03	2.86	1.80	2.78	0.65
AG 15N	6	10	195	23,500	1738	614	395	2	1.93	2.18	4.99	2.59	2.29	1.13
AG 48N	—	—	235	70,540	7388	1708	1367	6	2.43	1.70	5.98	2.46	3.52	.70
AG 50N	—	—	210	78,530	6744	2240	2129	6	1.86	2.08	9.89	5.32	4.75	1.12
AG 61N	5	8	250	70,510	5010	2009	1608	6	1.23	2.10	7.20	5.85	3.43	1.71
AG 63N	—	—	214	73,230	5560	1990	1540	6	1.48	2.13	6.82	4.61	3.20	1.44
AG 72N	5-6	8-10	200	75,800	3622	1910	1127	6	1.41	1.88	4.97	3.52	2.64	1.33
AG 80aN	5-12	10-20	280	72,080	2708	2199	1434	6	.59	2.41	6.62	11.22	2.75	4.09
Sand Bridge Formation[3], marsh and tidal-flat silty-clay facies														
AG 16N	8	13	280	—	—	—	—	—	—	—	—	—	—	—
AG 17N	6	10	290	25,980	2528	631	445	2	3.32	2.14	5.78	1.74	2.70	0.64
AG 18N	—	—	250	22,050	1835	560	387	2	2.20	1.85	4.91	2.23	2.65	0.84
AG 19N	—	—	250	—	—	—	—	—	—	—	—	—	—	—
AG 27N	4-5	7-8	230	61,680	4900	1360	1152	6	1.48	1.17	4.97	3.36	4.25	.79
AG 28N	4-5	7-8	250	66,870	5806	1563	1249	6	1.79	1.49	5.43	3.03	3.64	.83
AG 29N	—	—	250	66,500	5005	1526	1231	6	1.45	1.45	5.34	3.68	3.68	1.00
AG 30N	—	—	260	67,660	5480	1555	1241	6	1.65	1.51	5.36	3.25	3.55	.92
AG 31aN	2-4	3-7	230	66,200	5297	1493	1209	6	1.60	1.40	5.22	3.26	3.73	.89
AG 32N	—	—	240	73,110	6061	1813	1447	6	1.78	1.85	6.40	3.60	3.46	1.04
AG 33N	—	—	250	64,700	5553	1542	1147	6	1.69	1.57	4.88	2.89	3.11	.93
AG 34N	—	—	160	56,210	4253	1266	887	6	1.25	1.25	3.56	2.85	2.85	1.00
AG 35N[4]	—	—	300	76,930	7078	1941	1571	6	2.17	2.00	7.00	3.23	3.50	.92
AG 36N	6	10	275	69,040	6334	1722	1489	6	1.94	1.61	6.65	3.43	4.13	.83
AG 37N	—	—	225	75,650	5280	1724	1181	6	1.50	1.93	4.98	3.32	2.58	1.29
AG 38N	—	—	255	82,220	7776	2181	1866	6	2.36	2.21	8.53	3.61	3.86	.94
AG 39N	—	—	265	81,060	6695	2062	1874	6	1.93	1.95	8.60	4.46	4.41	1.01
AG 40aN	—	—	235	66,740	5093	1728	1410	6	1.39	1.71	6.23	4.48	3.64	1.23
AG 41N	—	—	250	77,140	7849	1880	1670	6	2.53	1.77	7.57	2.99	4.28	.70
AG 42N	—	—	240	69,210	6021	1716	1376	6	1.81	1.72	6.04	3.34	3.51	.95
AG 43N	—	—	215	67,090	4586	1656	1342	6	1.20	1.62	5.87	4.89	3.62	1.35
AG 44N	—	—	210	74,590	6083	1917	1651	6	1.73	1.86	7.46	5.22	4.01	1.08
AG 45N	6	10	259	69,850	7306	1637	1382	6	2.42	1.53	6.10	2.52	3.99	.63
AG 46N	—	—	230	73,060	7424	1750	1618	6	2.40	1.54	7.32	3.05	4.75	.64
AG 47N	8	13	258	74,740	5986	1728	1400	6	1.79	1.72	6.17	3.45	3.59	.96
AG 49N	8	13	190	84,250	7856	2356	2222	6	2.29	2.23	10.37	4.53	4.65	.97
AG 58N	—	—	175	53,500	2998	1214	875	6	.72	1.14	3.51	4.89	3.08	2.00
AG 59N	—	—	275	58,710	3810	1523	1161	6	.93	1.51	4.95	5.32	3.28	1.62
AG 60N	—	—	240	69,180	4976	1800	1416	6	1.31	1.85	6.24	4.76	3.37	1.41
AG 64aN	—	—	275	87,150	7334	2072	1892	6	2.21	1.96	8.69	3.93	4.43	.89

See footnote at end of table, p. 8.

TABLE 1.—*Ground-radiometric and aeroradiometric signatures of sample localities in the Coastal Plain of Virginia*—Continued

Sample number	Ground radiometric signature µR/hr.	Ur[1]	Aeroradio-metric signature (CPS)[2]	Total count	K^{40} count	Bi^{214} count	Tl^{208} count	T (min)	K (%)	eU (ppm)	eTh (ppm)	eTh (ppm)/ K(%)	eTh (ppm)/ eU (ppm)	eU (ppm)/ K(%)
Sand Bridge Formation[3], marsh and tidal-flat silty-clay facies—Continued														
AG 65N	—	—	260	72,470	6217	1886	1551	6	1.82	1.90	6.92	3.80	3.64	1.06
AG 66N	—	—	180	69,780	5192	1862	1597	6	1.37	1.80	7.19	5.25	3.99	1.31
AG 67N	—	—	200	76,020	7381	2077	1869	6	2.23	1.97	8.56	3.84	4.34	.88
AG 68N	7–8	12–13	200	79,070	7503	1979	1954	6	2.32	1.69	9.85	4.25	5.83	.73
AG 69N	6	10	250	—	—	—	—	—	—	—	—	—	—	—
AG 70N	6–7	10–12	250	—	—	—	—	—	—	—	—	—	—	—
AG 71N	6–8	10–13	240	—	—	—	—	—	—	—	—	—	—	—
AG 74N	6–7	10–12	300	84,910	4244	2087	1455	6	1.81	1.61	6.87	3.80	4.27	.89
AG 75N	6–8	10–13	180	—	—	—	—	—	—	—	—	—	—	—
AG 79N	6–7	10–12	260	—	—	—	—	—	—	—	—	—	—	—
Sand Bridge Formation[3], fluvial and lagoon silty-sand facies														
AG 21N	—	—	75	69,580	5226	1626	1425	6	1.49	1.48	6.33	4.25	4.28	0.99
AG 22N	—	—	330	61,800	4264	1451	1226	6	1.15	1.29	5.33	4.63	4.13	1.12
AG 24N	—	—	311	66,750	5176	1593	1349	6	1.49	1.48	5.93	3.98	4.01	.99
AG 25N	—	—	260	66,800	5570	1840	1509	6	1.55	1.84	6.71	4.33	3.65	1.19
AG 26N	—	—	200	61,090	4155	1453	1211	6	1.11	1.32	5.23	4.71	3.96	1.19
AG 51N	—	—	275	70,280	4599	2106	1828	6	.98	2.10	8.33	8.50	3.97	2.14
AG 52N	6	10	180	70,760	5632	2173	1562	6	1.44	2.11	6.61	4.59	3.13	1.47
AG 53N	—	—	270	70,620	5084	2104	1789	6	1.20	2.12	8.14	6.78	3.84	1.77
AG 55N	—	—	275	65,440	4391	1522	1294	6	1.17	1.38	5.66	4.84	4.10	1.18
AG 56N	—	—	160	70,230	4876	1755	1352	6	1.28	1.82	5.90	4.61	3.24	1.42
AG 57N	—	—	240	71,700	5027	2236	1771	6	1.12	2.43	8.00	7.14	3.29	2.17
Unit A, barrier island or spit-complex facies														
AG 20E	6	10	275	92,970	4271	2517	1237	6	0.99	3.46	5.62	5.68	1.62	3.49
Holocene, fluvial sand														
AG 23N	2–4	3–7	—	—	—	—	—	—	—	—	—	—	—	—
Sand Bridge Formation[3], estuarine and tidal-channel facies														
AG 54N	—	—	240	73,250	6231	2053	1640	6	1.74	2.17	7.35	4.22	3.39	1.25
Sand Bridge Formation[3], barrier-sand-ridge and mud-flat facies														
AG 73N	5–6	8–10	215	74,990	3908	1752	1232	6	1.77	1.18	5.73	3.24	4.86	0.67
Norfolk Formation[3], marine sandy-clay facies														
AG 81R	6.5	11	290	86,470	3689	2266	1509	6	1.27	2.18	7.06	5.56	3.24	1.72
AG 82R	8	13	290	88,900	4278	2420	1531	6	1.55	2.41	7.15	4.61	2.97	1.55
Norfolk Formation[3], fluvial and estuarine clayey-sand facies														
AG 83R[4]	8	13	280	85,570	3976	2250	1550	6	1.50	1.99	7.33	4.89	3.68	1.33
AG 84R[4]	8–9	13–15	275	91,110	3676	2390	1523	6	1.16	2.51	7.06	6.09	2.81	2.16
Undivided sand and gravel (Inner Coastal Plain)														
AG 86R[4]	6–8	10–13	230	95,900	4255	2782	1926	6	1.37	2.72	9.29	6.78	3.42	1.99
AG 87R	7–8	12–13	230	96,210	4374	2967	1837	6	1.30	3.35	8.66	6.66	2.59	2.58
AG 88R	7–8	12–13	215	93,750	4907	2460	1482	6	2.01	2.41	6.88	3.42	2.85	1.20
AG 89R	—	—	225	84,510	3100	2566	1692	6	.64	2.86	7.96	12.44	2.78	4.47
Undivided sand and gravel (Outer Coastal Plain)														
AG 91R	4–7	7–12	225	50,070	2441	1321	959	6	0.95	1.15	4.76	5.01	4.14	1.21
AG 90R	8	13	283	94,160	4378	2735	1546	6	1.39	3.20	6.96	5.01	2.18	2.30

[1]1ur=0.6µR/hr. A geological source of 1ur produces the same instrument response as an identical source containing only 1 part per million uranium in radioactive equilibrium (International Atomic Energy Agency, 1976, p. 16).

[2]CPS=counts per second.

[3]As mapped by Oaks and Coch (1963, 1973).

[4]No sediment sample collected.

TECHNIQUES

From 80 samples collected at aeroradiometrically anomalous localities (except sample AG 23N), approximately 14 ounces (400 grams) was split and dry-sieved into gravel (>18 mesh); coarse- to fine-grained sand (<18 mesh to >120 mesh, henceforth abbreviated CFS); very fine grained sand to coarse silt (<120 mesh to >320 mesh, abbreviated as VFSS); and silt and clay (<320 mesh) fractions. The CFS and VFSS fractions were processed for their heavy-mineral content in bromoform (s.g. 2.85). Samples of these two fractions that contained more than 1 percent total heavy minerals were studied to evaluate their economic value. First separated into groups of four magnetic fractions on a magnetic separator (hand-magnetic, 0.0 to 0.5-ampere, 0.5 to 1.0-ampere, and 1.0-ampere fractions), both CFS and VFSS fractions were studied independently under petrographic and binocular microscopes. Some opaque minerals were identified by X-ray techniques. Amounts of given mineral species were summed from each magnetic and size fraction in which they occurred, and their percentage of the whole heavy-mineral fraction was calculated. Density was not compensated for.

RESULTS

Of the 80 samples collected from aeroradiometrically anomalous localities, 65 samples were found to contain less than 1 percent heavy minerals separated in bromoform (fig. 2). Table 2 shows the sieve analyses, total heavy-mineral contents, and the heavy-mineral contents of each sieve fraction analyzed. In more than half the samples, the VFSS fraction contains a larger percentage of heavy minerals than the CFS fraction of a sample. Because the total heavy-mineral content of samples listed in table 2 is so low, no qualitative studies were made on their mineralogy, as they were considered to be of no economic value.

Detailed mineralogical study of the 15 samples that contained more than 1 percent total heavy minerals is shown in table 3. Ten of the fifteen samples containing more than 1 percent heavy minerals are from Oaks and Coch's Sand Bridge Formation. Sample AG 23N was collected from a Holocene fluvial sand deposit that had no aeroradiometric expression. As in the 65 samples containing less than 1 percent heavy minerals, but more consistently, the VFSS fraction was found to contain a higher percentage of minerals than the CFS fraction of the same sample. Whereas in the 65 samples, the average ratio of weight percent VFSS-fraction heavy minerals to the CFS-fraction heavy minerals per sample is approximately 2.7 in a range of 0.0 to 25.0, in the 15 samples containing more than 1 percent total heavy

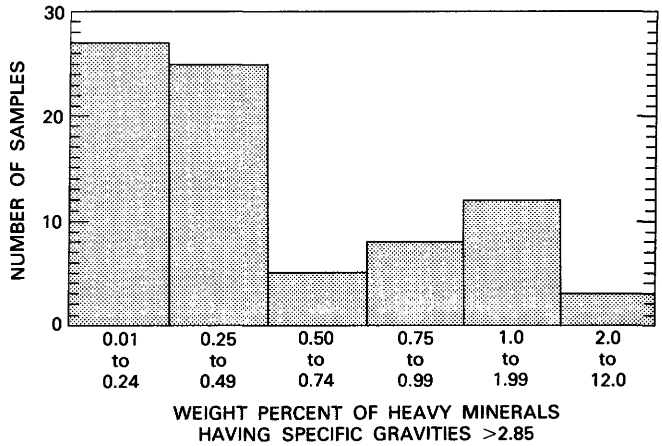

FIGURE 2.—Histogram of heavy-mineral percentages in 80 samples from aeroradiometrically anomalous localities in the Coastal Plain of Virginia (from tables 2 and 3).

minerals, the average ratio is approximately 9.15 in a range of 0.7 to 27.1. To see if and how heavy minerals partition according to grain size, mineralogical analyses were plotted on circular percentage diagrams (pl. 5). For each of the 15 samples analyzed, the total heavy-mineral suite and the heavy-mineral suites of the CFS and VFSS fractions are plotted independently to emphasize size-dependent mineral distribution.

Samples from Oaks and Coch's Sand Bridge Formation, marsh and tidal-flat silty-clay facies (AG 18N, AG 19N, and AG 66N) have heavy-mineral suites that are dominantly CFS. Furthermore, most of the economic minerals in the sample are CFS; for example, ilmenite, sillimanite, kyanite, rutile, leucoxene, monazite, and zircon. The heavy-mineral suites of these samples contain less than 2 percent economic minerals (table 3).

An auger sample from Unit A on the Delmarva Peninsula (AG 20E) yielded approximately 1.5 percent total heavy minerals in a 5-foot (1.5-meter) section from 15 to 20 feet (4.6 to 6.1 meters) beneath the surface. As it is deeply buried, the concentration could not have caused the aeroradiometric anomaly. In this sample, more heavy minerals are in the VFSS fraction, but most of the economic minerals are in the CFS fraction. Ilmenite, monazite, zircon, sillimanite, and kyanite tend to occur in the CFS fraction: however, garnet, rutile, and leucoxene are more common in the VFSS fraction. Of interest in this sample is the virtual lack of ilmenite in the VFSS fraction. Noneconomic minerals dominate the suite of heavy minerals in this sample by a wide margin, and, consequently, the economic value of this deposit is minimal.

A sample collected on the bank of the Elizabeth River (AG 23N) 0.25 mile (0.4 km) north of the Portsmouth Naval Hospital represents modern fluvial sediment deposited over granitic material placed in the 1950's to

TABLE 2.—*Sieve analyses and heavy-mineral contents of 65 samples that contain less than 1 percent total heavy minerals collected from aeroradiometrically anomalous localities in the Coastal Plain of Virginia*

[Sample localities are labeled on plate 1 by the sample numbers minus the prefix "AG." UTM, universal transverse mercator. Some sieve analyses by Dwight E. Wallace]

Sample number	UTM coordinates	7 ½-minute quadrangle	Thickness sampled (meters)	Gravel[1] (wt.%)	CFS[1 2] (wt.%)	VFSS[1 3] (wt.%)	Silt & Clay (wt.%)	S.G. >2.85 (wt.%)	S.G. >2.85 in CFS (wt.%)	S.G. >2.85 in VFSS (wt.%)
Norfolk Formation[4], shelf fine-sand facies										
AG 12N	4057520N 390840E	Fentress	0.75	17	62	11	10	0.42	0.37	1.75
AG 14N	4057740N 392030E	Fentress	.75	2	78	11	8	.36	.32	1.01
AG 62N	4081700N 395180E	Little Creek	1.0	13	57	16	13	.05	.09	.03
AG 76N	4056380N 385720E	Deep Creek	1.0	.7	64	21	14	.10	.07	.27
AG 77N	4055680N 389220E	Fentress	1.0	0	55	28	17	.13	.14	.18
AG 78N	4046900N 387440E	Lake Drummond SE	1.0	0	66	21	13	.19	.16	.39
Pleistocene, shoreline sand										
AG 13N	4056540N 392550E	Fentress	0.75	1	84	9	6	0.88	0.49	5.13
AG 15N	4055980N 391250E	Fentress	.35	25	51	14	10.8	.25	.29	.77
AG 48N	4072600N 394180E	Kempsville	1.0	1	81	12	3	.98	.49	4.77
AG 50N	4071530N 393190E	Kempsville	1.0	10	72	10	7	.28	.34	.36
AG 61N	4083380N 394480E	Little Creek	1.0	27	56	7	9	.01	.01	.07
AG 63N	4084000N 397650E	Little Creek	1.0	9	54	17	18	.01	.01	.03
AG 72N	4063420N 409140E	Pleasant Ridge	1.0	.05	62	7	9	.59	.45	3.18
Sand Bridge Formation[4], marsh and tidal-flat silty-clay facies										
AG 16N	4056610N 398400E	Fentress	0.35	1	61	22	16	0.07	0.06	0.17
AG 17N	4056050N 398620E	Fentress	.50	24	34	25	17	.04	.01	.13
AG 27N	4074620N 387000E	Norfolk South	1.0	.4	74	12	14	.35	.39	.54
AG 28N	4074420N 385860E	Norfolk South	1.0	1.0	72	16	11	.41	.51	.23
AG 29N	4075770N 387720E	Norfolk South	1.0	7.0	70	11	12	.25	.31	.28
AG 30N	4074920N 388070E	Norfolk South	1.0	0	74	14	12	.46	.46	.85
AG 31aN	4073330N 386330E	Norfolk South	1.0	1.0	74	14	10	.69	.70	1.23
AG 31bN	4073330N 386000E	Norfolk South	1.0	.3	98	1.5	.6	.28	.21	5.26
AG 32N	4074460N 380770E	Kempsville	1.0	.08	66	20	14	.30	.38	.25
AG 33N	4078300N 391940E	Kempsville	1.0	.5	70	16	13	.74	.93	.55
AG 34N	4080720N 393180E	Kempsville	1.0	3.1	81	8.5	7	.39	.33	1.49
AG 36N	4078650N 392150E	Kempsville	1.0	7.0	66	15	12	.31	.39	.34

See footnote on p. 12.

TABLE 2.—*Sieve analyses and heavy-mineral contents of 65 samples that contain less than 1 percent total heavy minerals collected from aeroradiometrically anomalous localities in the Coastal Plain of Virginia*—Continued

Sample number	UTM coordinates	7 ½-minute quadrangle	Thickness sampled (meters)	Gravel[1] (wt.%)	CFS[1 2] (wt.%)	VFSS[1 3] (wt.%)	Silt & Clay (wt.%)	S.G. >2.85 (wt.%)	S.G. >2.85 in CFS (wt.%)	S.G. >2.85 in VFSS (wt.%)
Sand Bridge Formation[4], marsh and tidal-flat silty-clay facies —Continued										
AG 37N	4077320N 392000E	Kempsville	1.0	0.3	56	27	16	0.17	0.25	0.10
AG 38N	4075440N 396580E	Kempsville	1.0	.4	42	41	17	.02	.05	.01
AG 39N	4074250N 396970E	Kempsville	1.0	7.0	60	23	9	.08	.13	.02
AG 40aN	4074900N 396090E	Kempsville	1.0	14	59	11	15	.10	.13	.21
AG 40bN	4074900N 396090E	Kempsville	1.0	13	86	.2	.6	.16	.19	.00
AG 41N	4076540N 394320E	Kempsville	1.0	.2	58	27	14	.30	.36	.31
AG 42N	4077440N 395680E	Kempsville	1.0	7	67	14	12	.30	.35	.47
AG 43N	4075500N 397810E	Kempsville	1.0	7	70	11	11	.11	.14	.12
AG 44N	4075000N 398100E	Kempsville	.75	1	55	28	15	.13	.17	.11
AG 45N	4072040N 397280E	Kempsville	1.0	4.5	61	21	14	.33	.38	.46
AG 47N	4069200N 398840E	Kempsville	1.0	.03	50	37	12	.04	.07	.01
AG 49N	4071050N 395620E	Kempsville	1.0	17	80	2	.6	.86	.68	13.74
AG 58N	4086700N 385450E	Norfolk North	1.0	2	82	7	9	.16	.19	.07
AG 59N	4088150N 387900E	Norfolk North	1.0	2.5	71	11	15	.46	.63	.05
AG 60N	4089380N 386600E	Norfolk North	1.0	3.5	63	22	11	.31	.42	.21
AG 64aN	4076090N 407400E	Princess Anne	1.0	0	52	30	18	.06	.10	.02
AG 65N	4075430N 405880E	Princess Anne	1.0	.1	60	22	18	.21	.31	.09
AG 67N	4070700N 405800E	Princess Anne	1.0	.1	46	39	14	.34	.42	.37
AG 68N	4071380N 401550E	Princess Anne	1.0	2	52	29	17	.11	.18	.03
AG 69N	4068220N 401400E	Princess Anne	1.0	0	56	28	16	.44	.45	.68
AG 70N	4064220N 406000E	Pleasant Ridge	1.0	.09	55	29	15	.04	.04	.05
AG 71N	4073580N 409140E	Princess Anne	1.0	0	48	31	20	.01	.01	.02
AG 74N	4054300N 400780E	Pleasant Ridge	1.0	.2	62	21	16	.02	.02	.03
AG 75N	4061370N 392250E	Fentress	1.0	0	44	39	16	.01	.02	.01
AG 79N	4050920N 379180E	Lake Drummond	1.0	0	52	33	15	.09	.05	.17
Sand Bridge Formation[4], fluvial and lagoon silty-sand facies										
AG 21N	4078580N 382890E	Norfolk South	1.0	0.2	91	6	4	0.37	0.36	1.57

See footnotes on p. 12.

TABLE 2.—*Sieve analyses and heavy-mineral contents of 65 samples that contain less than 1 percent total heavy minerals collected from aeroradiometrically anomalous localities in the Coastal Plain of Virginia*—Continued

Sample number	UTM coordinates	7 ½-minute quadrangle	Thickness sampled (meters)	Gravel[1] (wt.%)	CFS[1 2] (wt.%)	VFSS[1 3] (wt.%)	Silt & Clay (wt.%)	S.G. >2.85 (wt.%)	S.G. >2.85 in CFS (wt.%)	S.G. >2.85 in VFSS (wt.%)
		Sand Bridge Formation[4], fluvial and lagoon silty-clay facies —Continued								
AG 22N	4077700N 381870E	Norfolk South	0.75	2.0	88	4	6	0.48	0.42	2.60
AG 24N	4075250N 383780E	Norfolk South	1.0	.2	69	16	14	.12	.15	.11
AG 25N	4073810N 382670E	Norfolk South	.75	7.0	74	12	6	.59	.31	2.87
AG 26N	4072970N 382140E	Norfolk South	1.0	1.0	78	10	11	.39	.46	.35
AG 55N	4078960N 373840E	Bowers Hill	1.0	0	72	18	10	.92	.55	3.01
		Unit A, barrier island or spit-complex facies								
AG 20E[5] (0-5')	4204230N 458720E	Chincoteague W.	1.50	0.3	60	30	11	0.35	0.39	0.39
AG 20E[5] (5-10')	4204230N 458720E	Chincoteague W.	1.50	1	66	27	4	.79	.47	1.81
AG 20E[5] (10-15')	4204230N 458720E	Chincoteague W.	1.50	2	33	53	12	.63	.39	.95
		Norfolk Formation[4], marine sandy-clay facies								
AG 81R	4104200N 378030E	Hampton	1.0	5	65	16	13	0.80	1.00	0.93
AG 82R	4100000N 382110E	Hampton	1.0	2	62	25	10	.93	1.07	1.04
		Undivided sand and gravel (Inner Coastal Plain)								
AG 87R	4168050N 358860E	Urbanna	1.0	1	59	26	14	0.22	0.29	0.19
AG 88R	4192860N 341520E	Dunnsville	1.0	.02	67	19	13	.97	.98	1.67
AG 89R	4187640N 342060E	Dunnsville	1.0	1	61	22	15	.38	.41	.59
		Undivided sand and gravel (Outer Coastal Plain)								
AG 90R	4200100N 379130E	Heathsville	1.0	9	64	13	13	0.26	0.30	0.52

[1]Includes clayballs.
[2]Coarse to very fine sand.
[3]Very fine sand and silt.
[4]As mapped by Oaks and Coch (1963, 1973).
[5]Samples AG 20E were collected from 0 to 15 feet (0 to 4.6 m) below the surface.

stop shore erosion. A grab sample of this material yielded about 1.5 percent total heavy minerals, most of which are in the CFS fraction; only about 30 percent of the heavy minerals are of economic value. Rutile, leucoxene, monazite, and zircon are concentrated in the CFS fraction, and sillimanite and kyanite are more common in the VFSS fraction.

Some samples collected from Oaks and Coch's Sand Bridge Formation, fluvial and lagoon silty-sand facies (AG 51N, AG 52N, AG 53N, AG 56N, AG 57N), yielded 1.25 to 1.92 percent total heavy minerals. Samples 51, 52, and 56 have heavy-mineral suites that are dominantly VFSS, and samples 53 and 57 have heavy-mineral suites that are dominantly CFS. The distribution of economic heavy minerals in these samples is variable. Samples 51, 52, and 56 have slightly more economic minerals in the VFSS size fraciton, and samples 53 and 57 contain more in the CFS fraction. For all the samples, only 35 to 45 percent of the heavy-mineral suites are of economic value. Because of the small total heavy-mineral contents of these samples, economic considerations are precluded.

A sample from Oaks and Coch's Sand Bridge Formation, barrier-sand-ridge and mud-flat facies (AG 73N), contains about 1.2 percent total heavy minerals, 32 percent of which are of economic value. Most economic heavy minerals in this sample are in the VFSS fraction. Garnet is the single most abundant mineral present, and the concentration of titanium dioxide minerals is very low.

Samples from a Holocene beach dune (AG 80aN) and back dune flat (AG 80bN) yielded the largest total heavy-mineral contents of all the samples collected in the study area. Sample AG 80aN was collected from the surface to a depth of 2.5 feet (0.75 meter). The total heavy-mineral content of this sample is 5.1 percent, but only about 30 percent of the total is of economic value. The economically valuable heavy minerals are concentrated in the VFSS fraction. The overall economic value of this deposit is diminished by the very small concentration of titanium dioxide minerals. Sample AG 80bN is a 3.3-foot (1-meter) channel sample from a dune face. The total heavy-mineral content of this sample is 11.4 percent, but only about 30 percent of the total is of economic value. Titanium dioxide minerals are more abundant in this sample than in AG 80aN, particularly in the VFSS fraction. In this sample, ilmenite, monazite, and zircon are conspicuously more abundant in the VFSS frac, but garnet, sillimanite, kyanite, rutile, and leucoxene are more common in the CFS fraction. As in sample AG 80aN, the economic heavy minerals are mostly in the VFSS fraction. Because of the small size of this deposit, and, perhaps more importantly, because this deposit is in a national wildlife refuge, the economic value of the deposit is considered marginal.

Sample AG 91R was collected from undifferentiated sand and gravel (Outer Coastal Plain) in the northern part of the study area near the Potomac River. This sample yielded about 1.3 percent total heavy minerals, of which about 65 percent are of economic value. The total heavy-minerals suite is dominantly VFSS, and ilmenite is the single most abundant economic mineral present. The very fine grained nature of the economic heavy minerals and their small concentration limit the economic value of this deposit.

Inasmuch as the heavy-mineral suites of the above-described samples are dominated by noneconomic minerals and contain only small percentages of economic minerals, none of the areas sampled is considered to hold economic importance. Other factors that diminish the economic importance of these deposits include the fine-grained nature of the host sediments, small area and thickness of the deposits, and competing land use.

SPECTRAL RADIOMETRIC CHARACTERIZATION OF ANOMALIES

Previous studies on the applicability of spectral radiometric data to the exploration for heavy-mineral deposits in coastal areas, particularly beach sands, have shown that such deposits have radioelement spectra having characteristic photopeaks where radioactive heavy minerals such as monazite and zircon are included in the heavy-mineral suite. The radioactive elements are present either in the crystal lattices or as inclusions in the stable heavy minerals, or both, and therefore, secular equilibrium of daughter products with the parent element is likely. Where an anomaly is not caused by radioelement concentrations in resistate heavy minerals, the assumption of equilibrium is probably not valid. Application of spectral aeroradiometric data to the characterization of anomalies in the Charleston, S.C., area (Force and others, 1978) showed that heavy-mineral concentrations in that area have spectral signatures in which either all photopeaks are anomalous (that is, they show significant departures from K:U:Th proportions typical of soils in the area), the Th peak is anomalous and the U and K peaks are normal, or the Th and U peaks are anomalous and the K peak is normal. Robson and Sampath (1977) showed that the anomalous radioelement of heavy-mineral concentrations in eastern Australia is dominantly thorium. In a study of Atlantic and Gulf Coast beach sands, Mahdavi (1964) showed that thorium is the dominant radioactive element involved in the radiometric signature of heavy-mineral concentrations.

Under ideal circumstances, I expected the aeroradiometric anomalies caused by heavy-mineral concentrations in the Coastal Plain of Virginia to have either high U and Th values and minimal K values, or to have high values in all spectra. Because Oaks and Coch (1973, table 3, p. 38) indicated in their study that in the clay-sized minerals, feldspar and illite or muscovite, were present in amounts of trace to more than 20 percent and trace to 35 percent, respectively, in post-Yorktown Formation stratigraphic units, K spectral values were expected to be fairly high for sediments in southeastern Virginia. Force and Geraci (1975) found that the radioactive heavy-mineral concentration in the most favorable lithology for economic heavy-mineral accumulations (Pleistocene? shoreline sands) was low or absent. This fact is borne out by the observation that none of the deposits sampled in that study shows radiometric (airborne or ground) contrast with the surrounding lithology.

Knowledge of the low regional radioactive heavy-mineral content of sediments coupled with information on fertilizer applications in the study area strongly suggested that radiometric contrasts, particularly as seen by the spectrometer, may not be diagnostic of heavy-mineral accumulations.

Ground-radiometric and aeroradiometric signatures of sample localities are presented on table 1 grouped into lithologic types. Attempts at graphic correlation of aerial and ground radiation measurements failed to show distinct patterns. The reason for this lack of correlation most likely lies in the fact that aeroradiometric

TABLE 3.—*Sieve and heavy-mineral analyses of 15 samples that contain more than 1 percent total*

Sample number	UTM coordinate	7 ½-minute quadrangle	Thickness sampled (meters)	Gravel (wt. %)	CFS[3] (wt. %)	VFSS[4] (wt. %)	Silt and clay (wt. %)	S. G. >2.85 (wt. %)	S. G. >2.85 in CFS (wt. %)	S. G. >2.85 in VFSS (wt. %)
										Sand Bridge Formation[5], marsh
AG 18N	4057590 N 395000 E	Fentress	0.75	21.1	58.8	9.6	9.6	1.32	1.53	4.34
AG 19N	4057590 N 395000 E	Fentress	1.0	.8	87.0	4.5	7.3	1.74	1.35	12.72
AG 66N	4070150 N 407450 E	Princess Anne	1.0	0	78.7	10.7	10.4	2.44	2.83	2.00
										Unit A, barrier island
AG 20E[6]	4204230 N 458720 E	Chincoteague W.	1.5	6.2	69.3	20.4	3.9	1.38	0.96	3.52
										Holocene, fluvial
AG 23N	4079480 N 386600 E	Norfolk S.	GRAB	8.4	89.5	1.4	0.3	1.43	1.24	23.98
										Sand Bridge Formation[5], fluvial
AG 51N	4079975 N 368810 E	Bowers Hill	1.0	0	77.4	15.2	7.0	1.92	1.01	7.50
AG 52N	4078585 N 367580 E	Bowers Hill	1.0	.1	75.8	14.5	8.9	1.25	.67	5.12
AG 53N	4081050 N 368675 E	Bowers Hill	1.0	.1	78.4	13.0	7.9	1.40	.99	4.79
AG 56N	4083470 N 370040 E	Newport News S.	1.0	.03	71.6	19.4	8.3	1.70	1.11	4.67
AG 57N	4083030 N 371570 E	Newport News S.	1.0	.04	77.3	14.2	7.8	1.72	1.43	4.31
										Sand Bridge Formation[5],
AG 54N	4077980 N 373780 E	Bowers Hill	1.0	0	63.8	24.4	11.3	1.50	0.88	3.83
										Sand Bridge Formation[5], barrier-
AG 73N	4058350 N 408340 E	Pleasant Ridge	1.0	0.2	70.8	12.9	15.4	1.18	0.67	5.42
										Holocene, shore-
AG 80aN	4048380 N 421250 E	Knotts Island	0.75	0	93.7	6.0	0.08	5.10	2.29	49.65
AG 80bN	4048380 N 421520 E	Knotts Island	1.0	.2	91.3	8.1	.2	11.40	5.70	76.96
										Undivided sand and
AG 91R	4197090 N 381300 E	Burgess	0.75	6.5	74.4	17.5	0.9	1.26	0.23	6.24

[1]Sample AG 23N was not collected from an areoradiometrically anamalous locality.
[2]Includes subordinate pyroxene.
[3]Coarse to fine sand.
[4]Very fine sand and silt.

lation most likely lies in the fact that aeroradiometric values are extrapolated, as discussed above. Spectral radiometric characterization (see section on "Field-Spectrometer-Data Reduction") of different lithologies (table 4) in an attempt to distinguish lithologic type as a function of spectral characteristics also yielded inconclusive results. The average potassium content of sediments in the study area is about 1.5 percent; thorium and uranium are about 6.5 and 2 parts per million (ppm), respectively. Averages calculated for localities yielding samples that contain more than 1 percent total heavy minerals are about 1 percent potassium, 2 ppm uranium, and about 7 ppm thorium. These results indicate that, in general, anomalies caused by heavy-mineral concentrations in the Coastal Plain area of Virginia tend to have lower than the regional average potassium content, slightly lower than the regional average uranium content, and slightly higher than the regional average thorium content (table 4). However, the statistical precision (±10 percent) and absolute accuracy (±20 percent) of the spectral radiometric data may preclude the absolute certainty of these observations.

More distinct differences in spectral signatures of heavy-mineral-bearing samples can be defined if the *heavy minerals collected from aeroradiometrically anomalous[1] localities in the Coastal Plain of Virginia*

Weight percent of fraction having S.G. >2.85
P=>0.1 percent; —=none determined

Magnitite	Altered(?) ilmenite	Epidote	Amphibole[4]	Garnet	Tourmaline	Staurolite	Sillimanite and Kaynite	Leucoxene	Rutile	Zircone	Monazite	Sphene	Apatite
nd tidal flat silty-clay facies													
0.2	50.2	7.7	4.6	4.7	0.5	11.4	11.6	2.3	2.6	4.0	0.5	P	—
.4	53.6	5.9	8.3	1.6	.5	7.1	7.9	3.3	2.9	7.2	1.3	0.05	—
.2	54.5	11.1	5.6	.5	.34	3.4	16.2	1.3	1.5	3.9	.8	—	.67
r spit complex facies													
0.1	16.4	5.9	34.8	10.7	0.9	13.2	10.5	0.7	1.9	3.8	1.1	—	—
and facies													
3.8	27.0	11.0	28.6	0.8	0.05	7.7	7.7	4.3	3.1	5.6	0.5	—	—
nd lagoon silty-sand facies													
0.1	45.0	11.3	13.5	0.9	0.9	3.2	9.9	10.6	1.4	2.0	1.4	0.1	P
.13	23.7	9.2	24.2	.8	.8	3.3	23.3	7.1	2.5	4.2	.42	—	—
.1	32.1	12.4	24.5	P	.3	2.4	17.6	3.4	2.1	3.1	.3	—	—
.32	36.4	15.6	6.4	P	.6	2.6	22.7	7.0	2.2	5.4	.64	—	.6
.3	50.6	8.2	5.6	.6	.1	6.5	12.4	6.5	.9	8.2	.6	—	.3
estuarine and tidal-channel facies													
P	36.3	18.7	10.7	0.3	P	1.7	13.8	10.7	3.1	3.8	1.4	—	—
sand-ridge and mud-flat facies													
0.1	16.8	7.5	23.7	22.5	0.6	11.6	8.7	2.3	2.9	4.0	0.6	—	0.1
line sand													
0.04	14.4	15.7	29.8	5.0	2.7	9.3	8.4	5.0	2.4	5.9	1.2	—	—
.1	33.5	3.8	27.8	4.8	1.8	6.0	9.7	6.6	1.6	3.0	1.5	—	—
gravel (Outer Coastal Plain)													
0.1	58.4	1.8	1.4	P	2.1	5.3	2.5	18.5	3.6	5.3	1.1	—	—

[1]As mapped by Oaks and Coch (1963, 1973).
[3]Sample AG 20E was collected from 15 to 20 feet (4.6 total meters) below the surface.

spectral signatures of mineralized samples (>1.0 percent total heavy minerals) are compared with the spectral signatures of nonmineralized (<1.0 percent total heavy minerals) samples within the same lithology. For example, sample AG 80aN contains much less potassium than, slightly more uranium than, and a similar proportion of thorium as other samples from the same or similar lithologies (table 1). Distinctive about this sample, however, are the high thorium to potassium ratio and the high uranium to potassium ratio with respect to those of the other samples of the same lithology. Similarly, samples from Oaks and Coch's Sand Bridge Formation, fluvial and lagoon silty-sand facies, also show a dichotomy of spectral characteristics. Samples that contain more than 1 percent total heavy minerals have smaller potassium contents and higher uranium and thorium contents than do other samples from the same lithology that contain less than 1 percent total heavy minerals.

These results, then, indicate that heavy-mineral concentrations can be distinguished in a particular lithology by their spectral radiometric signatures by virtue of the fact that uranium and, more importantly, thorium are the dominant radioactive elements and

TABLE 4.—*Averages of equivalent thorium, equivalent uranium, and percent potassium in different lithologies measured in the field*

Lithology	Number of samples	K (%)	eU (ppm)	eTh (ppm)	eTh (ppm)/ K (%)	eTh (ppm)/ eU (ppm)	eU (ppm)/ K (%)
Norfolk Formation[1], shelf fine-sand facies. -----	3	1.72	1.66	6.02	3.52	3.64	0.97
Pleistocene and Holocene shoreline sands. -----	8	1.57	1.94	6.17	4.67	3.17	1.52
Sand Bridge Formation[1], marsh and tidal-flat silty-clay facies.	33	1.80	1.71	6.47	3.70	3.77	1.00
Sand Bridge Formation[1], fluvial and lagoon silty-sand facies.	11	1.27	1.76	6.56	5.30	3.78	1.42
Unit A, barrier island or spit-complex facies. ----	1	0.99	3.46	5.62	5.68	1.62	3.49
Sand Bridge Formation[1], estuarine and tidal-channel facies.	1	1.74	2.17	7.35	4.22	3.39	1.25
Sand Bridge Formation[1], barrier-sand-ridge and mud-flat facies.	1	1.77	1.18	5.73	3.24	4.86	0.67
Norfolk Formation[1], marine sandy-clay facies. -	2	1.41	2.29	7.10	5.09	3.10	1.64
Norfolk Formation[1], fluvial and estuarine clayey-sand facies.	2	1.33	2.25	7.20	5.49	3.25	1.75
Undivided sand and gravel (Inner Coastal Plain).	4	1.33	2.84	8.20	7.33	2.91	2.56
Undivided sand and gravel (Outer Coastal Plain).	2	1.17	2.18	5.86	5.01	3.16	1.76
Average values for the study area. -----------		1.46	2.13	6.57	4.84	3.33	1.64
Average values of localities from which samples yielded >1.0 percent total heavy minerals (11 locations).		1.33	1.92	6.69	5.71	3.57	1.67

[1]As mapped by Oaks and Coch (1963, 1973).

potassium is less abundant where radioactive heavy minerals are present in the heavy-mineral suite.

SUMMARY AND CONCLUSIONS

Prospecting for placer heavy-mineral deposits by airborne and ground radiometric methods is severely limited in efficiency by a number of factors, but none precludes its usefulness. Even if all instruments function properly during a survey and the resolution of the gathered data is good, the exploration targets must be exposed at or within inches of the surface, or the radiometric response is attenuated by overburden. Other factors that limit the radiometric response of a heavy-mineral deposit are (1) moisture content of the sediment because water attenuates the gamma-ray flux to the surface (and may force the radon precursor of Pb^{214} and Bi^{214} to deeper levels); (2) lack of or small concentration of radioactive minerals in the heavy-mineral suite; (3) fertilizer applications that mask the signature of a deposit by increasing the regional background of non-mineralized sediments; (4) dominance of radioactivity in the clay-sized minerals in heavy-mineral-bearing sediments; and (5) thick vegetation cover or cultural overprints, such as roads made of granitic rock.

My experience in the Coastal Plain of Virginia has shown that by very rigorous application of supplementary data, such as land-use and land-cover maps, fertilizer-use data, detailed geologic maps, and ground spectral radiometric data, most anomalies on an aeroradiometric map can be attributed to sources other than heavy-mineral deposits prior to field investigation.

This study, as well as previous studies in the area, shows that no currently economic heavy-mineral deposits are at or near the surface in the coastal Plain of Virginia. The deposits discussed in this and previous reports are not considered economic because of the very fine grained nature of the host sediments and the low percentage of economic heavy minerals. These results do not preclude the possibility of economically valuable deposits at depth, as the lithology on the Delmarva Peninsula is such that it may contain economic deposits. Furthermore, inasmuch as the James River drains an ilmenite-rich terrane (Minard and others, 1976), economic mineral deposits could possibly form in the offshore environment.

The aerial surveys used in this study were conducted to aid exploration efforts in general, and, for that purpose, they are well suited. If, however, aeroradiometric surveys were to be conducted specifically for economic placer deposits on coastal plain areas, a preliminary ground reconnaissance should be performed to ascertain radiometric contrasts, and the subsequent aerial survey should be appropriately tailored to the geology.

FIELD-SPECTROMETER-DATA REDUCTION[3]

By KENNETH L. KOSANKE[4]

At the completion of field work, the four-channel spectrometer was calibrated at the U.S. Department of Energy's facility at Walker Field in Grand Junction, Colo. (Stromswold and Kosanke, 1978). The calibration results indicated that the instrument was not functioning properly. The calibration parameters correcting the uranium window for potassium and the thorium window for uranium were both very much too large. A check of the instrument revealed that its energy gain had increased by approximately 6 percent relative to the K, U, and Th windows (see fig. 3). This increase in gain was unfortunate because it meant that the gamma peaks from K, U, and Th were falling about half outside their appropriate windows and that the peaks from K and U were falling partly within the windows for U and Th, respectively. Field data were checked using these (presently correct) calibration parameters as well as calibration parameters appropriate for a typical spectrometer of this type. The instrument's condition was found to have drifted systematically with time, and, thus, neither set of calibration constants was satisfactory.

In order to salvage the field data, the performance of the spectrometer had to be reconstructed as a function of time during the period in which field data had been collected. Fortunately, an accurate log of instrument settings had been kept. Figure 4 is a plot of spectrometer gain settings as an approximate function of time during the period of field-data collection. During the period of field-data collection, the instrument failed and was repaired; this repair is indicated in figure 4 by a dashed line. Gain settings before and after the malfunction are 5.9 and 7.7, respectively (corresponding to a gain drift of about 4 percent). I assumed that this

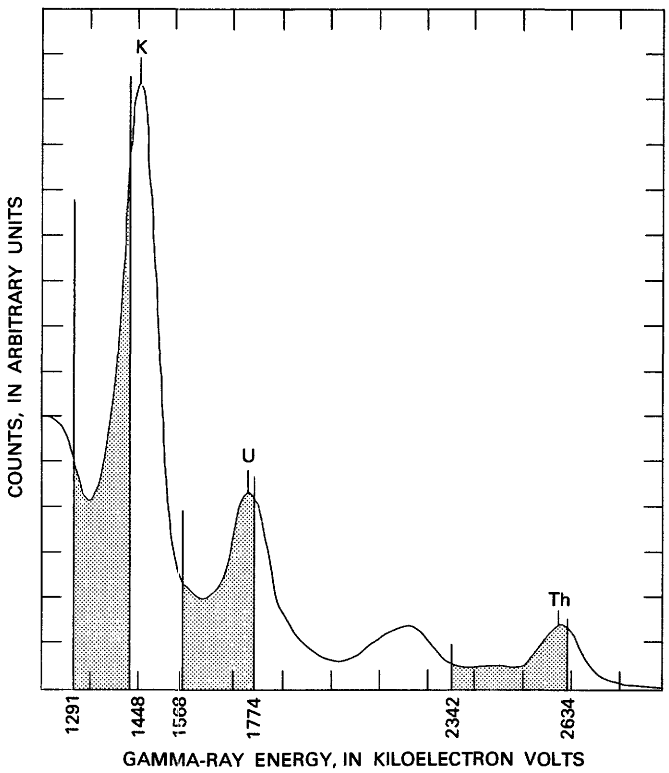

FIGURE 3.—Gamma-ray spectrum of a bulk source of K, U, and Th, showing the locations of improperly positioned spectrometer windows.

change in proper gain setting was the result of a stepwise deterioration of the instrument. Accordingly, the field data were treated as two separate groups (before and after repair) that had two sets of calibration constants. Additional confirmation of a change can be seen in background measurements made during the field-data collection period (see table 5).

The above information, coupled with data that had been collected during the field operation, was sufficient to allow a fairly accurate estimation of the two sets of calibration constants. Calibration constants were calculated by use of (1) results from spectral data from a large pile of potash fertilizer that had been sampled and could be used as a calibration standard; (2) data collected at the same site before and after the instrument change; and (3) computer simulation of the effects caused by improper positioning of the K, U, and Th spectral windows.

TABLE 5.—*Field-spectrometer background data before and after a change in gain setting coinciding with a repair of the instrument.*

	Window counts per minute		
	K	U	Th
Before repair	74	58	27
After repair	49	48	30

[3]This part of the work was supported by Bendix Field Engineering Corporation.
[4]Bendix Field Engineering Corporation, Grand Junction, CO 81501.

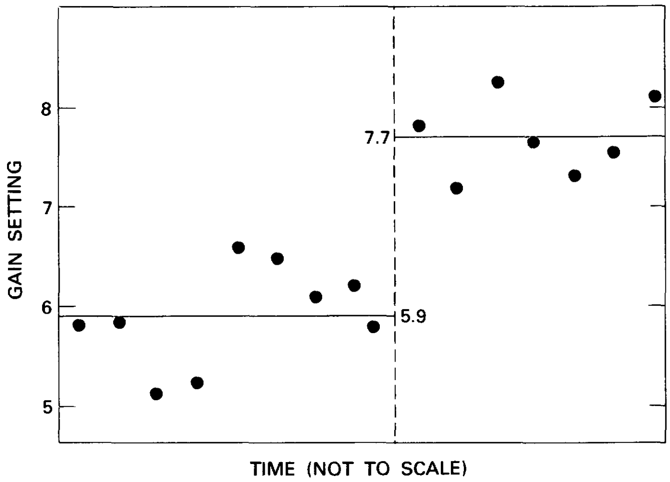

FIGURE 4.—Plot of sequence of spectrometer gain settings during the field-data collection period. The elapsed time between gain settings represented by points ranged from a day to a month. The time of instrument repair is shown as a dashed line. Horizontal lines represent average values.

The two sets of calibration constants are presented in table 6 as calibration matrices. The calibration matrix is a matrix of coefficients, each coefficient relating the counting rate in a gamma-ray energy window to the concentrations of K, U, or Th present in the material being evaluated. The matrix is derived from measurements made over calibration "pads" consisting of background, enriched-K, enriched-U, and enriched-Th concentrations of the radionuclides in concrete.

TABLE 6.—*Calibration matrices* (A) *for the spectrometer before and after change in performance.*

Calibration matrix (for rates in counts per minute)					
Before			After		
275	75	20	255	74	13
0	80	15	27	72	20
0	5	32	0	6	30

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