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Radioactivity of Heavy Mineral Sands as an Indicator of Coastal Sand Transport Processes

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ABSTRACT

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Heavy mineral-rich beach sands, concentrated by wave and wind action, have been found to contain significant gamma radioactivity, due primarily to trace amounts of uranium and thorium found in monazite and zircon. Concentrations of heavy minerals are found in beach berms and coastal dunes on the barrier islands ringing Apalachicola Bay in northwest Florida. The heavy mineral sands are detrital products of southern Appalachian crystalline rocks, transported to the Gulf of Mexico by the Apalachicola River. Field measurement of gross gamma radiation indicates that heavy mineral sand deposits within the shore zone are highly mobile, with observed radioactivity fluctuating by an order of magnitude within months. By combining field measurements with laboratory heavy mineral analysis and gamma spectrometry, bulk volume of heavy mineral-containing sand within a given area can be estimated. Changes in measured radioactivity as a function of time and position can be used to describe sand redistribution patterns. The resultant estimate of sand transport is obtained rapidly and easily relative to existing methods.

ADDITIONAL INDEX WORDS: *Barrier beaches, sediment transport, heavy minerals, sediment tracers, sediment dynamics, radioactivity.*

INTRODUCTION

Heavy mineral sands are detrital particles having a density greater than 2.85. They are generally found in high-energy environments such as beaches, having been sorted by hydrodynamic processes due to the density contrast between the heavy minerals and the predominant quartz. Heavy minerals typically found in the beach deposits of the northwest Florida region (Figure 1) include magnetite, ilmenite, kyanite, staurolite, tourmaline, zircon, and rutile, plus minor amounts of epidote, sphene, amphibole, sillimanite, leucoxene, garnet and monazite. Many of these have commercial uses, particularly the titanium minerals (rutile, ilmenite, leucoxene), the abrasives (staurolite, garnet, zircon), and the refractories (kyanite, sillimanite). Monazite is a source of thorium and cerium. Magnetite is a potential ore of iron, while staurolite is a potential aluminum ore.

In addition to their useful properties, some of the heavy minerals are also sources of environmental radioactivity, due to trace amounts of natural uranium, thorium and potassium. Zircon (ZrO_2SiO_2) and monazite (Ce,La,Nd,Th) (PO_4, SiO_4) in particular are potential sources of uranium and thorium radiation. Monazite can contain up to 12% thorium oxide and 1% uranium trioxide, and is used as an ore of thorium (MOORE, 1980).

Several investigators have studied the presence, composition, and grain size of heavy minerals containing uranium and thorium (GRIMALDI, *et al.*, 1954; MERTIE, 1953; MAHDAVI, 1964; OVERSTREET, *et al.*, 1968, 1969, 1970; deMEIJER *et al.*, 1987). All of these studies were primarily mineralogic, rather than sedimentologic, in nature. Only one of them (MAHDAVI, 1964) sampled northeastern Gulf of Mexico shorelines. This report focuses on the potential sedimentologic applications of heavy mineral radioactivity. Changes in measured radioactivity as a function of time and position are used to estimate the quantity of sand transported.

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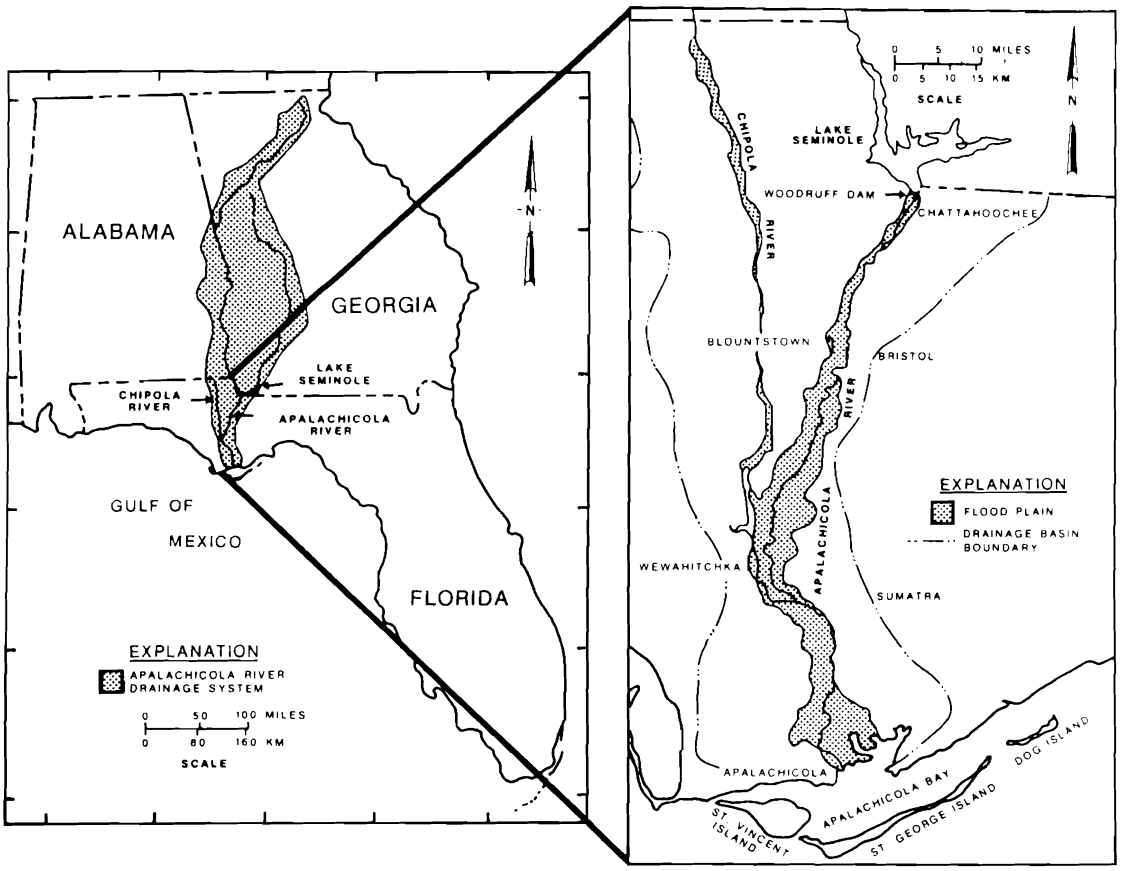

Figure 1. Regional map of the northeastern Gulf of Mexico watershed, with inset (right) showing Apalachicola Bay and barrier islands.

GEOLOGICAL SETTING

The Apalachicola River rises in the crystalline rocks of the southern Blue Ridge and Piedmont of Georgia and Alabama (Figure 1). It drains a watershed of 50,800 sq km, carrying an average sediment load of 1.5 million metric tons to the Gulf of Mexico each year (ISPHORDING, 1985). Over the past 4,000 years the river's sediment has built a large delta-estuary system and the barrier island chain which today nearly encloses the river mouth.

Apalachicola Bay, Florida (Figure 1) is ringed by three barrier islands. From west to east they are: St. Vincent, St. George, and Dog Islands. St. George was divided into two sections by the construction of an artificial inlet, Sikes Cut, in 1954. The western third of the island is now known as Cape St. George or Little St. George, while the eastern two-thirds is still called St. George. Heavy mineral sands are found to some extent on all beaches surrounding Apalachicola Bay, but are found highly concentrated by storm wave and wind action in certain locations on both the open Gulf of Mexico shorelines and the inner lagoon side of the barriers.

There is strong evidence that the heavy mineral sands have been delivered to the Gulf of Mexico via the Apalachicola River during late Quaternary low-stands, and deposited on the inner shelf of the northeastern Gulf. Airborne gamma surveys have located high concentrations of gamma activity in the broad, sandy floodplain of the modern Apalachicola. Figure 2 shows airborne gamma contours for the lower

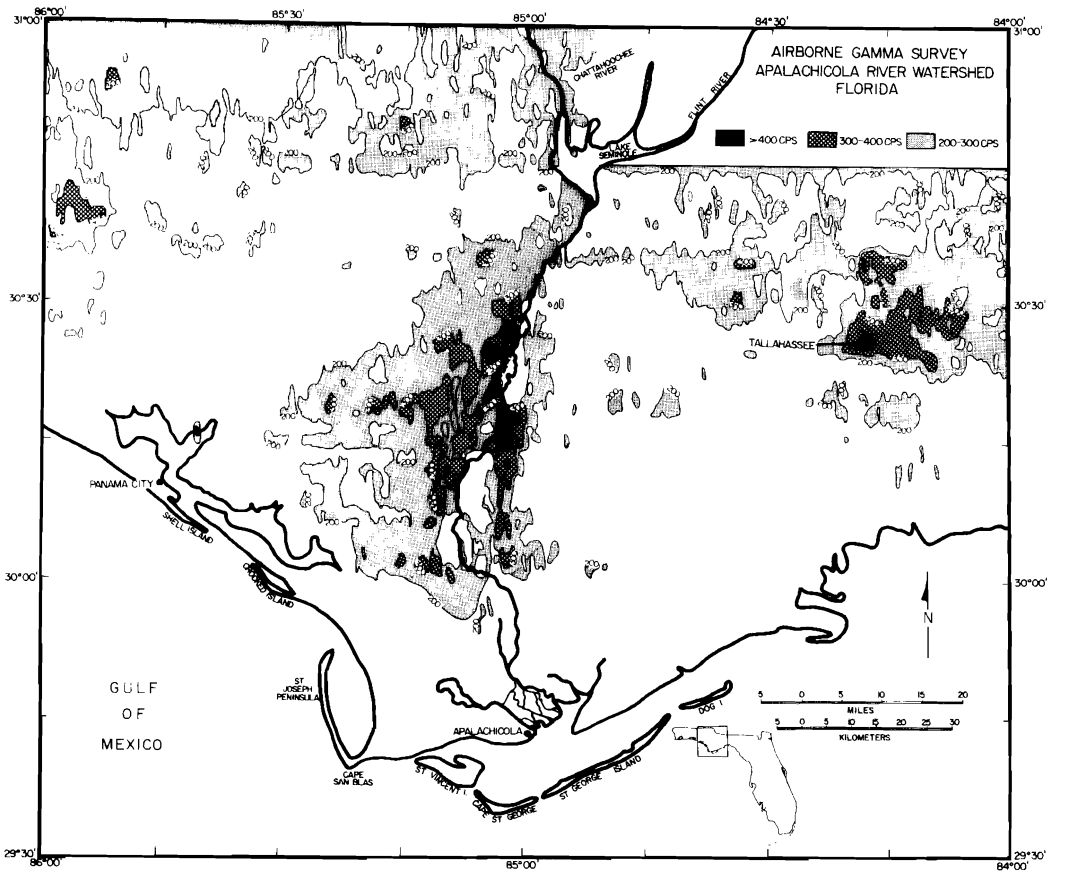

Figure 2. Gross gamma radioactivity for the lower Apalachicola River watershed. Contour interval 100 cps. Darkest areas are >400 cps. White areas are <200 cps. Adapted and redrawn from U.S. Geological Survey 1977 airborne gamma survey data: flight spacing 1 mile, altitude 500 ft. (U.S. Geological Survey, 1977).

Apalachicola watershed. Local gamma highs can be observed at the location of point bars along present and abandoned meander loops. During late Quaternary low-stands similar deposits were laid down on the inner shelf. These sands have subsequently been incorporated into the barrier islands and shoals by periodic storms, wave action and sea level rise. This process continues today.

PREVIOUS WORK

Various heavy mineral studies have been carried out in the northeastern Gulf of Mexico region. GOLDSTEIN (1942) described the heavy-mineral assemblage characteristic of the Eastern Gulf Province. He reported that the suite consists of low- and high-rank metamorphic and igneous minerals transported by river systems draining the Appalachian Piedmont and Coastal Plain regions. GILSON (1959) reached a similar conclusion in another regional study. Other projects characterizing the heavy mineralogy of the region include those of HSU (1960), FOXWORTH (1962), DRUMMOND and STOW (1979), and DOYLE and SPARKS (1980). VAN ANDEL and POOLE (1960) studied the sedimentary provinces of the Gulf of Mexico and their source areas. Rivers draining the southern Appalachians were identified as the primary source of the sediments of the Eastern Gulf Province.

TANNER *et al.* (1961) reported on the heavy mineral content in the prominent shoals off-

shore from the Apalachicola barriers. They observed that the heavy mineral abundance increases with depth in the shoals. LADER (1974) investigated the heavy mineral distribution offshore from Cape San Blas. He found an inverse relationship between mean grain size and heavy mineral content, and concluded that size, rather than density, was the significant factor controlling heavy mineral abundance. BRENNEMAN (1957) found a significantly larger proportion of heavy minerals in the fine sand fraction than in the coarse sand fraction off the coast of St. George Island.

CAZEAU (1955) described the heavy mineral suite of the upper reaches of the Apalachicola River as high-rank metamorphic, consisting predominantly of hornblends, epidote, kyanite, magnetite and ilmenite, while including small amounts of zircon and monazite. SAFFER (1955) found a similar suite in the beach and coastal river deposits of northwest Florida. STAPOR (1973a, 1973b) found the same minerals in a study of the delivery processes responsible for the deposition of heavy minerals in the Apalachicola coastal region. He found that a relatively fine-grained, heavy mineral-rich sand is concentrated and deposited on the beaches as a result of transport processes in the Gulf which remove the coarsest fraction.

MELKOTE *et al.* (1986) found a nearly identical heavy mineral suite in an extensive collection of surface sediment samples from the inner continental shelf off northwest Florida. EMMERLING (1975) analyzed the heavy mineralogy of mid-tide zone samples from the beaches of Dog Island. He reported the dominant heavy minerals as hornblends, epidote, kyanite, magnetite, ilmenite, rutile, tourmaline and zircon, with small percentages of five others, including monazite.

METHODS

Field Methods

Gamma Surveys. All gamma activities measured in the field were obtained by use of a hand-held Mt. Sopris SC-132 field monitor. The active volume of this monitor consists of a 3.75 cm x 3.75 cm diameter cylindrical NaI crystal. The crystal is coupled to a photomultiplier tube and associated electronics. An event is recorded as absorbed gammas produce sufficient light from ionization in the crystal to exceed an arbitrary but fixed detection threshold.

The monitor was calibrated by exposing it to a 10.4 mCi Co-60 source. The geometry of the monitor is such that the meter readings obtained were dependent only upon the distance from the calibrated source and were to the first order independent of the orientation of the detector about its geometric center. The observed count rates were inversely proportional to the square of the distance from the source. With this point source geometry, an effective area (product of gamma ray detection efficiency and the detection area normal to the flux) of 7.6 ± 0.8 cm^2 was obtained. The error in the effective area includes uncertainties in the source strength, edge effects, and detector orientation.

Field readings were obtained by holding the monitor at hip level (about 65 cm above the ground). Since the source geometry of the beach sand may to first order be approximated by a sheet with horizontal dimensions much larger than the distance to the detector, the measured count rate is, for the present purposes, independent of the height of the detector above the ground. Measurements of in-situ gamma ray activity of beach sands were obtained in three ways: spot surveys, profiles and grids. Spot surveys were taken along the shoreline and in some cases throughout the interior of the barrier islands. Profiles of gamma ray intensity as a function of horizontal position were taken at several locations of significant intensity. Grids of gamma ray intensity as a function of horizontal position within a two-dimensional grid were recorded in locations where significant local variations in intensity as a function of time were observed.

Laboratory Methods

Heavy Mineral Separation. Heavy mineral separation was achieved by use of the heavy liquid sodium metatungstate, density 2.90 g/cm^3. Ninety milliliters of heavy liquid was mixed with a sample in a separatory funnel. The funnel was then centrifuged for forty-five minutes at 1500 rpm. The separated heavy minerals were retrieved from the funnel and rinsed with 10 molar hydrochloric acid to avoid deposition of a tungsten precipitate on the grains. The heavy minerals were then rinsed

with double-distilled water and dried again. The light minerals remaining in the funnel were treated in the same manner as the heavy minerals. Both fractions of the samples were weighed to obtain relative dry weight percentages in each sample.

Heavy Mineral Identification. The components of the heavy mineral suite were analyzed by first removing magnetite with an electromagnet. The remaining heavy minerals were then separated into susceptibility groups using a Frantz Magnetic Separator. Individual susceptibility groups were analyzed for quantitative mineralogy by use of a Philips PW-1710 automated X-ray diffractometer. The samples were prepared by powdering for 3 minutes with a ball mill. The powder was spiked with a known weight of fluorite for use as a calibrating factor in quantitative x-ray diffractometry. The mixture was mounted on a 1"x1" glass microscope slide using a Duco cement and acetone solution. The slides were X-rayed over a range of 10 to 70 degrees at generator settings of 20 milliamps and 40 kilovolts.

The diffraction peaks and their heights from the X-ray spectra were compared to prepared standards comprised of a variety of heavy mineral compositions and proportions. Peak height was used for ease of measurement, and because preliminary tests showed that peak height is a reliable index of weight percent under the conditions of this project. To ascertain the reproducibility of the peak-height measurements, replicates were made for a number of the sample XRD slides. Mean percent deviation for all of the measured peaks for each of the minerals identified in the replicate samples was 12%.

Gamma Spectrometry. Determination of the gamma activity of individual radionuclides in the heavy mineral samples was accomplished by use of a well-type intrinsic germanium detector having a rated resolution (FWHM) of 1.95 keV. Gamma ray energies within the range 5-684 keV were recorded on a 1024-channel multichannel analyzer. Bulk samples of the heavy mineral sands were ground to less than 230 mesh, packed in plastic vials, sealed with epoxy and aged for three weeks to allow ingrowth of radon daughters. Samples were counted for 1-3 days. Activities were calculated by use of efficiency factors determined through calibration of the detector with various NBS and EPA natural radioactivity standards, as described in KIM and BURNETT (1983). Thorium-232 activity was determined by use of the actinium-228 photopeak at 338 keV. Uranium-238 activity was determined by averaging the 295 keV and 352 keV photopeaks of lead-214 and the 609 keV photopeak of bismuth-214.

RESULTS AND DISCUSSION

Gamma Radioactivity Data

Field Surveys. Field measurements of surface gamma radiation levels were made, in both transect and grid form, on St. George, Little St. George and St. Vincent Islands (Figure 1). The occurrence of heavy mineral concentrates and the associated activity levels varied from island to island and within a given island. Maximum levels of approximately 350 counts per second (cps) (0.053 mR/hr), 750 cps (0.113 mR/hr), and 300 cps (0.045 mR/hr) were recorded on St. Vincent, Little St. George and St. George, respectively. The greatest variation in activity levels was observed on Little St. George, and as a result most of the work focused on that island. Gamma activities on Little St. George varied from a low of 4 cps to a high of 750 cps.

A number of locations on Little St. George exhibited extensive and intensive distribution of activity. As shown in Figure 3 they are:

(1) *Location D.* The activity detected at location D, between the two docks on the lagoon side of Little St. George (Figure 3), was noteworthy in both extent and intensity. A shore-parallel strip of highly concentrated heavy mineral sand, 2-5 m wide and 300 m long, had been deposited by storm waves approximately 1 m above mean low water.

(2) *Location R-51.* A heavy mineral concentrate was found along both sides of Sikes Cut, the inlet between Little St. George and St. George Islands. These deposits were significant in that their intensities varied rapidly as a function of time. Levels as high as 350 cps were found to decrease by an order of magnitude over a period of a few weeks. Concentration of the heavy mineral sand appears to be a storm effect at R-51, as it is at the other locations. It is probable that amplification of waves and tidal currents within the narrow inlet is responsible for

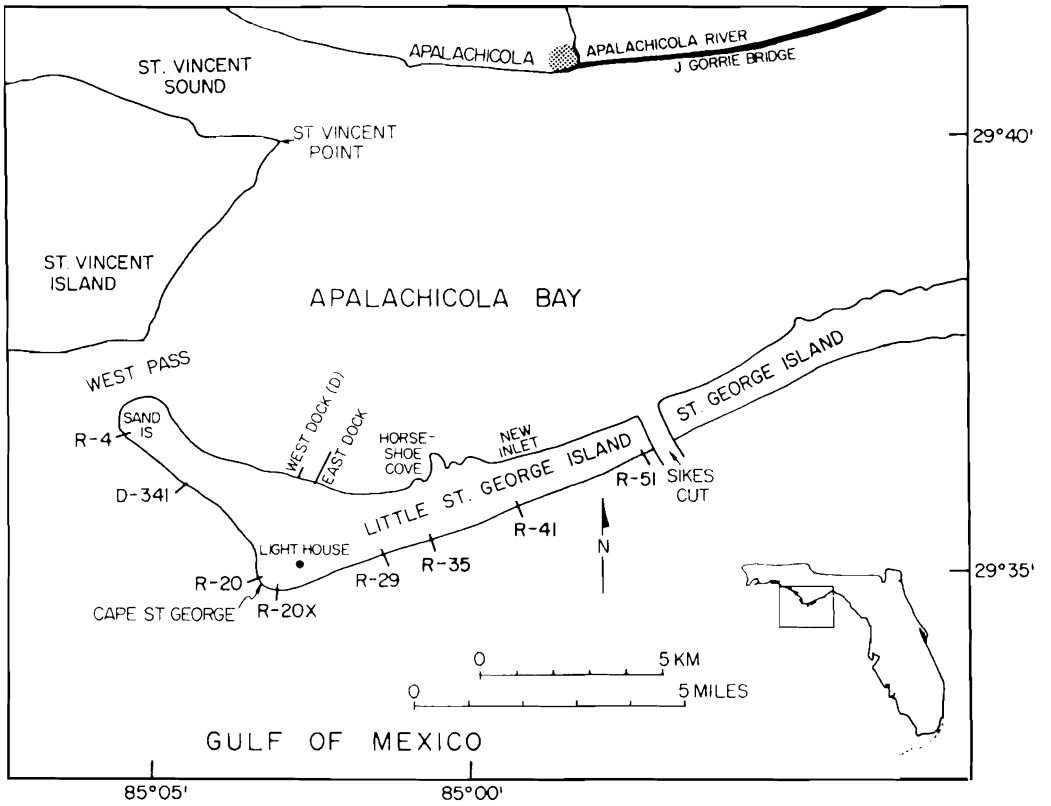

Figure 3. Map of Little St. George Island (Cape St. George), showing sampling locations and physical features. Migration rate of shorelines, based on air photos from 1941-1984, is shown by arrows, whose widths are proportional to migration rate. Arrows directed toward shore indicate erosion; arrows directed away from shore indicate accretion.

the rapid removal of heavy minerals from this locale.

(3) *Location R-20X*. The area on the Gulf shore of Little St. George that has been observed to have the most diverse and largest net integrated gamma activity is the littoral zone immediately west of the Cape St. George Lighthouse (Figure 3). Gamma readings averaging nearly 100 cps were recorded over an area of approximately 1000 m^2. This location is sedimentologically the most active on the island, as shown in Figure 3. Migration rates in excess of 7 m/yr have been documented through air photo measurements, with evidence of erosion on the southeast-facing beaches and accretion on the southwest-facing beaches. As in all of the other areas surveyed, the heavy minerals in this location appear to have been concentrated by storm events. But there is also clear evidence of aeolian influence on the subsequent distribution of the minerals. A wind shadow effect can be seen on the lee side of objects, such as dunes and the lighthouse. In the turbulent eddy behind such objects heavy minerals have been locally concentrated, producing high gamma levels.

The efficacy of gamma measurements as an indicator of such localized sand transport phenomena can be seen in Figure 4. Surface gamma radiation levels were measured at intervals around a 100 m diameter circle centered on a large lighthouse just east of location R-20X. (See Figure 3 for location). Surface sand samples were also collected at intervals around the circle for heavy mineral analysis in the laboratory. The figure superimpose gamma levels on heavy mineral percentages, showing reasonably good correlation between the two measurements, with correlation coefficient 0.43.

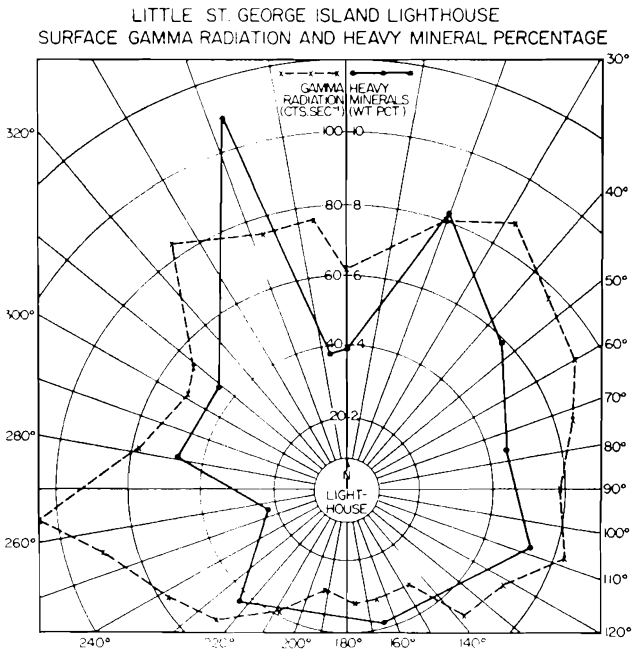

Figure 4. Surface gamma radiation levels and heavy mineral weight percent in surface sand samples, Little St. George Island lighthouse, east of location R-20X, March, 1987. North is at top. (See Figure 3 for location). Gamma readings and samples taken at a radius of 100 m from lighthouse. Radiation and heavy minerals are concentrated in the wind shadow north of the lighthouse. Prevailing wind was from SSE.

In order to confirm that the distribution of gamma radiation was not a result of selective sorting of the radiogenic heavy minerals (primarily monazite and zircon), the laboratory heavy mineral samples were subjected to quantitative heavy mineral analysis, as described in the Methods section. The heavy mineral suite in each of the sand samples was found to have identical proportions, within the limits of analytical error. At the time of the measurements (March) the prevailing wind had been from the SSE for a number of days. Three months later, when wind direction was more variable and intensity was less, similar measurements at the same location showed no correlation between compass direction and gamma activity. The field gamma measurements provided an easily measured and accurate indicator of: (1) competence of the wind for moving sand, including heavy mineral sand; (2) prevailing wind direction; (3) turbulence in the lee of objects, and subsequent concentration of heavier grains beneath the turbulent eddy. Similar results have been obtained in surveys around dunes and other objects, on scales both large and small.

(4) *Location R-35.* One heavy mineral deposit on the upper beach at location R-35 on the southeast-facing shore of Little St. George Island was of particular interest, with gamma levels changing by an order of magnitude in a period of less than eight months. This location was selected as one of the sites for periodic gamma surveys using an 18m x 18m rectangular grid on the upper beach. Figure 5 shows three-dimensional plots of gamma intensity on five different sampling dates. The peak level shown for the earliest sampling date is 200 cps (Table 1). The most recent date, 7½ months later, has a peak value of 18 cps, just above background levels. It can also be seen in Table 1 that the count rate diminished by a factor of two during the nine-day interval between the first and second sampling dates. It then remained nearly constant for almost three months, and dropped by another factor of four over the next four months. The good spatial resolution and counting statistics in the gamma

Table 1. *Surface Gamma Count Rates, 18m × 18m Grid, Location R-35, Little St. George Island.*

Date	Integrated Count Rate (cts sec^{-1})	Peak Count Rate (cts sec^{-1})	Mean Count Rate (CR)
6-23-87	4787	200	59
7-2-87	2322	142	29
7-28-87	2394	90	30
9-24-87	2720	90	34
2-2-88	632	18	8

activity at this location clearly indicate transport and/or redistribution of the sand, as described below.

Sand Transport. Attempts to measure rates of transport of sand within and across the littoral zone have always been subject to a large degree of uncertainty. The uncertainty arises from a number of causes, including the difficulty of trapping and measuring sand in such a dynamic environment, and the lack of marker beds or time horizons to use as datums for measuring accumulation. In the Little St. George Island area there have been two past attempts to measure littoral sand transport rates, with a wide variation in the results. STAPOR (1973b) investigated beach erosion for St. George Island as a whole, measuring historic changes in the shorelines. He concluded that a net westerly drift cell was eroding sand from the southeast-facing beaches, including the R-35 area, and depositing 127,000 cubic yards annually at the western end of the cell—Cape St. George (Figure 3). ZEH (1980), extrapolating from WALTON's (1973) data, calculated that approximately 12,000 cubic yards annually pass westward in the littoral zone in the vicinity of R-35. Although the sense of the two estimates is the same, they differ by more than an order of magnitude.

Although this project utilized field gamma measurement in a number of ways as a tracer for shore-zone sediment movement, the chief purpose was to correlate average gamma count rate for a specific area with redistribution of sand within that area. An estimate of the volume of sand involved is described below. The full quantitative treatment of these calculations, the assumptions required, and the error analysis, are beyond the scope of this paper and are presented in further detail elsewhere (GREENFIELD *et al.*, 1989).

The average integrated gamma count rate for a specific area, such as the 18m x 18m grid at location R-35 (Figure 5), may be used to estimate the volume of sand in transport. The conditions necessary for quantifying this estimate are as follows: (1) the activity is emitted from a source which to first order may be modelled as a sheet of large extent—rather than a point source—extending laterally distances much greater than the vertical distance to the detector; (2) the gamma activity is measured in the field over the same area at given points in time; (3) the activity observed may be assumed to be due to thorium and uranium; (4) the activity ratio of Th/U is measurable and known; (5) the mass fractions of Th and U in the radiogenic heavy minerals can be measured or reliably estimated; (6) the fraction of the radiogenic minerals in the heavy mineral sand can be measured; (7) the fraction of heavy minerals in the bulk sand can be measured; (8) the degree of absorption of the gamma radiation emitted from the heavy minerals can be reliably estimated, based on relatively simple models.

In this study the above conditions were met in the following ways. (1) The source of the gamma activity was observed to be a bed of heavy mineral-bearing quartz sand extending tens of meters laterally, thinly bedded and close to the surface. This would be the typical geometry for most beach deposits. (2) Gamma radiation was measured in the field periodically at a number of rectangular grids, including locations on Little St. George Island (Figure 3) at R-35 and R-20X and on St. Vincent Island (Figure 1). A graphical presentation of the gamma data for location R-35 is shown in Figure 5.

Conditions (3) and (4) were met by collecting sand samples from a number of locations on the island. Specific nuclides responsible for the observed activity were identified by use of a gamma spectrometer. A summary of the counting data is shown in Table 2. The counting method, as described in the Methods section, uses Ac-228 as a representative of the Th-232 decay series, and the average of three photopeaks in the U-238 series to represent U-238. The data are therefore reported in the table as a series. The radioactivity due to decay of K-40 was found to be negligible, in each case less than 6% of the total. All of the remaining activity is from decay within the U-238 and Th-232 series. The relative proportions of Th and U

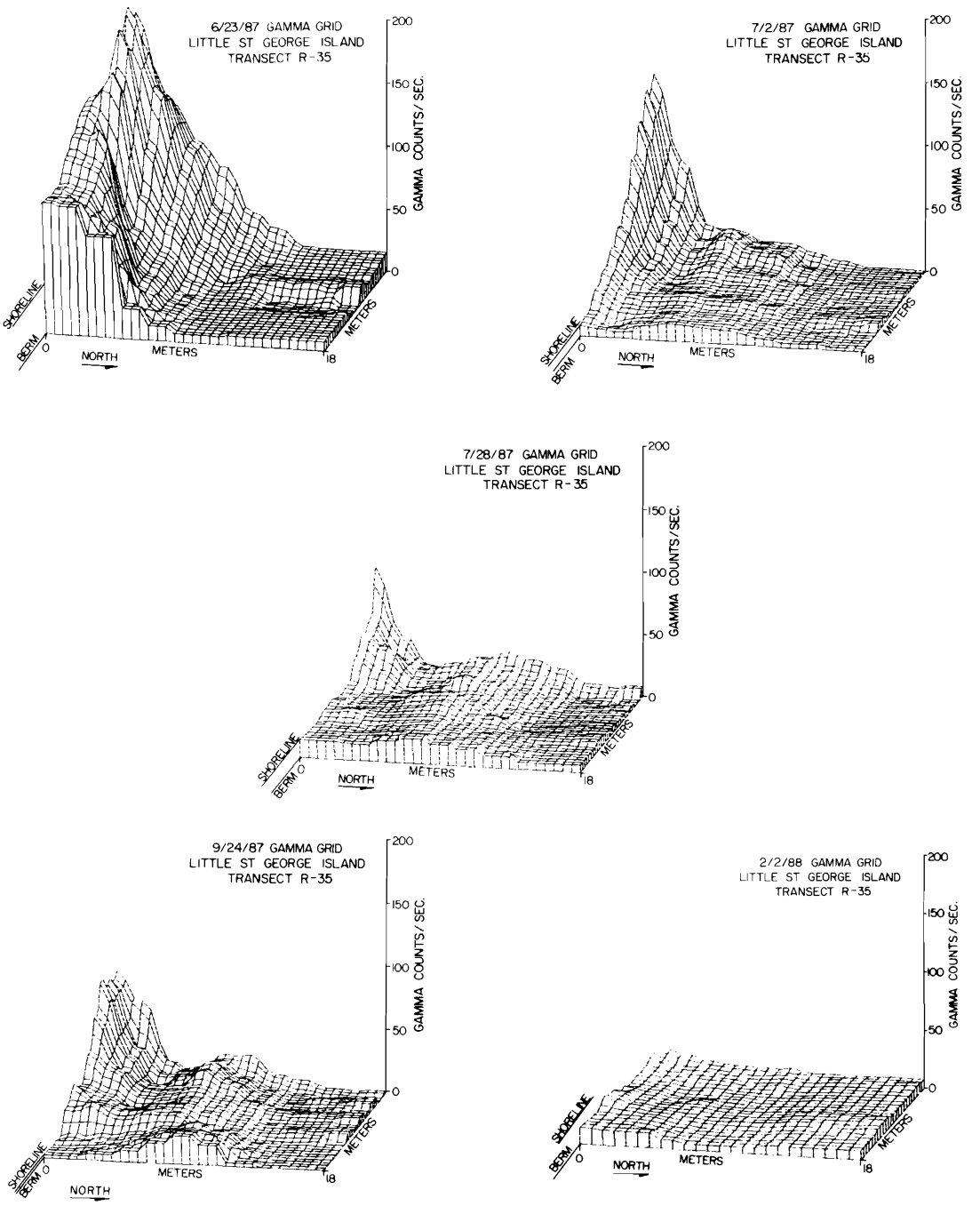

Figure 5. Field gamma radiation measurements within an 18m x 18m grid at location R-35 on Little St. George Island for five different sampling dates. (See Figure 3 for location of grid).

Table 2. *Concentration of Radionuclides in Beach Sand Little St. George Island.*

Location	Thorium-232 Series (dpm g^{-1})	Uranium-238 Series (dpm g^{-1})	Th/U
D	12.87	35.02	0.37
R-20X	31.44	58.77	0.53
R-35	116.89	105.10	1.11
R-51	129.49	80.20	1.61

vary among locations, due to different proportions of heavy minerals. Over a small area however, such as the 18m x 18m sampling grids, the Th/U ratio can be assumed to be constant at the given levels during the period of measurement.

Condition (5) was met by searching the literature for assays of the particular radiogenic minerals known to be in the region of the study, in this case monazite and zircon. As an example, the data reported by OVERSTREET *et al.* (1970) on Th and U percentages in detrital monazite from the southeastern Appalachians are used in the sample calculations below. Average percentages of Th and U in monazite, as calculated from the above source, are 4.7% and 0.45%, respectively. Conditions (6) and (7) were met by collecting sand samples at each of the sampling sites and separating and identifying the heavy minerals by use of the procedures described in the Methods section.

Condition (8) arises from the fact that the gamma count rate measured in-situ is not only a function of the amount of radiogenic minerals, but also of the degree to which the gamma rays are reabsorbed. Although one cannot distinguish, based on a change in count rate, whether the heavy mineral sand has been transported or whether it has been redistributed in-place, reasonable models based on qualitative observation may be used to estimate the volume of sand involved. The heavy mineral sand tends to be concentrated into beds of less than a few centimeters thickness. Gammas emitted from the surface of the beach contribute more to the total count rate than those from deeper below the surface. Covering heavy mineral-rich sand with successive layers of quartz sand, the gamma flux has been observed to be halved for each 10 cm thickness added. Therefore, two models provide approximate limits on the amount of absorption. It is assumed that a thin heavy mineral-rich bed is buried beneath 10 cm of inactive sand (large absorption model) or that it is uniformly dispersed in a 10 cm bed (small absorption model). Both models yield energy-dependent correction factors which for typical 200 keV gammas were about 2.3 and 1.5, respectively, in good agreement with the observation mentioned above. For the higher-energy gamma rays absorption is of decreasing importance. Due to buildup (i.e., scattering from the absorber into the detector of gammas somewhat degraded in energy), the effective visibility depth is greater than would be observed in a total absorption model and is approximately energy-independent.

In the sample calculation below, an estimate of the gamma ray absorption factor of 2.0 ± 0.5 is adopted. Due to uncertainties in the depth distribution of the emitted gammas, it is difficult to draw a direct correlation between change in count rates and transport of a volume of sand. It would require careful monitoring of the distribution of heavy minerals at least to the effective visibility depth (approx. 1 m) to know if the change in count rate was due to movement of the absorbing layer or to a redistribution of the heavy minerals themselves. Such detailed studies are in progress.

The data in Tables 1 and 2 are utilized as an example of estimating sand transport rates from changes in the associated field gamma count rates. Assuming a heavy mineral-bearing bed buried close to the surface of the beach, an estimate can be made for the mass of sand within the active stratum of the beach in the grid at location R-35 (see Figure 5). This stratum is the layer whose sand volume—including heavy mineral sand—is being directly affected by short-term changes in the energy levels available to transport sand along the upper beach and also across the beach and into the dunes. In the present case most of this energy is in the form of wind currents saltating sand grains. In the nearshore zone, however, littoral drift has a similar effect, and the same type of measurements could be made.

Based on this study, the following relation should result in a reliable estimate for the mass of sand incorporated in the active upper layer of the beach grid, as described above. The change in this mass with time is therefore a measure of erosion, deposition, and/or redistribution of the heavy mineral-bearing sand. Mea-

surements over time on a series of grids along and across a beach would provide information on sand transport. The element thorium and the mineral monazite are used here, although the calculation can be done for any radioelement and mineral for which data are available. (Using uranium in monazite in the same example agrees to within 30%). The relation is:

$$M = \frac{2 * CR * MT * AF * A}{DT * (s*e) * (C+1) * No * FT * FM * FH}$$

where
- M = Mass of sand in active layer of grid, in grams
- CR = Mean count rate, from Table 1
- MT = Gram molecular weight of thorium-232 (= 232 g mole^{-1})
- AF = Absorption factor for gamma radiation in quartz sand (= 2 for the simplified case described above)
- A = Area of the grid (= 18m x 18m)
- DT = Decay constant of thorium-232 (= 1.59 x 10^{-18} sec^{-1})
- s*e = Detector surface area (s) x detection efficiency (e) (= 7.6 cm^2, as described in the Methods section)
- C = U/Th activity ratio (= 0.90 for location R-35, from Table 2)
- No = Avogadro's number (= 6.022 x 10^{23} atoms mole^{-1})
- FT = Fraction of thorium in monazite (in this case 0.047)
- FM = Fraction of monazite in heavy mineral suite
- FH = Fraction of heavy minerals in bulk sand

(The factor of 2 results from the geometry of the model chosen, as described above.)

All of the factors on the right-hand side of the equation are effectively time-independent for a given location, with the exception of the mean count rate (CR), the monazite fraction in the heavy minerals (FM), and the heavy mineral fraction in the bulk sand (FH). The change over time in the mass of sand in the active layer of the grid may be estimated by using the mean count rate values for the first and last sampling dates in Table 1.

A rigorous estimate would entail using FH and FM values from multiple sand samples for each of the sampling dates. For this example, however, nominal values of 0.04 for FM and 0.08 for FH are used. These are within the range of values found in the study area. Substituting these figures into the equation, a value of 8.48 x 10^7 g is obtained for the mass of sand in the active layer of the grid on the earliest sampling date. For the latest sampling date, a value of 1.14 x 10^7 g is obtained. The change in mass, 7.34 x 10^7 g, which occurred over the 7½ month interval, converts to an annual erosion rate of 1.19 x 10^8 g/yr for the grid. The cumulative error in this calculation is estimated to be less than a factor of two, which is more precise than most such attempts to quantify sand transport. The uncertainty can potentially be made much smaller with more intensive sampling.

In order to place this kind of estimate in perspective, if we assume a bulk density of 1.6 g/cm^3, this erosion rate equates to a vertical loss of approximately 23 cm/yr. This figure is easily comparable to measurements of beach profile changes, which have been carried out concurrently with this project. Like the beach profiles, any erosion rate measured in this manner would have a seasonally fluctuating component as well as a long-term trend. In either type of analysis, greater accuracy in measurement would result from a higher sampling frequency. But the above provides an example of the potential utility of field gamma measurements for monitoring beach processes.

CONCLUSIONS

The following conclusions can be drawn on the basis of this study of the mineralogy and radioactivity of northwest Florida beach deposits: (1) An order of magnitude change in the gamma activity of shore zone heavy mineral sands is readily observable over relatively brief time spans, *i.e.*, weeks or months. (2) The radioactivity is directly related to certain of the heavy mineral species, namely monazite and to a lesser extent zircon. (3) The heavy minerals are derived from the Southern Appalachians of the upper watershed of the Apalachicola River.

(4) More than 90% of the gamma activity is due to Th-232 and U-238 series nuclides occurring as trace elements in the heavy mineral sands. (5) Distribution of surface gamma radiation levels around objects can be used to document entrainment and transport of heavy mineral sand in the prevailing wind direction, and deposition of heavier grains beneath the turbulent eddy downwind from such objects. (6) Estimates of transported sand volume may be made by recording the change in gross gamma radioactivity within a given area over time.

This work opens the possibility of estimating sand transport rates by observing changes in field-measured gamma activities as a function of time and position. The average integrated count rate over a given area is used to calculate the effective mass of uranium and thorium per unit area which would be needed to produce the observed activity. From these calculations, along with knowledge of the concentrations of thorium and uranium in heavy mineral sands and the percentage of heavy minerals in the sand, it is possible to correlate average integrated count rates with an associated volume of sand. Changes in gamma count rates over time may therefore be used to estimate sand transport rates in the shore zone.

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☐ ZUSAMMENFASSUNG ☐

Zwei eng miteinander in Beziehung stehende Prozesse, die Entwicklung der Oberfläche des Meeresbodens in Küstennähe bestimmen, werden untersucht: die Wellenbrechung und der daraus resultierende kütennahe Sedimenttransport. Der ursprüngliche Meeresboden ist ein isoliertes Unterwasserriff, das sich gleichmäßig parallel zur Küste und meerwärts erstreckt. Die Wellenbrechung wird mit standardisierten numerischen Verfahren berechnet, der küstennahe Transport mit Hilfe der Formel von CERC. Der Gradient dieser litoralen Drift und die Nivellierung durch ständige Sedimentzufuhr geben die Menge an erodiertem oder akkumuliertem Sediment an. Die anschließende Veränderung der Meerestiefe wird vorhergesagt. Diese Zyklen aus Wellenbrechung, küstennahem Transport und Veränderung der Wassertiefe werden wiederholt simuliert und dabei die Entwicklung des Unterwasserriffs verfolgt. Es wird der Versuch unternommen, das Problem in seinen Grundzügen zu lösen, indem die Anzahl der Variablen auf ein Minimum reduziert und jede Variable einzeln analysiert wird. Ausgleichsküsten und unausgeglichene Küsten werden dabei untersucht, da sie gegensätzlichen Einfluß auf die Prozesse der Strandentwicklung haben.—*Helmut Brückner, Geographisches Institut, Universität Düsseldorf, F.R.G.*

☐ RÉSUMÉ ☐

Etudie deux processus qui déterminent étroitment l'évolution de la topographie des fonds avec le temps: la réfraction de la houle et le transport sédimentaire littoral induit par la houle. Le fond origine est une barre isolée perpendiculaire à la côte. Elle s'étale légèrement le long du littoral et vers le large. La réfraction est calculée selon une procédure standard et le transport littoral calculé selon la formule de CERC. Le gradient du courant littoral, combi né à l'équation de continuité du sédiment donne la quantité de sédiment érodee ou déposée. Ces cycles réfraction littorale—transport et modification de la bathymétrie sont répétés. La modification de l'évolution de la barre est suivie dans le temps. Il est tenté de faire l'étude de ce problème en réduisant le nombre de variables au minimum et en les analysant séparément. Les côtes rectilignes et non rectilignes, dont les processus d'évolution sont dus à des influences opposées, sont traitées.—*Catherine Bressolier-Bousquet (Géomorphologie EPHE, Montrouge, France).*