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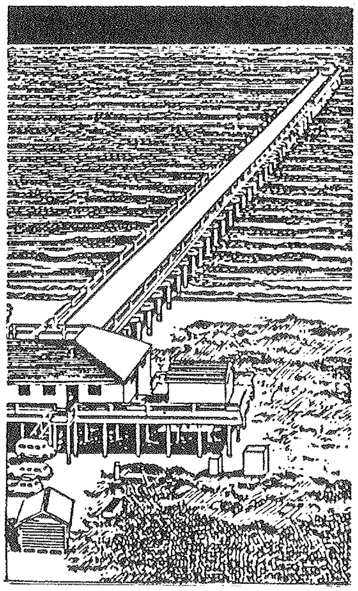

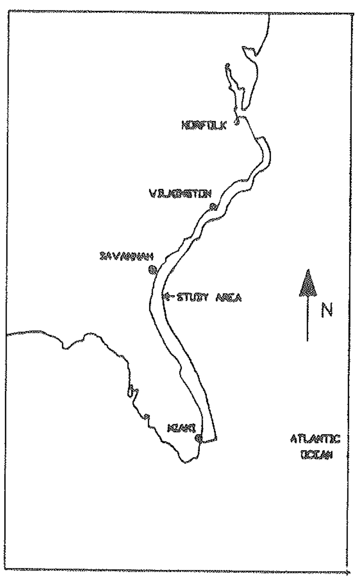

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SHORE NORMAL DISTRIBUTION OF HEAVY MINERALS ON OCEAN BEACHES: SOUTHEAST ATLANTIC COAST

by

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Cross-shore beach sample sets from 102 locations along the barrier-dominated Atlantic coast from Kitty Hawk, North Carolina, to Palm Beach, Florida, were studied to determine if there were systematic differences in heavy mineral abundance and species frequency distribution between sampling stations on each transect line and between barrier and mainland segments. Only the more commonly occurring heavy minerals species were counted, including rutile, garnet, staurolite, epidote, amphibole, and tourmaline. On each transect, samples were taken at the step, the existing limit of uprush, berm crest, midberm, and inland limit of the beach. The weight percent of the heavy mineral fraction was found to be consistently and substantially higher in backshore and berm crest samples than in the foreshore samples from the same transect. A comparison of the frequency distribution of heavy mineral species showed that mineral species having the higher specific gravity, i.e., rutile, garnet, and staurolite, are much more abundant in

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backshore samples than in foreshore samples from the same transect and that the amount of difference generally increases with increasing specific gravity. Amphiboles occurred in much greater abundance in foreshore samples, while epidote and tourmaline show less pronounced and consistent differences between backshore and foreshore samples.

PREFACE

The study herein results from research carried out at the Coastal Engineering Research Center (CERC) of the US Army Engineer Waterways Experiment Station (WES) under Barrier Island Sedimentation Studies Work Unit 31665, Shore Protection and Restoration Program, authorized by the US Army Corps of Engineers (USACE). Messrs. John H. Lockhart, Jr., John G. Housley, James E. Crews, and Charles W. Hummer were USACE Technical Monitors. Dr. C. Linwood Vincent is CERC Program Manager.

This report was prepared by Mr. Edward P. Meisburger, Coastal Morphology Unit, Coastal Processes Branch (CR-P), Research Division (CR), CERC, under general direction of Mr. H. Lee Butler, Chief, CR, and Dr. Steven A. Hughes, former Chief, CR-P. Chief of CERC during the investigation was Dr. James R. Houston, and Assistant Chief was Mr. Charles C. Calhoun, Jr.

Acting Commander and Director of WES during publication of this report was LTC Jack R. Stephens, EN. Technical Director was Dr. Robert W. Whalin.

CONTENTS

Shore Normal Distribution of Heavy Minerals on Ocean Beaches: Southeast Atlantic Coast

PART I: INTRODUCTION

Purpose and Scope

1. This study investigates the cross-shore variations in heavy mineral distribution on subaerial ocean beaches. It is based on analysis of sets of beach transect samples from sites between Kitty Hawk, North Carolina, and Palm Beach, Florida (Figure 1). Information on heavy mineral variations was derived from comparison of samples collected along the beach profiles.

2. Heavy mineral analyses have been used with varying degrees of success by Corps of Engineers and other agencies to identify the sources and transport paths of coastal sediments (see, for example, McMasters, 1954). In coastal plain regions, such as that considered here, the constituents of the heavy mineral suite--that is the mineral species present--generally show little variation over long reaches of coast, but the relative abundance of a given species may show wide variation. While these frequency differences may be source related, the effects of selective sorting during erosion, transportation and deposition can create large variations in the frequency of a given species over short distances. This difficulty introduces a large degree of uncertainty in interpretation of heavy mineral distribution data.

3. The general objective of this study is to investigate the existence and magnitude of shore-perpendicular variations in heavy mineral distribution and determine whether or not they are systematic. Three aspects of the subject have been considered. These are:

- a. Heavy mineral abundance, i.e. the total amount of heavy minerals of all types present.
- b. Variations in frequency of specific mineral types with location along a cross-shore profile.
- c. Relationship, if any, between the abundance of heavy minerals and frequency of specific mineral types.

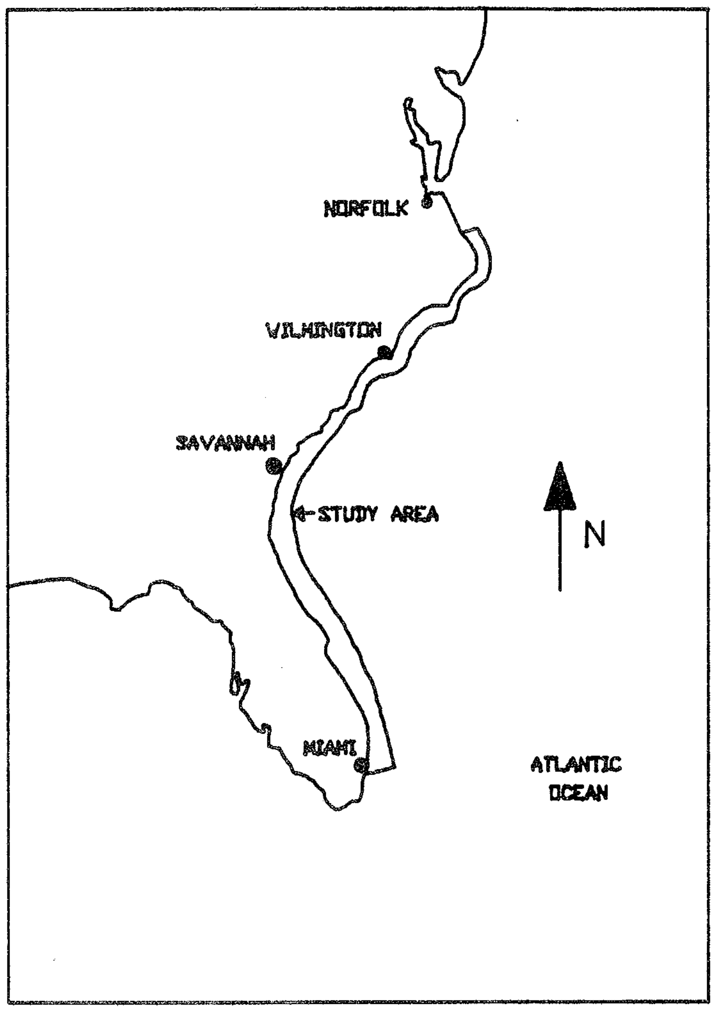

Figure 1. Location of samples

Knowledge of these factors may lead to more effective sampling strategies and improve interpretation of heavy mineral data. In addition, the data included here provide a measure of the extent to which heavy mineral distributions can be modified by selective sorting processes.

Previous Studies

4. A number of regional scale studies concerning heavy minerals in beach sediments of the area considered here have been published (Martens 1928, 1935; Miller 1945; Neiheisel 1962, 1965; Guy 1964; Giles and Pilkey 1965; Swift, Dill and McHone 1971; Flores and Shideler 1982). These studies are primarily concerned with lateral variations in heavy mineral distributions along a coastal reach. Some contain comparisons of beach, dune and offshore samples from specific locales. Flores and Shideler (1982) compared foreshore and mid-backshore samples of specific locales. Martens (1935) and Neiheisel (1962) discuss comparisons of heavy mineral concentrations and non-enriched samples from the same site.

Field Sampling

5. Samples for this study were obtained during a number of field site collections along the southeast Atlantic coast between 1980 and 1986. These samples were taken at specified points, referred to as stations, along shore normal transects at 102 locations, referred to as sites, along the coast (Figure 1). Initially sediment samples were taken from the foreshore swash zone and mid-backshore area at each site. As field and laboratory work progressed, it became apparent that more samples were needed to characterize the heavy mineral distribution along each transect. Eventually the sampling stations were increased to as many as six per transect site. These basic stations are illustrated in Figure 2 and described below.

a. Heavy Mineral Concentrate (HMC). Consists of sediments on the beach that are clearly distinguished by a black or reddish color due to the presence of abundant heavy minerals. May occur on any part of the beach but usually found on the backshore.

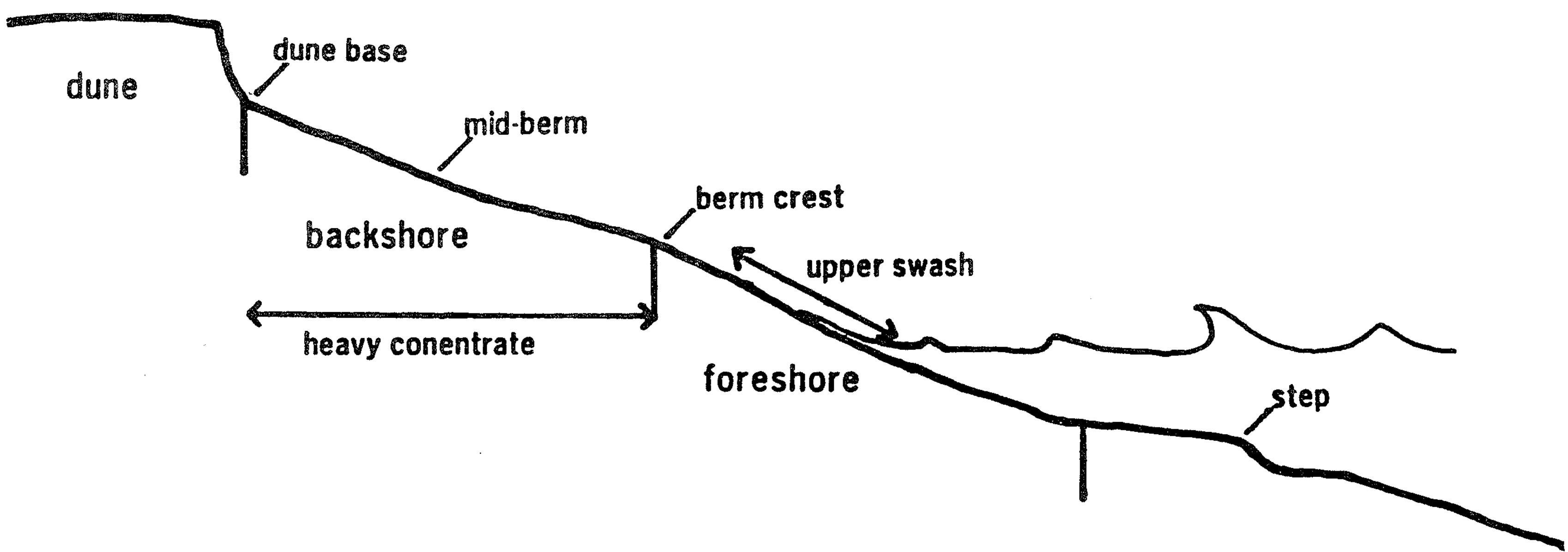

Figure 2. Idealized beach profile showing the approximate position of sampling stations

b. Dune Base. Located just seaward of the frontal dune or, in absence of a dune, the seawall, cliff, or vegetation margin marking the inland border of the beach. Samples were obtained from a 30 cm deep hole to lessen or eliminate aeolian effects.

c. Mid-Berm. Taken from the backshore zone midway between the dune base and berm crust.

d. Berm Crest. Located at the point of inflection between the normally flat berm and the steeper foreshore slope. Where no berm was evident, sample was obtained at the approximate high water line which is often marked by a line of debris.

e. Upper Swash. At the limit of wave uprush as it existed at the time samples were taken. If beach was visited at time of high tide, sample was taken from a mid swash position.

f. Step. At the limit of wave backrush which is usually marked by a small declavity in the profile. This feature, known as the step, may not be always evident.

6. Large differences in heavy mineral distribution occur mostly between stations on the backshore part of the beach and those on the foreshore; therefore, it will be convenient at times to refer to them as a group. Stations (or samples) from the backshore will be referred to collectively as backshore stations or samples. This designation includes the dune base mid-berm, berm crest, and, because it is nearly always on the backshore, heavy mineral concentrate. The upper swash and step stations (or samples) will be referred collectively to as the foreshore stations or samples.

7. Heavy mineral concentrate samples were taken from any area of the site that showed a black or reddish discoloration due to the presence of substantial amounts of heavy mineral grains. This discoloration ranged from a overall black or reddish black color to the "salt and pepper" aspect of lesser but still apparent heavy mineral enrichment. The actual weight percent of heavy minerals in these samples varies widely.

8. Many sites sampled in the early part of the study were later resampled so that a sufficient number from each site were collected to provide a reasonable estimate of the basic relationships between transect stations. In all, 401 samples, providing from four to six samples per site, were collected and analyzed.

Laboratory Procedure

9. Samples used for this study were wet sieved in a 0.063 mm sieve to remove fines and heavy minerals that were separated from the light fraction in bromoform (sp gr 2.85). The 0.125-0.250 mm grain size fraction was used exclusively for the study. This size fraction was recommended by Carver (1971) as the best compromise among the many different size fractions utilized by previous workers.

10. Examination and enumeration of heavy mineral species were made with both petrographic and binocular microscopes. Identification was facilitated by the fact that the heavy minerals in beaches for most of the study area were the subject of previous investigations as listed under "Previous Studies" section of this report). Only nine mineral species occurred with any regularity in the study area. These minerals included zircon, rutile, garnet, staurolite, kyanite, epidote, sillimanite, amphibole (largely green hornblende) and tourmaline. Of these, zircon, sillimanite, and kyanite occurred in too small quantities for comparative analysis and were not included in the study.

PART II: HEAVY MINERAL ABUNDANCE AND DISTRIBUTION

Heavy Mineral Abundance

11. The abundance of heavy minerals at the various sampling stations along a shore-normal beach transects vary considerably between sampling sites and between individual sample stations from a given site. Despite these variations some distinct trends are apparent.

12. Data concerning the heavy mineral abundance are shown in Table 1 and the same data is depicted graphically in Figure 3. Table 1 lists the percentage of total samples from every transect sampling station categorized by a weight percentage of heavy minerals falling into the following groups: 0-1, 1-3, 3-5, 5-7, 7-9, and greater than 9 percent. Because of the great variation in heavy mineral content between samples at any given site, average values are considered less meaningful than the incremental divisions used in the table.

Table 1

Weight Percentage of Heavy Minerals in Samples from Each Transect Sampling Station

Station	Weight Percent					
	0-1*	1-3	3-5	5-7	7-9	9
Heavy Conc.	1.6	3.1	18.8	3.1	7.8	69.6
Dune Base	25.3	38.0	11.4	8.9	5.1	11.4
Mid-Berm	22.7	43.2	9.1	20.5	2.3	2.3
Berm Crest	39.5	34.9	12.8	2.3	3.5	7.0
Upper Swash	75.6	20.3	2.4	1.6	0	0
Step	82.0	18.0	0	0	0	0

Station	Cumulative Percent Greater				
	1	3	5	7	9
Heavy Conc.	98.4	95.3	76.5	73.4	65.6
Dune Base	74.8	36.8	25.4	16.5	11.4
Mid-Berm	77.4	34.2	25.1	4.6	2.3
Berm Crest	60.5	25.6	12.8	10.5	7.0
Upper Swash	24.3	4.0	1.6	0	0
Step	18.0	0	0	0	0

* Percentage increments

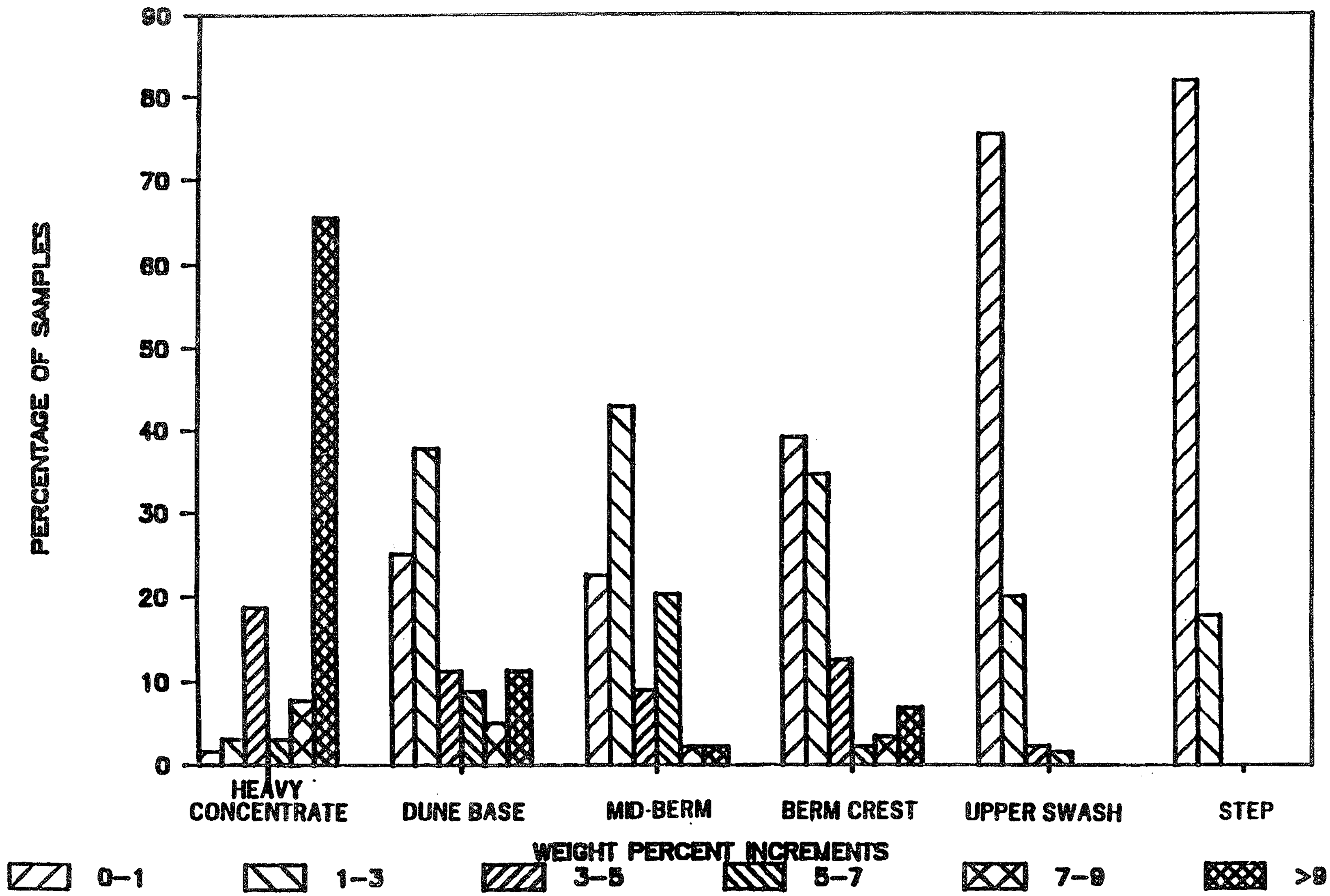

Figure 3. Percentage of samples having weight percent heavy minerals in specified increments

13. An important aspect of the data in Table 1 is the contrast between (a) the heavy concentrates, (b) other samples from the backshore area of the beach (i.e. dune base, mid-berm, berm crest), and (c) samples from the foreshore zone (i.e. upper swash, step). The heavy concentrates contain much larger quantities of heavy minerals than any of the other sample stations. For example over 70 percent of the heavy concentrate samples contain more than 7 percent heavy minerals while only 16.5 percent or less of the backshore samples and none of the foreshore samples contain as much.

14. In general the weight percent of heavy minerals is highest near the coastline and decreases in a seaward direction. This is consistent with Rasmussens' (1941) observations of a beach on Lake Michigan. The decrease is not gradual; however, most of it occurs between the berm crest and upper swash stations which lie nearest to the backshore-foreshore boundary.

Mineral Species Distribution

15. Of the nine non-opaque heavy mineral species occurring with some regularity in the study area, six are present in a sufficient number of samples and in sufficient quantity to permit reasonably reliable analysis of any systematic differences in relative abundance between the sample stations. These minerals are rutile, garnet, staurolite, epidote, amphibole and tourmaline. Comparison of data for these mineral species shows that significant differences between sampling stations do occur and that they tend to persist from site to site.

16. Similarly, with the differences in heavy mineral abundance previously described, the frequency differences of heavy mineral species between sampling stations is usually largest when the backshore stations (i.e. dune base, mid-berm, berm crest, and heavy concentrate) are compared to foreshore stations (i.e. step and upper swash). This is shown in Table 2 which compares the overall average frequency values of all foreshore stations to the overall average value of all backshore stations. Smaller differences occur in comparisons between backshore stations or between the two foreshore stations.

Table 2

Overall Average Frequency of Heavy Mineral Species at All Foreshore and Backshore Stations

Species	Foreshore	Backshore	Ratio
rutile	3.9	8.6	2.2
garnet	6.1	10.9	1.8
staurolite	16.8	25.2	1.5
epidote	26.6	27.9	1.0
amphibole	30.3	14.0	2.2
tourmaline	13.7	12.7	1.1

17. Figures 4 through 8 illustrate the distribution pattern in more detail by a comparison of the percent frequency of a given mineral species in the upper swash sample, which is representative of the foreshore zone, and its frequency in each of the four backshore samples from the same transect. The differences are expressed in terms of orders of magnitude (ratio) which were derived by dividing the larger value of the pair being compared by the smaller value. Thus, for example, a garnet frequency of 4.0 percent in the uprush sample and 12.0 percent in the coastline sample of the same transect would make the garnet content of the coastline sample larger by 3.0 orders of magnitude than the garnet content of the uprush sample.

18. The histograms of Figures 4-8 show the percentage of sites where the frequency difference between specified stations on the same transect were 1-2, 2-3, 3-4, 4-5, or greater than 5 orders of magnitude. Data plotted above the midline pertains to sites where the frequency in the uprush sample is less than that of the compared sample and data plotted below the midline represents the reverse conditions. This procedure is judged to provide a more meaningful value for the comparison than a simple arithmetic difference for the following reason. There are large and persistent differences in the abundance of heavy mineral species between different parts of the study area. This is apparently

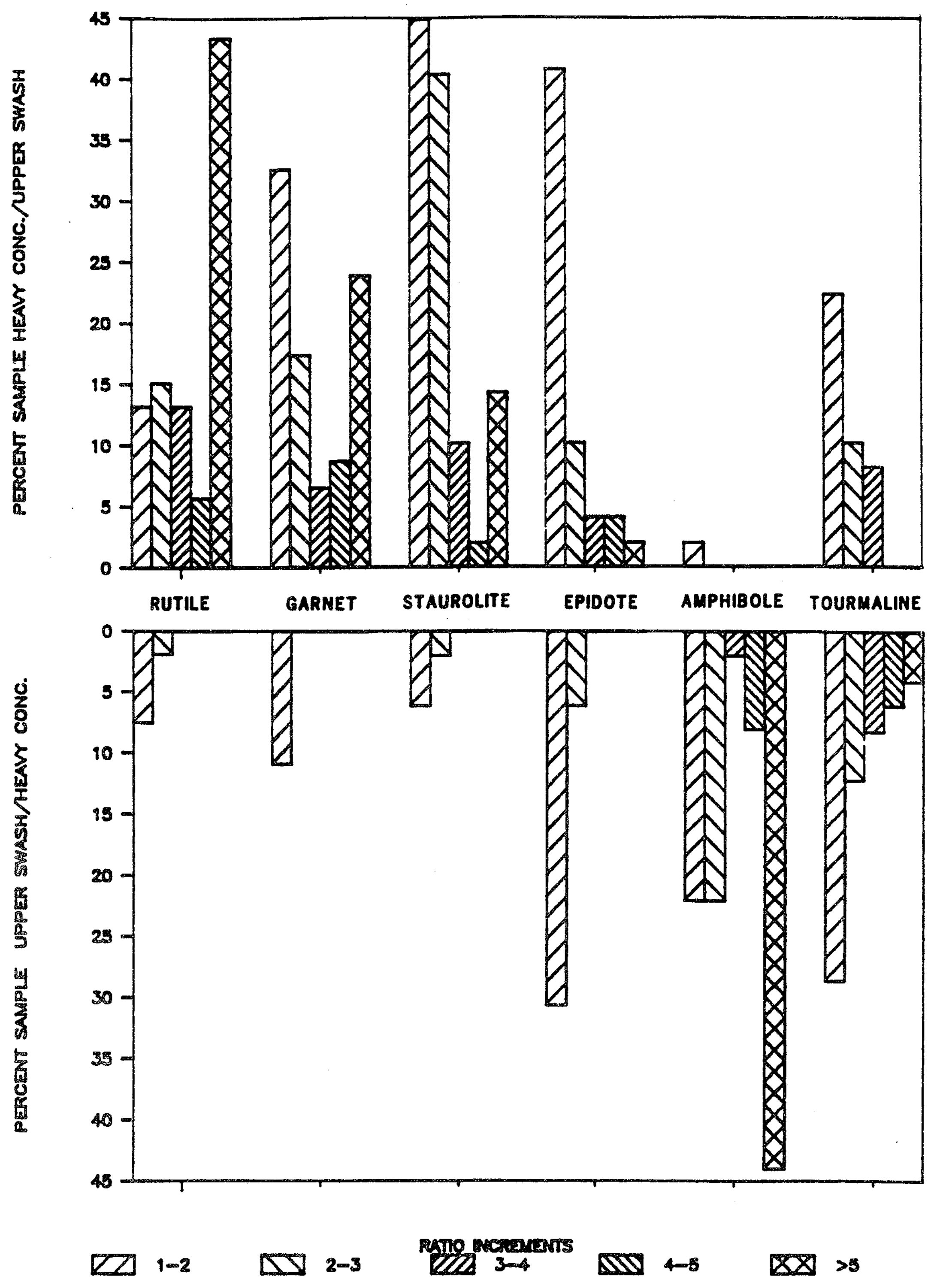

Figure 4. Percentage of samples in which the ratio between the frequency of specified minerals in the upper swash and heavy concentrate samples from the same transect is within designated increment values

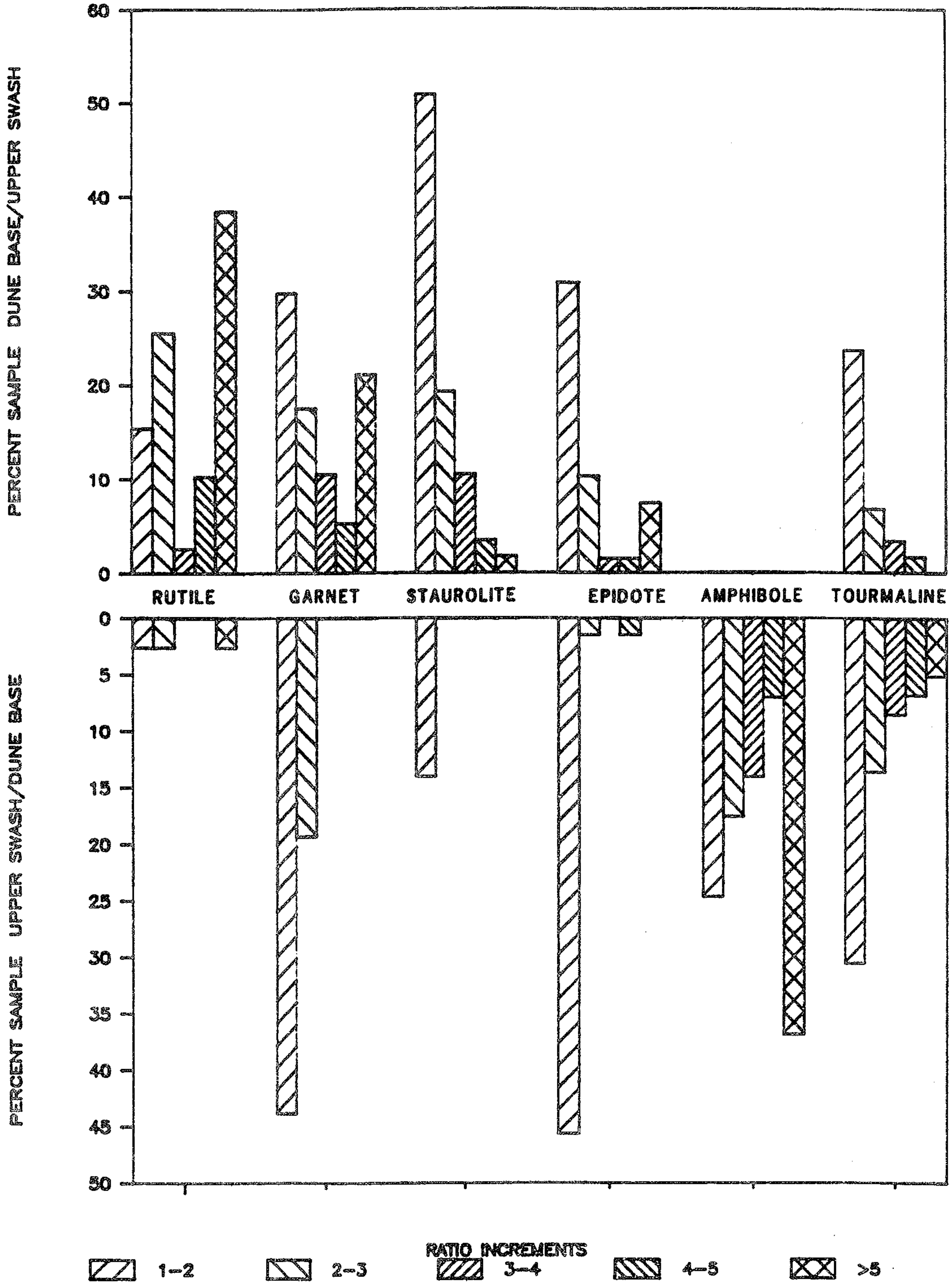

Figure 5. Percentage of samples in which the ratio between the frequency of specified minerals in the upper swash and dune base samples from the same transect are within designated increment values

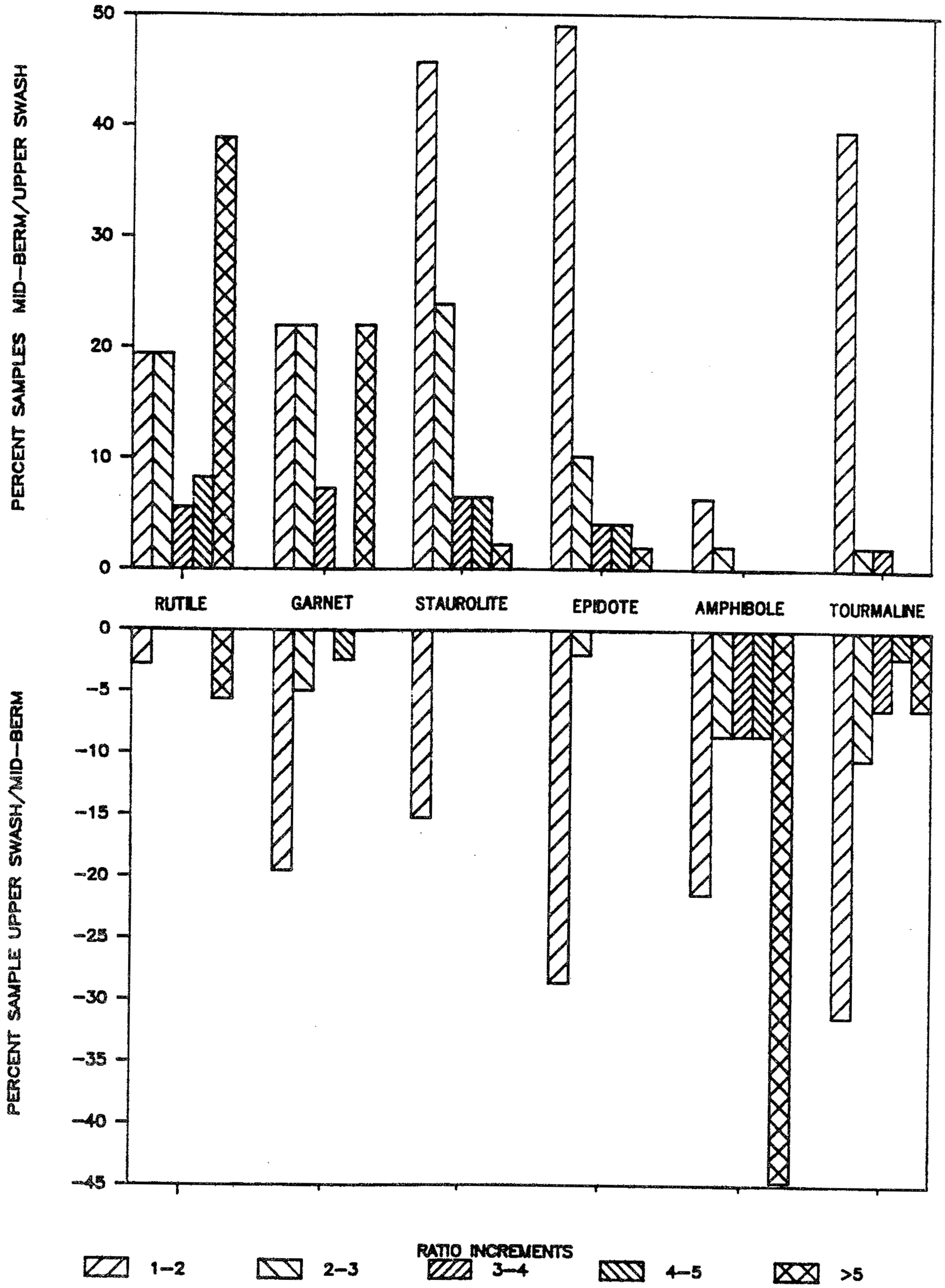

Figure 6. Percentage of samples in which the ratio between the frequency of specified minerals in the upper swash and mid-berm samples from the same transect is within designated increment values

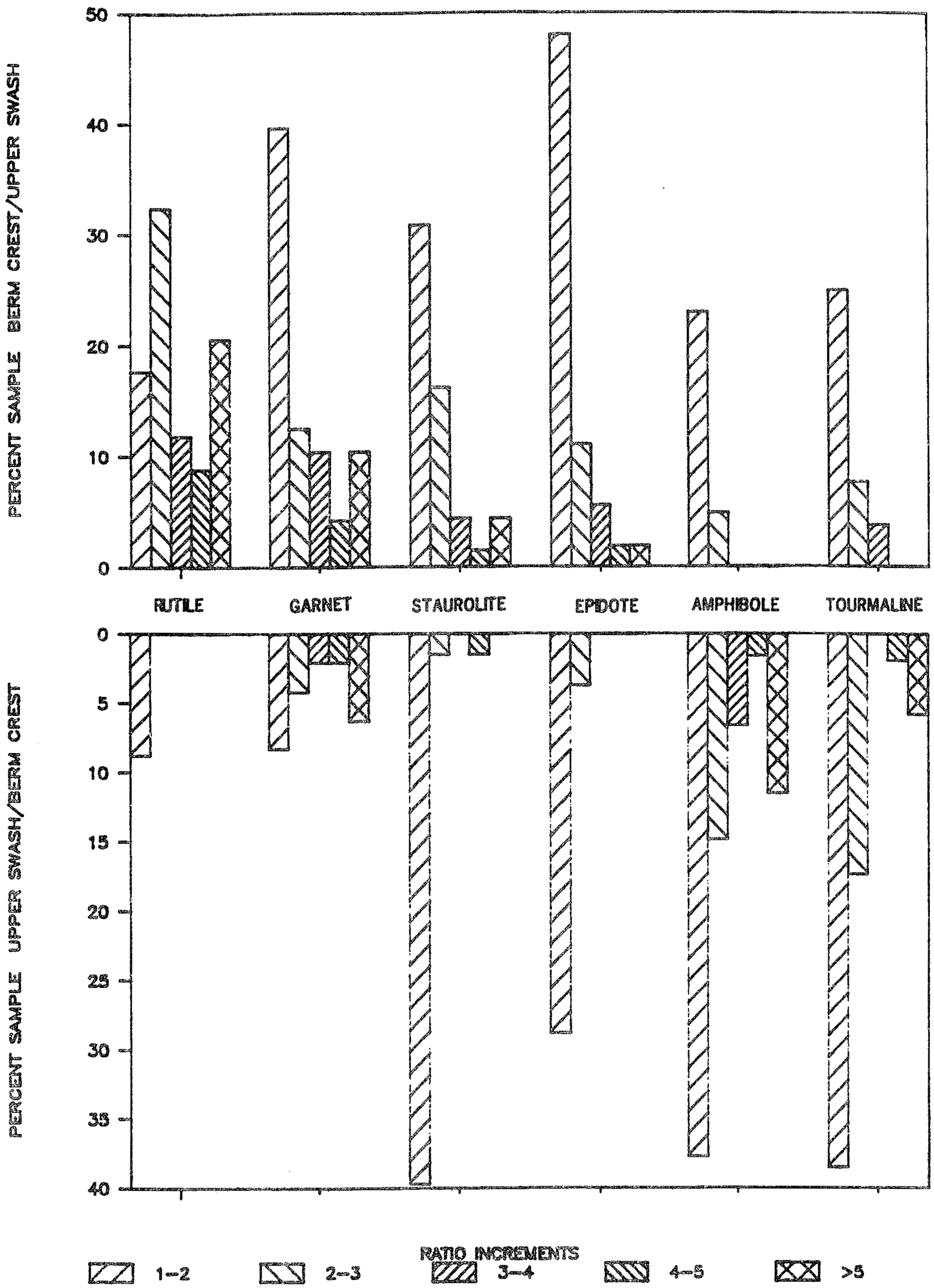

Figure 7. Percentage of samples in which the ratio between the frequency of specified minerals in the upper swash and berm crest samples from the same transect is within designated increment values

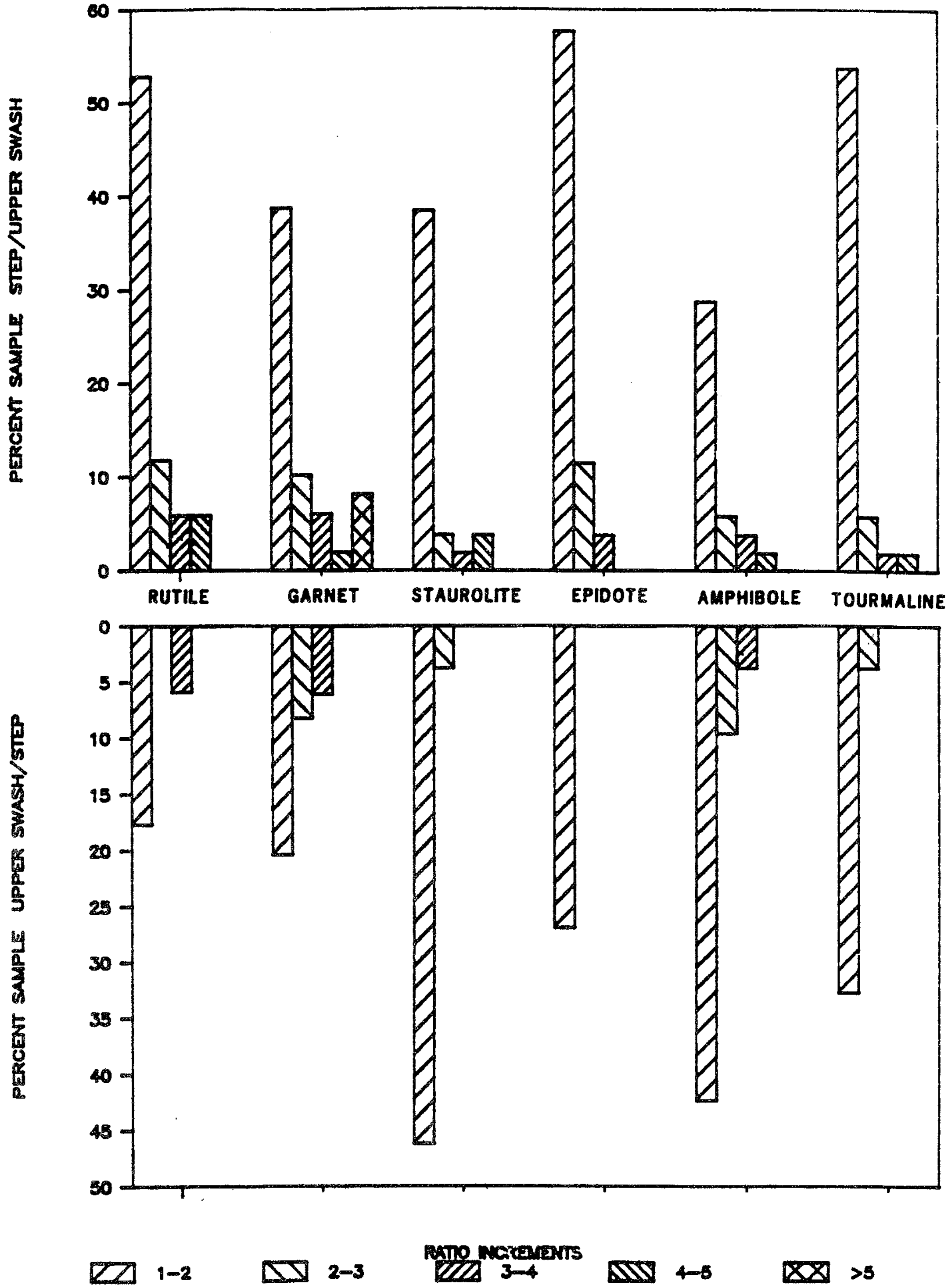

Figure 8. Percentage of samples in which the ratio between the frequency of specified minerals in the upper swash and step samples from the same transect is within designated increment values

due in many instances to changes in the availability of mineral species from place to place. Since the maximum possible arithmetic difference between mineral frequencies of a given pair is limited by the absolute abundance of the species concerned, the potential differences are higher for samples from areas where the mineral is relatively more abundant. For example garnet in the Georgia and South Carolina beaches rarely exceeds 10 percent and is usually less than 5 percent, while north of Cape Lookout, abundance values of 40 percent or more are common and arithmetic differences values 20-40 percentage points often occur. Because of the low abundance of garnet in Georgia and South Carolina beaches, the maximum potential difference is much lower than along the beaches north of Cape Lookout. Because of this factor order of magnitude differences are used to provide a measure of proportional difference that is not directly influenced by the absolute abundance of any mineral species.

19. Examination of the histograms show definite, but not invariable, trends in the cross-shore distribution of mineral species. The three mineral species having the highest average specific gravity, rutile (sp gr 4.2), garnet (sp gr 3.9) and staurolite (sp gr 3.7) are in most cases much more numerous in backshore samples than in upper swash samples. The reverse is true of amphibole (sp gr 3.2) which is much more abundant in upper swash samples. Both epidote (sp gr 3.4) and tournaline (sp gr 3.1) have a more balanced distribution with epidote somewhat more abundant in the backshore samples and tourmaline somewhat more abundant in the upper swash samples.

20. An indication of the magnitude of differences in mineral abundance in given in Table 3. This table shows the order of magnitude differences between the combined average abundance of the backshore stations in each transect as compared to the corresponding upper swash stations. The percentage figures shown are averages of the combined heavy concentrate, dune base, mid-berm and berm crest sample values for each transect compared to the corresponding upper swash sample. Unlike the histograms, the table does not include distinction between cases where the uprush values are higher or lower than the compared value but records all differences equally.

Table 3

Percentage of Sites Where the Difference Between Mineral Frequency in the Upper Swash Station and Average Frequency for Backshore Stations Falls Within Specified Values

	Percentage of Sites				
Mineral Species	1-2*	2-3	3-4	4-5	5
rutile	21.8	24.3	8.3	8.3	37.4
garnet	44.2	20.1	9.2	5.7	20.9
staurolite	58.4	20.8	7.9	3.8	5.4
epidote	75.6	13.8	3.8	3.3	3.8
amphibole	34.3	17.5	7.8	6.3	34.5
tourmaline	59.9	20.1	10.1	4.7	5.4

* order of magnitude difference

21. Table 3 also shows that the greatest differences are recorded for rutile and amphibole and the least difference by epidote. For example, rutile and amphibole have ratios of 5 or more in over 30 percent of the samples while the corresponding value for epidote is only 3.8 percent. Values for garnet, staurolite, and tourmaline are intermediate. Garnet has the higher of these intermediate values while staurolite and tourmaline have values that are very similar and relatively low.

Relationship of Mineral Frequency and Heavy Mineral Abundance

22. In similar heavy mineral investigations within the present study area, Martens (1935) and Neiheisel (1962) noted a relationship between the concentration of heavy minerals and the abundance of certain heavy mineral species. They found that, in general, minerals with the higher specific gravities within the mineral suite tended to be more abundant in samples having a relatively high heavy mineral concentration. Conversely minerals of comparatively low specific gravity were most abundant in samples with low concentrations of heavy minerals.

23. A similar relationship is also evident in samples collected for this study. For example, Table 1 shows that the highest concentrations of heavy minerals occur in the heavy mineral concentrate and backshore samples and comparatively low concentrations prevail on the foreshore. Figures 4 through 8 show that among the common minerals of the study area those with the highest specific gravity, especially rutile and garnet, are much more abundant in the heavy mineral concentrate and backshore samples than in foreshore samples. In contrast, amphiboles which have a relatively low specific gravity and flattened shape making them more sensitive to erosion and transportation are concentrated largely in foreshore deposits.

PART III: DISCUSSION

Heavy Mineral Abundance

24. Areal difference in heavy mineral abundance on beaches have been noted by several investigators (see for example Martens 1928, 1935; Rao, 1957; McCauley, 1960; Neiheisel 1962, 1965; Stapor, 1973; and Woolsey, Henry, and Hunt, 1975). In most cases their observations were concerned with the occurrence of heavy mineral concentrates on beaches rather than overall distribution of heavy mineral abundance. The heavy mineral concentrates which they describe are marked by a black or reddish discoloration of the sediment due to its content of black minerals such as ilmenite and magnetite or reddish garnets. In most cases these deposits were on the backshore part of the beach, especially near the dune base. Most investigators have concluded that their formation in associated with storm conditions and wind deflation of lighter minerals.

25. During field sampling of beaches for this study, heavy mineral concentrates were frequently encountered. These deposits ranged from layers several centimeters thick to thin laminea and surficial crusts. The heavy mineral abundance of these concentrates varied, up to 75 percent abundance.

26. The areal distribution of heavy mineral abundance in normal beach sand was studied by Rasmussen (1941) on a Lake Michigan beach. Rasmussen concluded that there was a systematic decrease in the abundance of heavy minerals in a lakeward direction. Samples collected for the present study also indicate a decrease in heavy mineral abundance in a seaward direction. The decrease does not occur at a constant rate but changes rather abruptly near the berm crest.

27. The process of heavy mineral enrichment of beach deposits is largely related to the uprush and backrush flow created by incoming breakers. During the uprush phase water flows up the foreshore slope under the impetus of the breaking waves. At the limit of uprush the velocity decreases to zero and is followed by the return flow under the impetus of gravity. Particles of different size, shape, and density are transported by the uprush and deposited

during the short time the velocity of the swash is near zero at flow reversal. The backrush may then preferentially entrain some of the larger and less dense particles and return them down the foreshore slope. This process of transport and winnowing can result in enrichment of the uprush deposits in the denser mineral species.

28. During fair weather periods the process of enrichment appears to be much less effective than during storms. This is because fair weather, relatively low energy uprush/backrush processes, tend to preferentially entrain and transport lighter minerals and to distribute them more equally throughout the swash zone (Figure 9). During storms a much larger proportion of the denser minerals are carried to the beach by the uprush and subsequent winnowing of the lighter minerals during the backrush leads to enrichment of heavy minerals in the upper swash zone. The differences in the heavy mineral content and the frequency of the denser minerals between backshore and foreshore deposits can be attributed to the fact that foreshore deposits are the result of fair weather processes while backshore deposits are related to storm conditions when higher water levels and erosion of the foreshore leave the backshore area accessible to wave and current action.

29. It also seems likely that heavy mineral enrichment by wind depletion of the lighter minerals is a much more important process on the normally dry backshore than on the usually damp foreshore sand. Many of the thin heavy mineral crusts that occur on the backshore may be the result of this process.

Heavy Mineral Distribution

30. The non-uniform distribution of heavy mineral species in the beach deposits of the study area appear to be related to differences in those characteristics of the individual mineral species that influence their response to the processes of erosion, transport, and deposition. The main characteristics appear to be specific gravity, shape, and size. These factors cause some minerals to be more susceptible than others to entrainment and transport under a given set of hydraulic conditions. As a consequence, selective sorting of the individual particles takes place whenever sediment is eroded and transported from one locale to another.

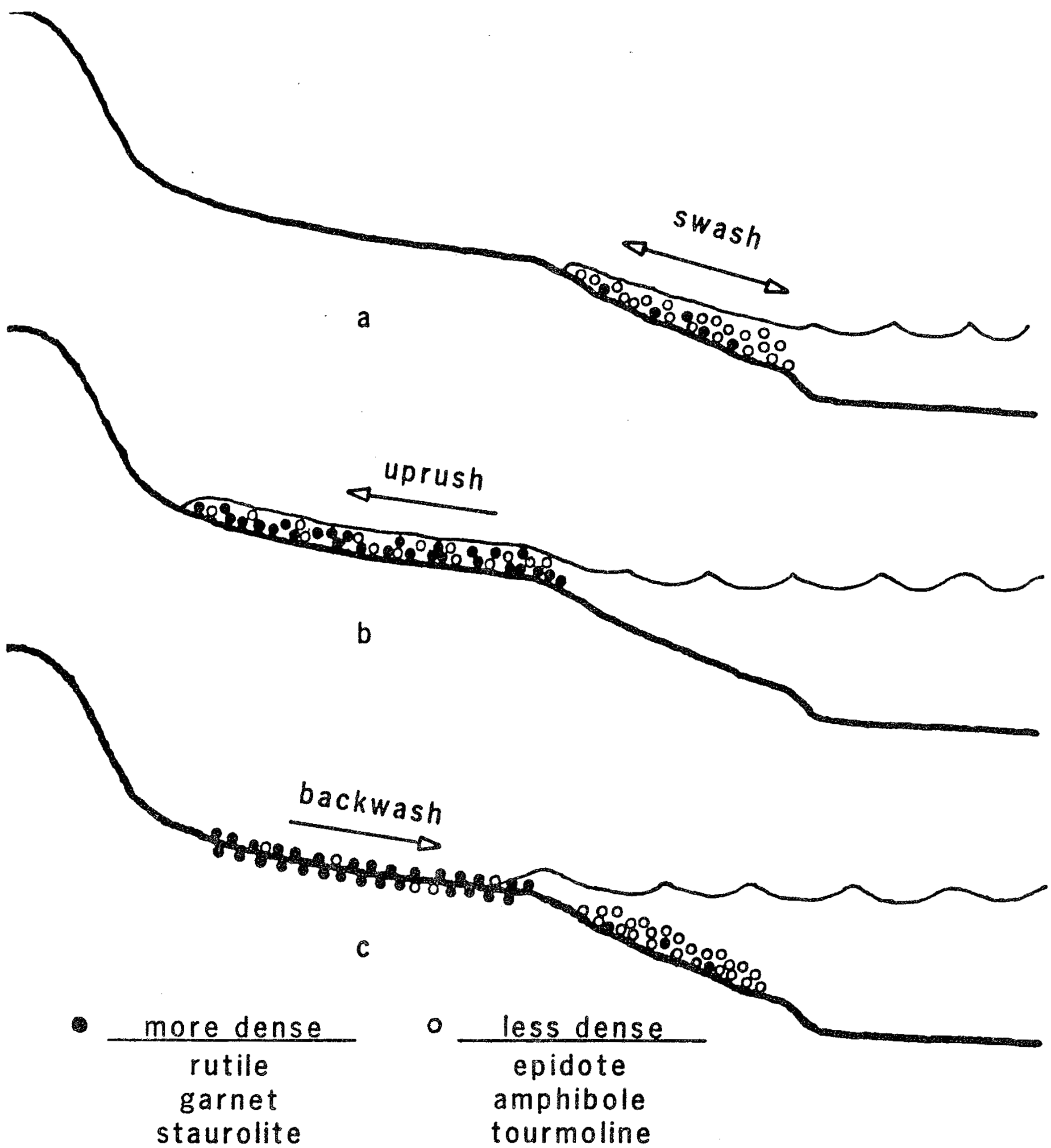

Figure 9. Sketch illustrating the processes of selective sorting of minerals of different specific gravity in beach deposits: (a) fair weather conditions, less dense mineral species predominant, deposition only on foreshore; (b) storm conditions, uprush phase: denser minerals much more numerous, waves reach backshore zone; (c) storm conditions, backrush many of less dense minerals winnowed and carried back down the beach leaving backshore deposits enriched in denser heavy minerals

31. Studies such as those of Rubey (1933) and Rittenhouse (1943) have shown that relatively small differences in specific gravity between two minerals of identical size and shape can, during the process of erosion and transportation greatly alter their hydraulic response. The specific gravity ranges of heavy minerals considered in this study are shown in Figure 10. The data presented here strongly suggest that the frequency distribution of minerals species along the beach transects is considerably influenced by difference in their specific gravity. Evidence for this is presented in Tables 4 and 5.

Table 4

Percentage of Samples with Specified Minerals More Numerous in Backshore Samples than in Upper Swash Samples of Same Transect

Mineral Species	Av. Sp. Gr.	Percentage
rutile	4.2	91.4
garnet	3.9	81.3
staurolite	3.7	78.2
epidote	3.4	61.8
amphibole	3.2	10.2
tourmaline	3.1	38.9

Table 5

Cumulative Percentage of all Backshore Samples with Specified Mineral Species More Abundant than in the Corresponding Upper Swash Samples by Factors of 2.0, 3.0, 4.0, and 5.0

		Cumulative Percent Greater			
Mineral Species	Av. Sp. gr.	2.0	3.0	4.0	5.0
rutile	4.2	82.5	58.2	48.7	39.9
garnet	3.9	70.0	40.0	30.0	30.0
staurolite	3.7	46.2	21.3	11.5	6.9
epidote	3.4	33.0	16.2	10.3	5.9
amphibole	3.2	18.2	0	0	0
tourmaline	3.1	29.6	12.3	1.2	0

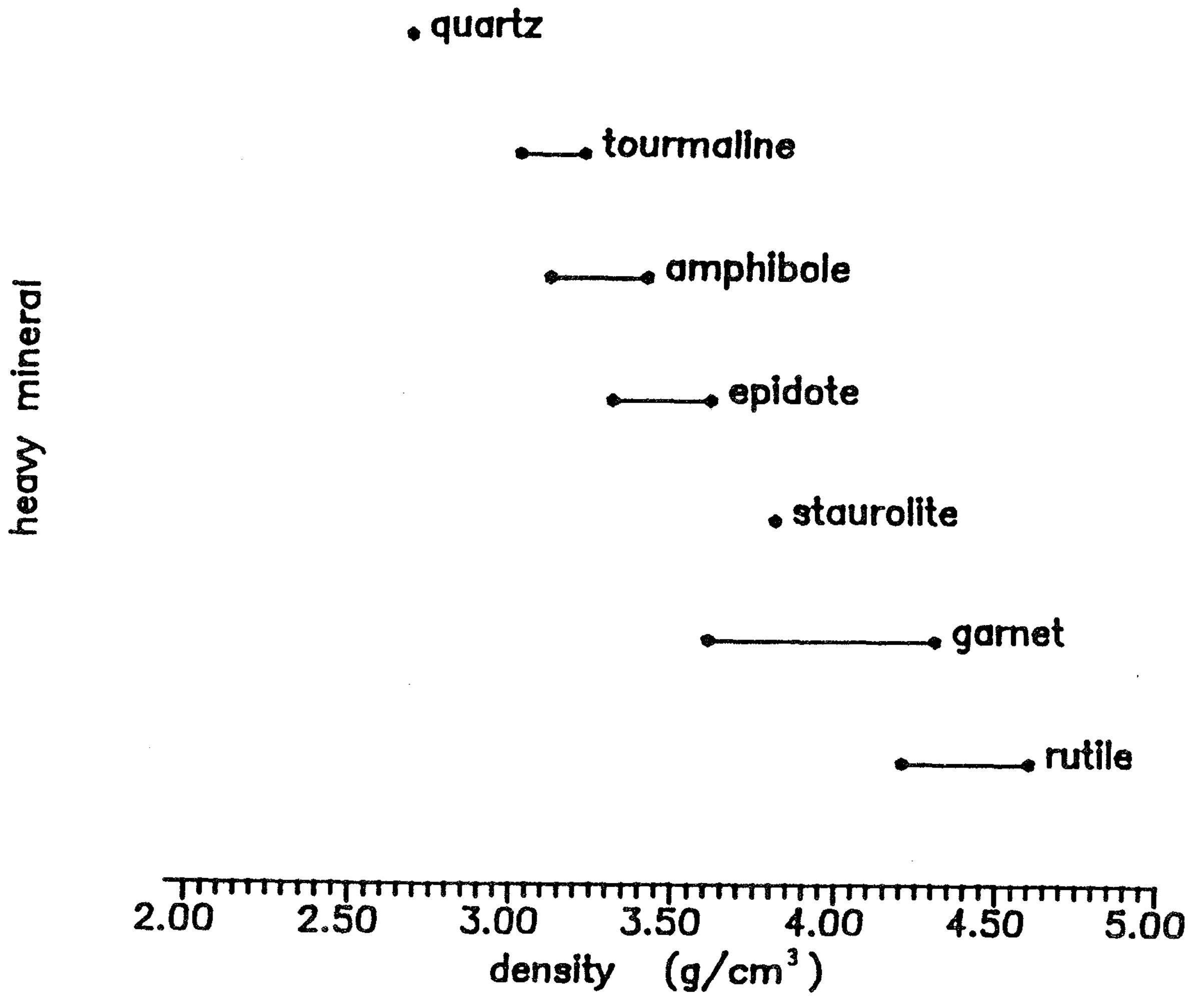

Figure 10. Approximate specific gravity ranges for mineral species considered in this report

32. Table 4 shows for each mineral species the percentage frequency of all backshore samples (i.e. heavy concentrate, dune base; mid-berm and berm crest) that contain a larger amount of a specified mineral than the upper swash sample from the same transect. If specific gravity is a factor this should be manifested by correspondence between the frequency and the specific gravity of each mineral species such that minerals of relative high specific gravity are more dominant in the backshore samples than minerals of lower specific gravity. Table 4 shows that this pattern is essentially followed. Rutile which has the highest specific gravity has the highest frequency; 91.4 percent of all backshore samples contain more rutile than is found in the uprush sample on the same transect and, with the exception of amphibole, there is a progressive decrease in frequency on the backshore with decreasing specific gravity.

33. Table 5 shows data on the magnitude of differences in abundance of heavy mineral species between the average value of the four backshore samples and the upper swash sample from the same transect. The data are in the form of cumulative percentages of the number of samples in which the abundance of a heavy mineral species is greater in the backshore samples than in the upper swash sample by a factor of more than 2, 3, 4, or 5. The data show that with the exception of amphibole there is a progressive decrease in the number of samples with differences factors of 2 or more with decreasing specific gravity. Tables 4 and 5 suggest that specific gravity is an important factor in the variations that occur in mineral species distribution on beaches of the study area.

34. The anomalous values for amphibole in Tables 4 and 5 are apparently caused by some factor other than specific gravity. Size differences do not seem to be responsible; all the heavy minerals examined were in the 0.125 - 0.250 mm size range and it does not appear from observation under a microscope that amphiboles were restricted to one part of the range. A more likely factor is the differences in shape between the amphibole grains which tend to occur in flattened tabular or bladed form and the more-or-less equidimensional shape of the other minerals.

35. Opinions in the literature on the effects of shape in the erosion and transportations of heavy minerals vary. For example Neiheisel (1965) considered the shape of hornblende particles created a hydraulic response exceeded probably only by mica in susceptibility to erosion and transport.

Rittenhouse (1943) surmised that the flatness of mica and perhaps blue-green hornblende were sufficient to make their settling velocities less than expected by their specific gravities. Other investigators have reached different conclusions. Hand (1967) found that garnet and hornblende from New Jersey settled with the same velocity and concluded that shape difference were of little importance. Rubey (1933) believed that except for micaceous minerals, the effects of shape were minor. Stapor (1973) observed that staurolite grains and flattened kyanite grains from the Gulf Coast were in settling equivalence reflecting a minimum effect of shape. Other studies such as those of Lowright et al. (1972) and Slingerland (1977) have shown that settling equivalence between two minerals does not necessarily mean that they will respond to selective sorting processes in identical ways. Differential entrainment and transport along with size availability may have a decided effect.

36. The magnitude of the anomalous values for amphibole as compared to minerals of such closely related and bracketing specific gravities as tourmaline and epidote (Tables 4 and 5) is not adequately explained by specific gravity alone. It seems most likely, that differential entrainment and transport of amphiboles due to their unique shape is an important element in their distribution relative to other heavy mineral of similar specific gravity. Amphibole grains clearly respond to hydraulic processes as if they had a specific gravity substantially lower than tourmaline which has the lowest actual specific gravity of the group considered here. Presumably such other characteristically flattened mineral species in the study area such as sillimanite and kyanite, would be affected in like manner; however, none of these species are present in sufficient quantity for study.

Sample Collection

37. The data presented here indicates that in field sampling of beach sediments a number of samples collected along a shore normal transect at each site yield considerably more information on heavy mineral distribution than a single sample collected from any given point along the profile. At a minimum, a sample from one station on the backshore and one on the foreshore, are needed to show the approximate range of mineral frequencies at a given site.

38. Of the backshore stations used in this investigation the dune base samples are the most useful because they usually provides a good crop of heavy minerals and the distribution is more consistent, barring any source changes, from site to site. The berm crest sample is least consistent, probably because of is marginal location between th backshore and foreshore zones. The heavy mineral concentrate, though of value, is limited by the fact that concentrated heavy mineral deposits are sporadic in occurrence and it is usually not possible to collect a set covering all sites sampled.

39. In the foreshore zone the upper swash and step samples in most cases have a similar heavy mineral distribution. Neither station provides many heavy minerals compared to backshore stations but the uprush sample is likely to yield the larger amount. Since at high tide the uprush and high water stations may be more-or-less coincident, sample collection during high tide stages should be avoided if possible.

Interpretation of Data

40. From the data presented in this study, it is apparent that epidote and tourmaline are not affected as much by selective sorting than the other minerals of the suite. The reason for this is not clear but seems to be related to their low specific gravity. This is suggested by the data in Figures 4-8 which indicate that differences in the frequency of a given mineral species between the various backshore samples and the corresponding upper swash sample tend to decrease progressively with decreasing specific gravity.

41. The fact that some mineral species are likely to be more evenly distributed between transect sample stations than others has implications for interpretation of heavy mineral data. In terms of the minerals considered in this study, coastwise changes in the frequency of epidote and tourmaline between common stations of a series of transect sites are more apt to be source related than changes of a similar magnitude in the other mineral species. It is not known if a similar relationship would be found in a difference suite of heavy minerals. If such a relationship exists it could be established by comparative analyses between transect stations in the area of study.

42. Another factor that may be of value in evaluating whether or not a lateral change in heavy mineral frequency distribution is source related or the result of selective sorting processes is the characteristic pattern of frequency changes that occur as a result of the selective sorting processes. This is illustrated by Table 6 which compares the upper swash and corresponding dune base samples from a series of sites on the south Florida Atlantic coast. It seems reasonable to assume that differences shown in heavy mineral frequency between the two closely positioned transect stations at any given site are not source related but must be the result of selective sorting processes. In general the comparison indicates that the relative changes between the two stations are characterized by an increase of denser heavy minerals accompanied by a decrease of less dense minerals in the dune base samples and the reverse of this in the comparatively low energy upper swash samples. Any departure from this general pattern would suggest possible changes in the immediate source of the beach sediment.

43. Table 7 shows a likely example of a source related change in distribution pattern from a reach of shore on Onslow Bay, North Carolina. It can be readily noted on Table 7 that a significant change in the frequencies of staurolite, epidote and amphibole occur between sites 85-42 and 85-43. The increase of amphiboles and epidote and decrease in staurolite are consistent with the effects of selective sorting; however, garnet which is somewhat denser than staurolite, would also be expected to decrease significantly; however, actually shows a slight increase suggesting a possible increase in the availability of that mineral in the sources of supply. In this particular example other natural tracers including oolites and glauconite filled foraminifera tests also suggest the introduction of new elements in the sediment supply at site 85-43.

Table 6

Comparison of Percentage Frequency of Heavy Minerals in Dune Base and Upper Swash Samples of a Portion of the South Florida Atlantic Coast.

Site	Station	rutile	garnet	staurolite	epidote	amphibole	tourmaline
		Percent Frequency					
82-21	dune base	19.1	27.2	23.3	21.7	0.6	1.2
	upper swash	8.8	16.4	25.9	36.9	2.7	6.8
82-23*	dune base	10.8	11.3	24.9	32.8	4.0	12.9
	upper swash	4.7	4.1	17.6	40.6	11.2	20.0
82-24	dune base	14.2	11.5	23.9	34.9	4.1	5.1
	upper swash	4.4	8.7	14.9	46.7	8.7	13.4
82-26	dune base	23.1	19.6	22.8	24.3	0.7	1.1
	upper swash	1.2	3.7	14.8	44.4	16.5	15.6
82-27	dune base	7.8	23.2	15.9	38.2	2.1	8.2
	upper swash	0.7	4.9	15.3	46.4	13.9	27.8

* Missing sites have too few heavy minerals in the uprush sample for analysis

Table 7

Percent Frequency of Heavy Mineral Species on a Portion of the North Carolina Coast

Site	Station	rutile	garnet	staurolite	epidote	amphibole	tourmaline
		Percent Frequency					
85-39	dune base	3.2	8.5	61.4	12.7	0.6	12.3
84-26	dune base	0.4	15.8	67.0	7.7	0.4	7.7
85-40	dune base	3.9	18.4	59.0	7.0	0.0	4.3
84-27	dune base	0.7	17.8	54.9	12.0	0.4	11.3
85-41	dune base	1.8	12.2	59.0	11.3	1.4	13.5
85-42	dune base	1.2	14.7	54.0	15.5	2.4	11.1
85-43	dune base	1.1	18.9	26.7	24.1	12.2	15.6
85-44	dune base	0.4	13.0	30.2	18.7	21.2	14.8
84-29	dune base	2.1	19.6	37.9	17.1	12.1	9.6
85-45	dune base	1.1	24.4	32.1	19.6	11.4	9.2
85-46	dune base	0.2	13.6	24.1	25.6	21.4	14.0
84-32	dune base	0.3	11.9	28.3	28.3	19.8	11.2
avg loc	85-39 to 85-42	1.9	14.6	59.2	11.0	0.9	10.0
avg loc	85-43 to 84-32	0.9	16.9	29.9	22.2	16.4	12.4

PART IV: SUMMARY AND CONCLUSIONS

44. Heavy mineral abundance and frequency distribution in samples collected along shore normal beach transects were studied to determine if systematic differences in these factors existed between stations along the profile. Transect sample sets from sites along the Atlantic coast between Palm Beach, Florida and Kitty Hawk, North Carolina were collected and their heavy minerals were analyzed for the study. Up to six samples, two from the foreshore zone and four from the backshore zones, were obtained at each transect site. These samples were collected from common identifiable points along the profile.

45. The weight percent of heavy minerals in the samples was found to be consistently higher in samples from the backshore zone than in samples from the foreshore zone. These differences are large enough and sufficiently consistent to rule out chance variations as a cause. The probable cause is judged to be a consequence of the fact that backshore deposits are related to the more energetic storm processes while foreshore surficial deposits are, at most times, generated by weaker fair weather processes.

46. A comparison of the frequency of heavy mineral species between stations on the same transect shows that, in a large majority of cases, species having the higher specific gravities: rutile, garnet, and staurolite, are substantially more abundant in backshore than in foreshore deposits. The reverse is true of amphibole which occurs in much greater abundance on the foreshore. This appears to be due to its shape as well as lower specific gravity. Epidote and tourmaline are more equally divided between backshore and foreshore deposits and their quantitative differences between these zones is less. This suggests that, of the mineral suite considered, epidote and tourmaline are not as sensitive to selective sorting processes in the beach environment as the other minerals.

47. Comparison was made between the weight percent heavy mineral content of samples from the study area and the frequency of heavy mineral species in these samples. This comparison indicates that there is a tendency for the denser heavy minerals to be more numerous in those samples having the larger heavy mineral content.

48. Comparative analysis of the heavy mineral species distribution along beach transects indicate that a number of samples taken along cross-beach transects at each sampling site yield considerably more information on heavy mineral distribution than a single sample. At least two samples, one at a foreshore station and one at a backshore station, are needed to show the range of frequency values characteristic of the distribution at a given site.

49. Based on all mineral suites considered in this study, epidote and tourmaline seem less affected by selective sorting which suggests that substantial coastwise variations in these minerals may be indicative of source changes.

50. Enrichment of the denser heavy minerals in backshore as compared to foreshore deposits appears to be related to the influence of alternating storm and fair weather processes. During fair weather conditions, when only the foreshore zone is affected by incoming waves, proportionally fewer of the more dense heavy minerals are transported to the beach. During storms much greater numbers of the more dense heavy minerals are transported to the beach because of elevated water levels and higher wave runup, are deposited in the backshore zone. Further enrichment of the more dense minerals can be attributed to winnowing of the less dense minerals during the backrush phase.

51. Variations in heavy mineral distribution that result from selective sorting tend to follow a pattern in which an increase in the denser heavy minerals is matched by a decrease in minerals of lesser density when changes are due to an increase in process energy and the opposite effect resulting from a decrease in process energy. Coastwise variations in this pattern may also indicate source changes.

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