

THE HYDRAULIC SORTING OF LIGHT AND HEAVY MINERALS,
HEAVY-MINERAL CONCENTRATIONS, AND GRAIN SIZE

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ABSTRACT

The heavy-mineral fractions of twelve samples from Smith Island shoals and offshore of False Cape, on the inner continental shelf of Virginia, have been examined in an effort to characterize the relationship between grain size and heavy-mineral concentrations for these areas. The study is concerned primarily with the hydraulic sorting of minerals by size and density and the effect of this sorting on heavy-mineral concentrations. The distinctions among the overall concentration of a mineral, its concentration within a particular size fraction, and its abundance within that size fraction have, out of necessity, been emphasized.

Initial concentration of the heavy minerals was accomplished using a Humphreys spiral; this was followed by separation in a heavy liquid. The heavy-mineral fraction was then divided into 1/2-phi size fractions, and the minerals in each size fraction were identified. A computer spreadsheet program was used to calculate concentrations and grain-size distributions for each mineral.

The results show that amphibole, the pyroxenes, apatite, and, to some extent, garnet increase in overall concentration in the finer samples, probably as a result of abrasion. Staurolite, kyanite, sillimanite, and tourmaline have greater overall concentrations in the coarser samples; these minerals also tend to be coarser than the other heavy minerals and to be concentrated in the coarser size fractions within samples. The overall concentrations of both zircon and andalusite were found to be independent of sample grain size, even though zircon is finer than the other minerals and is concentrated in the finer fractions within samples. The results for magnetite/ilmenite, a major component of the heavy-mineral fraction, are inconclusive.

In order to determine which processes were largely responsible for the hydraulic sorting of these sediments, the relative grain sizes of the light and heavy minerals within samples were compared with those predicted for sediments in settling, entrainment, and dispersive equivalence, and for lag deposits enriched in heavy minerals. Hydraulic equivalence, for the sandy samples, appears to be a function of both settling and entrainment, with an increase in the relative effect of entrainment corresponding to an increase in the mean grain size of the sample. For the muddy samples, the effects of flocculation and cohesion apparently have altered the usual hydraulic-equivalence relationships.

In general, the patterns of overall concentration exhibited by the heavy minerals of this study depend largely upon the influence of source and the effects of transport. Local hydraulic processes do not seem to be working to concentrate these minerals, although they are responsible for determining the relative sizes of the various minerals within a deposit.

THE HYDRAULIC SORTING OF LIGHT AND HEAVY MINERALS,
HEAVY-MINERAL CONCENTRATIONS, AND GRAIN SIZE

INTRODUCTION

There has been some recent interest in the economic potential of the heavy minerals of Virginia's inner continental shelf. Berquist and Hobbs (1986, 1988a, 1988b; Berquist, 1990), in a major reconnaissance study of this area, have located several sites having high concentrations of the "economic minerals." This study examines samples from two of these sites, Smith Island shoals and False Cape, in more detail in order to determine the relationship between grain size and heavy-mineral concentrations for these areas.

Differences in grain-size distribution and in overall concentration among the minerals in a sedimentary deposit result from the complex interactions of a number of factors. These factors include both those which determine the "availability" of certain minerals and grain sizes and those which relate to the hydraulic sorting of grains by size, density, and shape (see Table 1). This study is concerned primarily with the hydraulic sorting of minerals by size and density and its effect on heavy-mineral concentrations, rather than with the differences in heavy-mineral availability which may result from variations in source. However, another influence upon heavy-mineral availability, abrasion, will be considered.

The processes involved in hydraulic sorting and their effects on

Table 1. Factors affecting grain-size distributions and concentrations of the minerals in a sedimentary deposit (compiled from: Rubey, 1933; Rittenhouse, 1943; Folk, 1980; and others).

- A. Factors affecting availability¹
 - 1. Source
 - a. Grain-size distribution
 - b. Relative abundance
 - 2. Differential weathering and abrasion
 - a. Chemical stability
 - b. Physical durability
 - c. Size
 - d. Mode of transport (bedload, suspended load)
 - e. Distance and/or duration of transport
 - B. Factors affecting hydraulic sorting
 - 1. Grain parameters
 - a. Size
 - b. Density
 - c. Shape
 - 2. Hydraulic parameters
 - a. Current velocity and variability
 - b. Rate of sediment supply
 - c. Type of deposition (e.g., gentle swash-zone sorting, rapid burial)
-

1. Rittenhouse (1943) used the term "availability" (either "absolute" or "relative") in referring to the amounts of the various minerals and grain sizes which are "available" to be deposited (i.e., carried in the stream load) at a given place and time.

the distribution of heavy minerals in sediments are inadequately understood. These processes include differential settling, entrainment, and transport of light and heavy minerals. Mackie (1923) discussed many of the effects of hydraulic sorting; for example, he observed that heavy minerals tend to be finer than the light minerals with which they were deposited, and that there is often, in fact, an inverse relationship between mineral density and grain size within a given deposit. Hydraulic sorting affects not only the size distributions of the various minerals, but may also affect their overall concentrations. For example, differential entrainment sometimes results in lag deposits which are highly concentrated in heavy minerals.

The concept of hydraulic equivalence, introduced by Rubey (1933) and defined more comprehensively by Rittenhouse (1943), is useful in dealing with the size-density relationships among the different minerals in a deposit. Rittenhouse stated that "whatever the hydraulic conditions may be that permit the deposition of a grain of particular physical properties, these conditions will also permit deposition of other grains [that have the same hydraulic equivalence]." Although many authors have used the term "hydraulic equivalence" to mean equivalence in settling velocity alone, in this paper, a broader meaning, one which encompasses not only deposition, but other processes as well, will be assumed. Thus, the term "settling equivalence" will be used for equivalence in settling velocity alone; "entrainment equivalence" for equivalence only in the

probability of entrainment; etc. These process-specific forms of equivalence are included within the broader scope of the term "hydraulic equivalence."

Objectives

This study was undertaken with the idea of examining both the overall concentrations of the various heavy-mineral species in deposits of differing grain size and their size distributions within those deposits, with some emphasis on the economic minerals. During the course of the study, however, it became clear that there was widespread misunderstanding of the possible effects of the method used in studying heavy minerals on the apparent relationships between overall heavy-mineral concentrations and sample grain size. An attempt will be made, therefore, both to demonstrate the potential for mis-interpretation, using examples from this study, and to define certain terms more clearly in order to avoid such misunderstanding in the future.

Initially, the samples to be studied were chosen from among the cores taken by Berquist and Hobbs (1988a, 1988b; Berquist et al., 1990) from Smith Island shoals, an area in which they found relatively high concentrations of the economic minerals. However, there seemed to be little variation in grain size among the samples taken from this area. Since variation in sample grain size was deemed a necessary

component of the study, another site, False Cape, was chosen in order to increase the range in grain size of the samples. Samples from the two sites were later compared to determine whether the difference in location, possibly reflecting differences in source, transport distance, or local hydrodynamic processes, affected the grain-size distributions of the heavy minerals.

In spite of these developments, however, the fundamental objectives of this study have not changed. These objectives are:

(1) to determine the relationship between the overall concentrations of each of the various heavy-mineral species and the grain size of the sample. For example, one might expect to find those minerals which are easily abraded, or perhaps those which have the highest densities, to have higher overall concentrations in the finer samples.

(2) to compare the grain sizes of light and heavy minerals within samples in an effort to relate the hydraulic sorting of these minerals to the processes responsible for this sorting. In other words, do the relative sizes of the light and heavy minerals correspond to those predicted for grains in settling or entrainment equivalence?

(3) to examine differences in the concentration of certain minerals among the various size fractions within samples.

LITERATURE REVIEW

Early Work---Settling Equivalence

One of the most significant early papers on heavy minerals was a descriptive paper by Mackie (1923) which outlined many of the processes affecting the distribution of heavy minerals in sediments and sedimentary rocks. Mackie observed that heavy minerals generally are finer and somewhat better rounded than the light minerals with which they are associated, and that the coarser heavy minerals are associated with the coarser lights. He mentioned the inverse relationship that often exists between mineral density and grain size, noting that the larger, lighter particles, because of their larger cross-section, would be moved by a weaker current than that required to move the smaller, denser grains. He also showed, through a simple experiment, the separation of grains by density, with grains of the lowest density (the light minerals) being carried the furthest by the flow. He described the concentration of heavy minerals in lag deposits, and explained the variation in relative abundances of the minerals in different areas of a deposit through variations in current strength. As will be seen, Mackie's observations have, in general, been verified through later studies.

In another fundamental paper on heavy-mineral distributions, Rubey (1933) explained, using a theoretical approach, why the heavy-mineral concentrations in certain sediment samples apparently depended upon the grain size of the sample, and not upon its source. He described a source rock consisting of 98% quartz, 1% tourmaline, and 1% magnetite, uniformly distributed by size, and assumed that the weathered grains were carried only a short distance before being deposited. Then, using Stokes' law to calculate the relative sizes of different minerals that have the same settling velocity, he determined the grain-size distributions of tourmaline and magnetite which would be expected for a deposit with a given quartz size distribution. Rubey showed that the heavy-mineral grains would be concentrated in the finer portions of the sample, with the magnetite (the denser mineral) somewhat finer than the tourmaline. Then, he repeated this procedure for both coarser and finer deposits, and compared the heavy-mineral size distributions of these deposits. He showed that, using the standard method of determining heavy-mineral concentrations by examining the heavy minerals from a single sieve fraction, there appeared to be a greater percentage of magnetite in the coarse-grained sample than in the fine, even though the actual amounts of magnetite and tourmaline were the same in all three samples. The implications of this observation and their significance for studies involving heavy minerals will be discussed elsewhere in this paper.

Rubey (1933) then examined the effects of the overall sorting on his theoretical size distributions, and concluded that, as expected,

the apparent differences in heavy-mineral concentrations among samples were somewhat smaller in poorly sorted samples. He also evaluated the effects of departures from Stokes' law. For grains larger than 1.5 mm. (about -0.5 phi), settling velocity varies as the square root (rather than the square) of the grain diameter. This results in an even greater difference in the grain sizes of light and heavy minerals of a given settling velocity, in other words, in relatively finer heavy minerals. For grains of intermediate size (between 0.2 and 1.5 mm., or about 2.25 and -0.5 phi), the size distributions of the heavy minerals become better sorted than that of the lights (Rubey, 1933). Rubey also discussed the effects of abrasion, the size distributions of minerals in the source, and other factors.

Abrasion, unlike hydraulic sorting by itself, alters the actual amounts of various minerals in a given deposit. Since abrasion increases the number of small grains of a mineral, and is more effective with the heavier and "softer" minerals, it increases the actual abundance of these minerals in fine-grained deposits. Abrasion depends, in part, upon the distance traveled and the mode of transport. Whereas hydraulic sorting of heavy minerals increases their apparent concentration (using a single sieve fraction to determine mineral percentages) in coarse-grained samples, abrasion increases the actual concentration of heavy minerals in fine-grained samples (Rubey, 1933).

Rittenhouse (1943) introduced the method of using "hydraulic ratios" instead of weight percentages for comparing the heavy-mineral

compositions of different samples. The hydraulic ratio is the weight of a mineral in a particular size class (times 100) relative to the weight of the light minerals, not in the same size class, but in the hydraulically equivalent size class. Hydraulic-equivalent size must be determined empirically for each mineral. The method is an attempt to eliminate or compensate for the effects of varying hydraulic conditions, so that questions of (for example) source or stratigraphic correlation can be addressed (Rittenhouse, 1943). However, the determination of hydraulic-equivalent sizes by Rittenhouse's method is time consuming, and is not even possible unless other sources of variation in heavy-mineral composition can be eliminated for some group of samples. Hydraulic equivalence depends upon both the density and the shape of the minerals, and so may be different in different sedimentary systems, where the varieties of certain minerals, the history of mechanical wear, etc., may also differ. Finally, hydraulic equivalence often is not a function of settling velocity alone, as Rubey (1933) and Rittenhouse assumed. Rittenhouse, in fact, mentioned some possible effects of selective entrainment and differing modes of transport, but he never specifically related these to hydraulic equivalence.

Entrainment Equivalence and Selective Entrainment

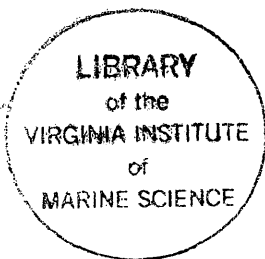
Early work on hydraulic equivalence considered only the effects of settling velocity on the selective size sorting of the various minerals. Later studies indicated that settling equivalence alone could not accurately account for the actual differences found in the size distributions of light and heavy minerals. In some samples, the heavy minerals were found to be slightly finer than expected under settling equivalence; in others, they were coarser, nearly equal in size to the lights. One explanation given for this apparent hydraulic inequivalence has been an inferred deficiency of certain grain sizes in the sediment source (e.g., see Rittenhouse, 1943, McIntyre, 1959, and Briggs, 1965). However, these size relationships have also been explained in terms of the process of entrainment.

Hand (1967) pointed out that in a deposit consisting of grains of equal settling velocity, the heavy minerals would be smaller than the light minerals. These smaller grains would be sheltered from the flow by the larger grains, and so would be less easily re-entrained. In order for the heavy minerals to be truly equivalent to the lights, it would be necessary to decrease further the grain size of the heavy minerals. With only a small decrease in size, the sheltering of the heavies would not change appreciably, but the "ratio of fluid drag to grain mass" would increase considerably, making entrainment more likely (Hand, 1967). Entrainment equivalence occurs when the light and heavy minerals in a deposit are equally likely to be entrained.

McIntyre (1959), Briggs (1965), and White and Williams (1967) also studied examples of this type of deposit, where the heavy minerals are slightly finer than settling equivalence alone would make them.

"Modal separation," as defined by Briggs (1965), is the difference in phi units between the modes of the light- and heavy-mineral grain-size distributions. An increase in modal separation (or in similar measures) with an increase in sample grain size was noted by Briggs, Hand (1967), and White and Williams (1967). Briggs attributed this to a restricted upper size range for the heavies (i.e., coarser heavies were unavailable to be deposited). White and Williams, however, found that the increase in modal separation occurred along with an increase in the percentage of deposition which took place by traction. When deposition is from suspension alone, light and heavy minerals should be in settling equivalence. But deposition from traction involves re-entrainment of sediment, resulting, as described above, in a decrease in the size of the heavies, and therefore, in an increase in the modal separation.

McIntyre (1959) used selective entrainment to account for heavy minerals that were larger than would be expected by settling equivalence alone. He suggested that the reworking of the sediment had resulted in the differential removal of the larger quartz grains, leaving behind a lag deposit of smaller quartz grains and heavy minerals. Komar and Wang (1984) have argued that the larger grains in a bed of mixed sizes will be more easily entrained because the pivoting angle of these grains is smaller, so they are more easily



rotated out of position. The larger grains will also be more exposed to the flow, subjecting them to greater lift and drag (Reid and Frostick, 1985). In addition to these size-related effects, the higher density of the heavy minerals will contribute to the preferential entrainment of the lights. Whereas the processes involved in hydraulic sorting do not necessarily result in a change in the overall concentration of the heavy minerals in a given deposit, but only in their grain size, this selective removal of the larger grains can play a significant role in the actual concentration of heavy minerals and the formation of placer deposits (Komar and Wang, 1984).

Does the process of entrainment, then, lead to the association of light and heavy minerals that are hydraulically equivalent, or does it create lag deposits of nearly equal-sized grains? According to Slingerland (1977), the relative grain sizes of the light and heavy minerals in a deposit depends both upon the boundary Reynolds number (R_* , an expression of flow conditions near the boundary) and upon the heavy-mineral grain size relative to the bottom roughness (the grain size of the established bed). When the available heavy-mineral grains are smaller than the bottom roughness, a smooth turbulent flow ($R_* < 5$) will allow deposited grains to be in settling equivalence, whereas a rough turbulent flow ($R_* > 70$) will produce a deposit containing heavy minerals finer than those in settling equivalence, representing entrainment equivalence. When the grain size of the available heavy

minerals is about equal to the size of the roughness elements and the flow is smooth, a deposit of nearly uniform grain size, enriched in heavy minerals, will result (Slingerland, 1977).

Heavy-Mineral Concentration in Coarse-Grained Deposits

The preferential entrainment of the larger grains from a bed of mixed sizes applies to deposits of fine to medium sand. However, for deposits of medium sand to gravel, it is the larger particles that are the more difficult to entrain. This is because the smaller grains are no longer immersed within the viscous sublayer of the boundary-layer flow (Komar, 1987), and therefore are no longer sheltered from the full effects of the turbulence.

Reid and Frostick (1985) have suggested that the trapping of heavy minerals in the pore spaces of coarse-grained deposits ("interstice trapping") may be an important mechanism leading to the formation of placers. Such trapping may occur when a fine-grained matrix filters into the pore spaces of a gravel laid down during conditions of extreme flow. They argue that a fining-upwards sequence of gravel allows the accumulation of fine-grained heavy minerals throughout the gravel layer, whereas a coarsening-upwards sequence may permit larger particles to clog the upper part of the gravel layer, leaving the pore spaces in the lower part of the layer unfilled.

Thus, more extensive concentrations of heavy minerals in coarse-grained deposits should be associated with fining-upwards sequences.

Selection in Transport

Differential transport of light and heavy minerals is the result of the combined effects of selective entrainment, the various velocities of the grains in motion, the different settling velocities of grains in suspension, and the mode of transport. Steidtmann (1982) concluded from flume experiments of bedload transport that larger grains have higher transport velocities than smaller grains of the same density. He also found that, where grain motion is intermittent, light-mineral grains have higher transport velocities than heavy-mineral grains of the same size. This is because the heavy minerals both are harder to entrain and tend to stop or settle to the bottom more quickly than the light minerals. These inertial effects, however, are unimportant when the grains are under continuous motion, since no acceleration of the grains occurs, and light and heavy minerals travel at the same speed. The style of grain motion seems to be a function of both the shear velocity and the grain size relative to the size of the roughness elements (Steidtmann, 1982). In addition, Steidtmann found that, whereas the transport velocities of the various grains appeared to be related to their sorting during transport over a plane bed, sorting during ripple-bed transport

depended more upon the deposition and recycling of grains on and through the bedforms.

Both Komar and Wang (1984) and Slingerland (1984) have used Einstein's (1950, 1964) bedload equation to evaluate the relative transport rates of light and heavy minerals. This equation, which was formulated to provide rates of sediment transport in stream channels (and, therefore, does not consider wave motion), includes a correction factor to account for the sheltering of small grains among larger grains or in the viscous sublayer of the boundary-layer flow. For transport at a low flow stress, Komar and Wang found quartz to have the highest transport rate of the minerals in their placer sample, with progressively lower rates for the various heavy minerals as they increased in density and decreased in size. These results agree with the findings of Steidtmann (1982) cited above. Slingerland concluded from his calculations that transport rates decrease with increasing bottom roughness, and that the relative concentration of heavy minerals, as well as the relative grain sizes of light and heavy minerals, in the transported sediment depend upon both the shear velocity (or that portion of it which affects the grains) and the roughness (compare Slingerland, 1977, summarized above, noting that the boundary Reynolds number incorporates the shear velocity).

Slingerland (1984) pointed out that grains of different settling velocities traveling in suspension would tend to be carried at different elevations in a turbulent, open-channel flow. If one part of the flow is later separated from the main flow, and its load

deposited, the deposit may be relatively enriched or impoverished in heavy minerals. This process has been called "suspension sorting" (Slingerland, 1984).

Dispersive Equivalence

In his analysis of inertial grain flows, Bagnold (1954) reasoned that a dispersive pressure should exist normal to the direction of shear, due to collisions between the grains. In other words, as one layer passes over another during the process of shearing, collisions between grains from the different layers result in a repulsive force between the layers, supporting the grains against the force of gravity. Although he experimented using only grains of uniform size and density, Bagnold further suggested that this dispersive pressure, which is proportional both to the square of the grain diameter and to the square of the shear stress, would cause the larger grains to move towards the area of lowest shear stress (i.e., toward the free surface) in a bed of mixed sizes. Sallenger (1979) extended this concept to beds of mixed size and density. Assuming the rate of shear and other variables to be constant along any one horizon of the flow, he used Bagnold's equation for dispersive pressure to calculate the size of a heavy-mineral grain which should be associated with a light grain of a given size, calling this the "dispersive-equivalent size" of the heavy mineral.

It is important to note that the concept of dispersive equivalence, as developed by Sallenger (1979), pertains to the size relationships of the light and heavy minerals within a single horizon of an inversely graded deposit, a horizon of approximately one grain diameter in thickness. Sallenger used this concept to explain the size relationships found in several beach foreshore deposits, including those sampled by McIntyre (1959) and Slingerland (1977). He suggested that these deposits were formed by grain flow and that sorting by dispersive pressure, and not by selective entrainment, determined the relative sizes of the light and heavy minerals therein.

Komar and Wang (1984) have described how the sorting of grains into different horizons by dispersive pressure during the process of shearing, or "shear sorting," could contribute to the formation of a placer. They pointed out that the shearing of beach sand by the swash of the waves would concentrate the heavy minerals a few layers below the light minerals within a single lamination. If the light minerals were then carried offshore, and this process were repeated many times, a relatively thick layer of heavy minerals could accumulate (Komar and Wang, 1984). Thus, as Reid and Frostick (1985) also concluded, shear sorting plays a secondary role, if any, in placer formation, that of moving the larger, light minerals to the surface layers, where the preferential entrainment of these same minerals results in the formation of a lag deposit of heavy minerals.

Beach Placer Deposits---Mechanisms of Heavy-Mineral Concentration

May (1973) proposed a mechanism to explain the formation of the discrete laminations of heavy minerals that often are observed on beaches. He noted that the asymmetry of shoaling waves results in a greater maximum velocity under the wave crests (i.e., in the landward direction) than under the troughs (seaward). Under certain wave conditions, the larger, more easily entrained light minerals will be moved landward under the wave crests and seaward under the troughs (no net motion), while the smaller, less easily entrained heavy minerals are moved landward under the crests, but are unable to return seaward under the lower velocities associated with the troughs (net landward motion). This differential transport of light and heavy minerals leads to the concentration of heavy minerals on the beach. When conditions are such that all of the grains are transported together (higher velocities), or none are transported (low velocities), then there will be no separation of the heavy minerals from the lights.

Slingerland (1977) presented an analysis of the concentration of heavy minerals in the swash zone. He suggested that the coarser grains would be the first to be deposited on the beach face as velocity decreased, leaving the finer grains to be deposited in the upper swash zone. These upper swash-zone deposits would then consist of approximately equal-sized grains of light and heavy minerals, and would be relatively enriched in heavies. Any higher-than-usual swash would preferentially resuspend and remove the light minerals, further

concentrating the deposit. In addition, the exchange of sediments between the upper swash zone and the dunes would serve, first, to enrich the dunes, and second, by re-erosion of the dunes, to allow relatively thick deposits of heavy minerals to accumulate on the beach.

On the other hand, Stapor (1973) believed that the heavy minerals he studied were concentrated offshore, then transported to the beach face en masse, probably during periods of high wave energy. He suggested two concentrating processes, one leading to the removal of the coarser grains, the other, operating in the more sheltered environments, tending to remove the finer ones. His descriptions of these processes, however, are somewhat inadequate.

The beach placer studied by Komar and Wang (1984) is covered during the summer months with a typical quartz-feldspar beach sand, and exposed during the winter when higher wave energy causes large quantities of this sand to be transported offshore (compare Stapor, 1973, above). They believe that it is during this period of offshore sand transport that the processes which concentrate the heavy minerals are most active. Komar and Wang concluded that differential entrainment and transport rates both play a significant role in the formation of the placer, and that both size and density differences among the minerals contribute to the effectiveness of the sorting. Because the settling velocities of the minerals on the beach were found to be approximately equal, they also concluded that selective sorting according to settling velocity does not affect the formation

of the placer. However, if their settling velocities are equal, then minerals of higher density will also be smaller. Since selective entrainment and transport result from differences in size as well as in density, a condition of equal settling velocity actually favors the differential entrainment and transport of light and heavy minerals and, thus, the concentration of heavy minerals leading to the formation of a placer deposit.

GEOLOGICAL SETTING OF THE STUDY AREA

Samples from two locations on the inner continental shelf of Virginia, Smith Island shoals and False Cape, were included in this study (Fig. 1). The samples were taken in water depths of 25 to about 50 feet (Appendix A).

The history of the mid-Atlantic continental shelf has been one of marine transgression since the end of the last glacial period (the Wisconsin glaciation). Shideler et al. (1972), who studied the stratigraphy of the inner shelf south of Cape Henry, described the Holocene deposits there as a "discontinuous sand sheet," formed by erosion of the retreating coast. The underlying boundary with the Pleistocene is marked by an unconformity which "may represent ... both subaerial erosion during the late Wisconsinan regression and subsequent shoreface erosion during the following Holocene transgression". Beneath the unconformity are Pleistocene deposits of mud and fine sand (Shideler et al., 1972). Hobbs (1990a) extended this section shoreward somewhat to include the False Cape study area.

The ridge-and-swale topography which is exhibited at both the Smith Island and False Cape sites is characteristic of much of the mid-Atlantic shelf. There has been some debate concerning the origin of these ridges (see Duane and Stubblefield, 1988, for a brief summary

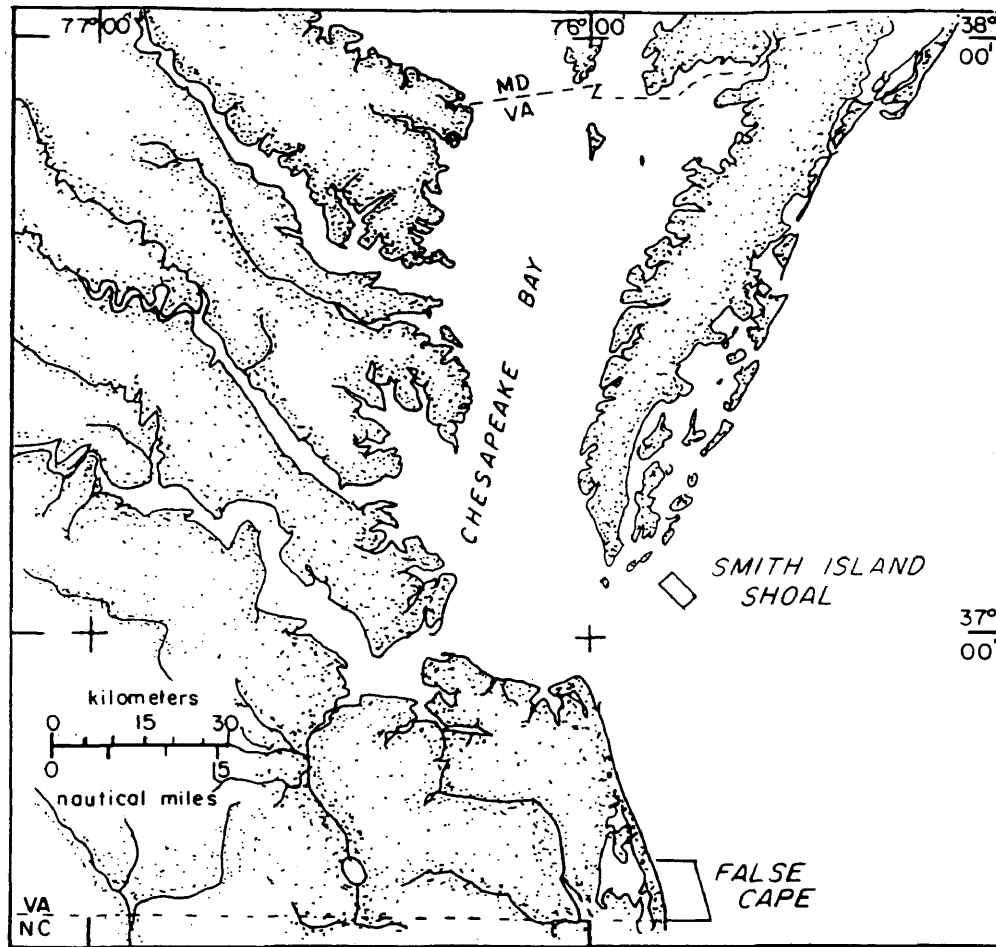


Fig. 1. Map showing the approximate locations of the Smith Island and False Cape study sites.

of the various hypotheses). Swift et al. (1972) studied the ridge system at False Cape and concluded that the ridges are both formed and maintained by the present hydraulic regime, and are not features inherited from the Pleistocene. Sediment grain size varies systematically with the topography (Swift et al., 1972), which apparently reflects the distribution of the Holocene sand sheet. In other words, the ridges consist of Holocene sediments; in the troughs, Pleistocene sediments are exposed or covered only by a thin lag deposit (Hobbs, 1990a).

Swift et al. (1972) found that fine sand is being transported southward through the ridge system at False Cape, whereas the coarser sand may be carried northward by longshore drift. Shoreward of the Smith Island site, longshore drift is toward the south and into the Chesapeake Bay (Colman et al., 1988). In a study of ridge-and-swale topography off the coast of Maryland, Swift and Field (1981) found that, in general, sediment transport within the ridge system occurs only during storms.

Recent studies of the heavy minerals at Smith Island shoals and False Cape have shown that there are some differences in mineralogy between the two areas, which suggests a difference in source (Hobbs, 1990a). The high percentage of zircon found in samples from False Cape is indicative of the reworking of older sediments (Calliari et al., 1990). Hobbs (1990b) has noted an apparent relationship between the locations of filled paleochannels on the Virginia shelf and areas

of possible economic interest for heavy minerals, which include both the Smith Island and False Cape study sites.

METHODS

The twelve samples used in this study were selected from the core samples taken during the heavy-minerals reconnaissance study of Berquist and Hobbs (1988a, 1988b; Berquist et al., 1990). The initial processing of these samples (i.e., through the tetrabromoethane separation) was accomplished in connection with their project, and is explained in detail by Grosz et al. (1990). A brief description is presented here.

Sample Preparation

The cores were obtained using a 9-cm.-diameter vibracorer. They were split lengthwise and logged, then divided into approximately 1 1/2-m.-long sections. Each section comprised one sample; only the top section of selected cores were chosen for this study. (A description of these samples may be found in Appendix A.) A channel sample was taken from each section to serve as an archive. Each sample was then taken to be weighed and sieved.

The samples were wet-sieved through a 2-mm. (-1 phi) screen to remove the gravel. Next, a partial separation of heavy minerals from

the light fraction was accomplished using a 3-turn Humphreys spiral. In this procedure, a sample is washed down the spiral in a continuous flow of water. The water is pushed by "centrifugal force" toward the outer rim of the spiral channel until a balance is achieved between the components of centrifugal force and gravity which are tangent to the channel cross-section (see Fig. 2). However, along the bottom boundary of the flow, the along-channel velocity is reduced by friction, and this decrease in velocity causes a decrease in centrifugal force. The net gravitational force moves the water in this layer toward the inside of the channel. The heavy minerals, which are carried along the bottom in the "bedload," are thus moved inward, while the lighter, less-dense grains are suspended and carried along the outside of the flow (Gleeson, 1945; see also Sivamohan and Forssberg, 1984). Within this broad separation of light minerals from the heavy, there is a further division which can be seen as color banding within the broader band of heavies. In addition, there are secondary separations of grains by size (coarser grains toward the outside; silt and clay in the "suspended load") and by shape (tabular grains moving outward), but the predominant effect is the separation according to density (Anonymous, n.d.). An adjustable splitter at the bottom end of the spiral funnels the light fraction into one bucket and the heavy-mineral concentrate into another. For this project, the splitter was placed so that some excess lights would end up in the heavy concentrate, but few heavies would be lost into the "spiral light" fraction. Several runs were made for each sample in order to

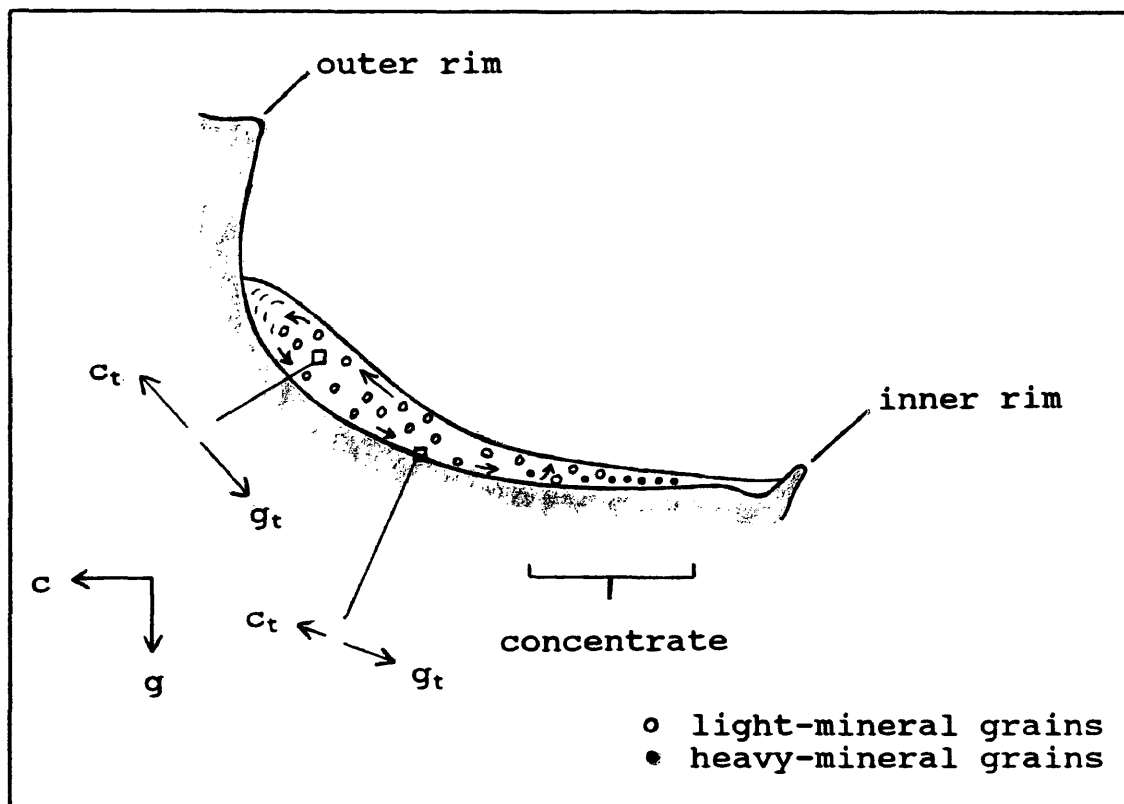


Fig. 2. Cross-section of the Humphreys spiral channel, showing the separation of light and heavy minerals. Directions of centrifugal force and gravity (c and g , respectively) and their tangential components (c_t and g_t) are shown. (The lengths of the arrows are suggestive of relative magnitudes, but are not to scale.) Other arrows indicate the direction of flow at various points in the channel (after Gleeson, 1945).

increase the effectiveness of the separation. During both the wet-sieving and spiral processes, most of the suspended silt and clay was washed down the drain.

A final separation of the heavy minerals from the light fraction was made from the spiral concentrate using tetrabromoethane (specific gravity: 2.96) and standard heavy-liquid separation techniques (gravity method; see Carver, 1971). After being washed with acetone, dried, and weighed, the "recovered heavy-mineral fraction" was split several times using a Jones splitter. Part of the fraction was saved as a repository sample.

The samples used in the present study were obtained by further splitting of the repository. These samples were sieved at 1/4-phi intervals by running a sieve shaker for 15 minutes. Then, after each size fraction was weighed, slides were made using Caedax (a synthetic Canada balsam, refractive index: 1.56) as the mounting medium. For two of the samples (H06-1 and H08-1), grain mounts were made for each 1/4-phi size fraction; for the others, neighboring 1/4-phi intervals were combined to create 1/2-phi size fractions. The terminology used in labeling the fractions was such that, for example, grains in the 3.5- to 4.0-phi size range would comprise the "4-phi fraction"; the "pan fraction" consisted of grains finer than 4.0 phi. The heavy minerals on each slide were identified as described in the following section.

A size analysis of the original (bulk) samples was also completed. For this procedure, about a 30-gram sample was taken from

each of the archived channel samples of the original core sections. These samples were wet-sieved through a 4-phi sieve, and the percent of fines (silt and clay) obtained through pipetting. The coarser fraction was dried, the gravel and sand sizes separated, and each weighed. A small portion of the sand was run through the Rapid Sediment Analyzer (RSA, a settling tube) and the rest was sieved at 1/4-phi intervals in the sieve shaker. Both procedures provide a size frequency distribution for the sand; the RSA data are quickly obtained and were used in choosing the samples to be studied, whereas the sieve data are more appropriately compared with the heavy-mineral size distribution obtained, likewise, through sieving.

Mineral Identification

The minerals were identified under a petrographic microscope using the line method of point counting (see Galehouse, 1971). A minimum of 300 heavy-mineral grains were counted from each slide. Identification of the grains was based on both their aspect, or general appearance as seen through the microscope, and on their optical properties. The aspect of a grain includes its color, shape, relief, and surface texture. The optical properties which contributed to the identification of the transparent minerals are pleochroism, extinction and extinction angle, birefringence, and sign of elongation.

Color is variable for many minerals, but is readily observed, and is particularly useful in differentiating among the opaques. Shape depends upon the crystal form and cleavage of the mineral and, to some extent, the degree of weathering of the grain. Several minerals have characteristic shapes; for example, hornblende typically has an elongate form. Relief is a distinguishing characteristic for certain minerals, especially when used in combination with other attributes. The surface texture of a grain, which may include its luster, is affected by the presence of inclusions and striations, and by weathering. Examples include zircon, which is distinguished in part by its high relief and adamantine luster, and sillimanite, a clear, finely striated mineral.

Pleochroism, the extinction angle, and the sign of elongation are frequently used when trying to differentiate between minerals. For example, hornblende generally is more pleochroic than augite and has a smaller extinction angle. Tourmaline exhibits inverse pleochroism and has parallel extinction, and so can be distinguished from hornblende. Hypersthene and andalusite have similar properties, but hypersthene has a positive elongation, whereas andalusite is negative. Birefringence, one of the most useful properties for mineral identification, depends upon both the grain thickness and its orientation. Whereas grain thickness is approximately equal for the grains on any one slide, especially in the finer fractions, it differs for those of different size fractions. (Other properties as well,

such as color and relief, also may vary somewhat with grain size.) This makes identification of some minerals more difficult.

The references which were relied upon most heavily for mineral identification are Parfenoff et al. (1970) for detailed descriptions, the chapter on heavy minerals in Lindholm (1987) for quick reference, and Shelley (1985) for general information on optical properties. Appendix B lists the main criteria used for identifying minerals in these samples.

Data Analysis

A computer spreadsheet program (20/20 by Arcus Technology, Inc.) was used to calculate the overall concentrations of the various heavy minerals. First, the mineral counts were weighted by the specific gravity of the mineral (Appendix C), and weight percents within each size fraction were calculated. (The volumes of the individual grains in a single size fraction were assumed to be approximately equal.) Then, using the total weight of the size fraction, the weight of each mineral in the fraction was calculated. The overall concentration of each mineral (as a percentage of the heavy minerals) was computed by adding together its weight in all the fractions and dividing this sum by the total weight of the heavy minerals.

The size distribution for each mineral was then calculated by dividing the weight of the mineral in each size fraction by its total weight in the sample.

The spreadsheet was also used to calculate the size distributions of both the light- and heavy-mineral fractions. The weight percent of each 1/4-phi fraction of the bulk sample was determined, first in terms of the sieved sand fraction alone, then as a percentage of the entire sample. Similarly, the weight percent was calculated for each size fraction of the heavy minerals, first as a percentage of the total heavies (this gives the heavy-mineral size distribution); then, using the weight percent of "total heavy minerals" in the sample (Appendix D; from Berquist and Hobbs, 1988b; also in Berquist *et al.*, 1990), in terms of the entire sample. By subtracting the weight percent of heavy minerals in each size fraction from that of the bulk sample (all percentages in terms of the entire sample), and dividing each fraction by the total weight of the lights, the size distribution of the light minerals was obtained.

In order to determine whether the size distribution of a heavy mineral depends upon the sample grain size, the location (Smith Island or False Cape), or the particular mineral in question, the SPSS-X Hiloglinear program was run. This program can be used to test the independence of discrete (or categorical) variables in a multi-dimensional contingency table (Norusis, 1988). The size distributions of the heavy minerals were described by their weight percents in six 1/2-phi size fractions, and sample grain size was divided into four

categories on the basis of the median grain size of the sample (Appendix D). Two tests were performed. One included only the False Cape samples, which range in size from medium sand (1.0 to 2.0 phi) to mud (>4.0 phi); the other included all of the samples in the size classes common to both localities, i.e., fine and very fine sand (2.0 to 4.0 phi).

Another spreadsheet program (Quattro Pro by Borland International, Inc.) was used primarily for graphing. First, the overall concentrations (for most of the heavy minerals) and concentrations within the 4.0-phi fraction (for some minerals) were plotted against sample mean grain size (as determined by the RSA). The correlation coefficient was calculated for each pair of variables (each graph), and tests of significance were performed. Under the null hypothesis that the population correlation coefficient was zero, critical values at the 5% and 1% levels of significance were determined (using Table Y of Rohlf and Sokal, 1969) and were used to evaluate the conclusions drawn from visual examination of the graphs.

Next, graphs of the mean grain sizes of garnet, magnetite/ilmenite, amphibole, sillimanite, and zircon vs. those of the light minerals were prepared. For this purpose, it was necessary to plot the cumulative frequency distributions for each mineral, including the lights, by hand in order to calculate their graphic mean grain sizes (see Folk, 1980). In addition, settling-, entrainment-, and dispersive-equivalent size relationships were determined and plotted on the graphs for each of these minerals, so that the actual and

predicted size relationships between the light and heavy minerals could be compared. Settling equivalence was calculated using an equation derived from Stokes' law, which is valid for grains finer than about 2.25 phi (Rubey, 1933). McIntyre's (1959) linear approximation to Rubey's fall-velocity curve was used for the coarser grains. An expression describing entrainment equivalence was derived from the Shields threshold criterion for entrainment. Assuming that the Shields criterion holds for the sediments studied here (see discussion below), then it can be used to calculate the relative diameters of two grains of differing density which are entrained together off the bottom. (It is interesting to note that the resulting expression is the same as that derived from the impact law to describe settling equivalence of grains coarser than about 0.0 phi (see McIntyre, 1959)). Dispersive equivalence was determined from the equation developed by Sallenger (1979). All of these expressions are listed in Table 2, in a form similar to that used by McIntyre. Stokes' law and the Shields threshold criterion for entrainment are given, for reference, in Table 3.

The cumulative frequency distributions mentioned above were also used to calculate the graphic standard deviations (see Folk, 1980) for those minerals which were plotted. The graphic standard deviation is used as a measure of sorting, and was used in conjunction with the verbal classification scale outlined by Folk (1980).

Finally, in order to examine the variation in concentration among the different size fractions within a sample, average concentration

Table 2. Equations used in calculating settling, entrainment, and dispersive equivalence (Rubey, 1933; McIntyre, 1959; Sallenger, 1979).

Settling Equivalence:

$$\phi_H = \frac{1}{2} \log_2 \left(\frac{\rho_H - \rho}{\rho_L - \rho} \right) + \phi_L \quad \text{for grains finer than 2.25 phi.}$$

$$\phi_H = \frac{1}{1.5} \log_2 \left(\frac{\rho_H - \rho}{\rho_L - \rho} \right) + \phi_L \quad \text{for grains between 2.25 and 0.0 phi.}$$

Entrainment Equivalence:

$$\phi_H = \log_2 \left(\frac{\rho_H - \rho}{\rho_L - \rho} \right) + \phi_L$$

Dispersive Equivalence:

$$\phi_H = \frac{1}{2} \log_2 \left(\frac{\rho_H}{\rho_L} \right) + \phi_L$$

ϕ_H, ϕ_L = grain size of heavy and light minerals, respectively, in phi units.

ρ_H, ρ_L = specific gravity of heavy and light minerals, respectively.

ρ = specific gravity of the fluid, assumed to be 1.00.

Table 3. Stokes' law and the Shields threshold criterion for entrainment, from which the equations for settling and entrainment equivalence (Table 2) were derived (Rubey, 1933; Miller et al., 1977).

Stokes' Law:

$$v = \frac{g}{18} \frac{(\rho_s - \rho)}{\mu} D^2$$

Shields Criterion (θ_t):

$$\theta_t = \frac{\tau}{(\rho_s - \rho)gD}$$

v = settling velocity in cm./sec.

D = grain diameter in cm.

ρ_s, ρ = density of the grains (sediment) and of the fluid, respectively, in g./cm.³

μ = viscosity of the fluid.

τ = shear stress of the fluid flow.

g = acceleration due to gravity in cm./sec.²

factors were calculated and plotted for several minerals, all of economic interest---magnetite/ilmenite, leucoxene, sillimanite, kyanite, and zircon. For each mineral, concentration factors were calculated by dividing the concentration of that mineral within each size fraction by its overall concentration in the sample. Concentration factors were used as a means of standardizing the individual fraction concentrations so that an average over all the samples could be obtained, in spite of the variation in overall concentration among samples.

Assumptions and Sources of Error

In a study such as this, which is concerned with a variety of physical processes, not all of which are well understood, and which entails a large amount of sample preparation, there are many potential sources of error. The discussion which follows outlines those attributable, at least in part, to the methods used and explains what attempts have been made to minimize the effects of those errors.

It is clear that in order to study hydraulic equivalence, the hydraulic conditions must not have changed appreciably over the sampling interval. However, the thickness of the sampling unit which is most relevant to studies of this kind has never been clearly established. McIntyre (1959), following some discussion of the subject, concluded that "the macrolaminae are the fundamental units"

to be sampled. Sallenger (1979) argued for a sampling thickness of approximately one grain diameter in deposits characterized by graded bedding. For the present study, the samples were taken from a single bed, deposited in a shallow-shelf environment. Thin layers or laminations within the bed, characterized by a change in grain size, represent only short-term variations in the flow. Neither the overall circulation patterns nor the sediment sources have changed over the time that the sections were being deposited (Hobbs, pers. comm., 1989). Although the samples comprise a broader interval than those advocated by McIntyre and Sallenger, it was felt that these more representative samples would be more appropriate to an understanding of the distribution of heavy minerals in the region, and would minimize the effects of small-scale variability and the risk of sampling an anomalous layer of sediment.

During the wet-sieving and spiral procedures, most of the suspended silt and clay present in the original samples was washed down the drain. Because the heavy minerals are less likely to be suspended and washed away than the lights, it is believed that few of the heavy minerals, especially in the silt size range, were lost. However, some of the concentrations determined for the "pan" (finer than 4.0 phi) fraction may be inaccurate, possibly biased toward the denser heavy minerals. In addition, some heavy minerals ended up in the "light" fraction during the spiral separation and so were not counted in the identification procedure; these appear to be mostly flakes of mica and pyrite (Fischler, pers. comm., 1988). In general,

spiral efficiency seems to be relatively poor (i.e., more heavy minerals are lost to the light fraction) when muddy or poorly sorted samples are processed (Grosz et al., 1990).

The samples used in this study were chosen from only the top sections of the available cores to help ensure that older sediments, which could have been deposited under different environmental conditions, were not being sampled. From the initial size analyses of the samples (using the RSA and pipette data), the median size class (medium sand, fine sand, very fine sand, or mud) was determined for each core section under consideration. Of the samples from False Cape, two from each size class were chosen for this study. All but one of the Smith Island samples fell into the fine- or very-fine-sand size class; two samples from each of these categories were selected from this area. This sampling design was chosen in order to make the best use of a limited number of samples, considering also the narrow range in grain size exhibited by the Smith Island samples. The classification of sample grain size used here was also used for the hierarchical log-linear tests of independence described above.

The identification of some minerals was made more difficult by the variation in birefringence, color, and relief that may occur with variation in grain size. For most minerals, it is unlikely that this significantly affected the results. However, the identification of epidote was almost certainly biased because its distinctive color (actually, a clear to greenish-yellow pleochroism), which was used as a major criterion for the identification of this mineral, often does

not appear in the finer grains. For this reason, epidote was excluded from any further analysis. Because epidote, when mis-identified, is most likely to be placed into the category of "other" (unknown) minerals, the percentages obtained for the other heavy minerals in this study are unlikely to have been affected by any bias in the identification of epidote.

In calculating the weight percents of the heavy minerals within each size fraction, the original grain counts were weighted by the specific gravity of the mineral (Appendix C). However, the variation in composition exhibited by some minerals (or, more precisely, mineral groups) results in a wide range in specific gravity. For these minerals, the specific gravity used in the calculations should be considered, at best, an approximation.

Different measures of overall sample grain size were used in this study for different purposes. The initial choice of samples, as noted above, was made according to the median grain-size class of the sample (given in Appendix D). This statistic was used because it was easy to obtain and took the entire sample, not just the sand fraction, into account. The relationships between the overall concentrations of the various minerals and sample grain size were evaluated using the mean grain size of the sand fraction of the samples (Appendix D). This is because the mean generally is considered to be the best measure of the overall size of the sediment (Folk, 1980); and only the size distribution of the sand fraction, not of the silt and clay, had been determined precisely. Finally, the graphic mean grain sizes of a

few selected minerals were determined by plotting their cumulative frequency distributions by hand, and extrapolating into the finer grain sizes when necessary. This was done in order to compare the grain sizes of the light and heavy minerals within samples; for this purpose, it was considered important to include the entire sample, even though this required some estimation of grain-size parameters.

The results of the hierarchical log-linear test of independence in which samples from both locations, Smith Island and False Cape, were included, indicate that the size distributions of the heavy minerals are not independent of location. However, the graphs that were plotted during the course of this investigation include all of the samples chosen for study, from both sites. Because the graphs showed no clustering of samples or variations in the overall trends which could be attributed to differences in location, it was assumed that the effect of location on the relationships between overall concentrations and sample mean grain size, for example, was minimal, and did not significantly affect the results of this study.

The correlation coefficient is an estimate of the interdependence of two variables, neither of which is determined in advance (or fixed) by the design of the study (Sokal and Rohlf, 1969). The two variables in this study are the overall concentration (or concentration within the 4.0-phi fraction) of a particular mineral and the sample mean grain size (as determined by the RSA, i.e., using only the sand fraction of the sample). Because the samples were chosen on the basis of their median grain-size class (determined using the entire sample),

sample mean grain size cannot be considered to be a completely random variable. However, since this variable was not predetermined, correlation, and not regression, analysis was considered the appropriate statistical procedure for use with the data (see discussion in Sokal and Rohlf, 1969). The significance tests used for the correlation coefficients assume a bivariate normal distribution (Sokal and Rohlf, 1969), which is probably a reasonable approximation in this case.

The Shields threshold criterion for entrainment was developed using non-cohesive, spherical grains of nearly uniform size, planar beds, and conditions of uniform, steady flow (Miller et al., 1977). Although these conditions do not apply, for the most part, to the sediments sampled at Smith Island and False Cape, the Shields criterion was used to give an indication, only, of the relative sizes of two grains of differing density which would be entrained together off the bottom. However, it should be understood that this use of the Shields criterion is not strictly justified.

RESULTS AND DISCUSSION

Abundance vs. Concentration

In his 1933 paper, Rubey concluded that the relative percentages of the minerals in a particular size fraction could depend upon either the grain size or the degree of sorting of the samples. This relationship between the mineral percentage and the sample grain size may be only an apparent one due to the hydraulic sorting of minerals within the sediment, or there may be actual differences among samples resulting from selective abrasion of certain minerals or from source differences. In either case, the examination of a single size fraction, as opposed to the entire sample, may lead to errors in interpretation (Rubey, 1933).

Although Rubey's (1933) paper has been cited frequently, his arguments concerning the effects of using a single size fraction for determining heavy-mineral concentrations have been widely misunderstood or ignored. Because some of the misunderstanding seems to stem from semantic confusion, it is appropriate to begin this discussion by defining a few terms. Following these definitions, an attempt will be made to provide further clarification of the problem, so that similar mistakes can be avoided in the future.

When considering a particular size fraction within a sample, the "abundance" of a mineral will refer to the weight of the mineral in that fraction relative to the total weight of the mineral in the sample. The size distribution of a mineral shows the abundance of the mineral in each size fraction. The mineral is most abundant in the fraction which contains the greatest amount (by weight) of that mineral.

In contrast, the "concentration" of a mineral in a given size fraction will be the weight of the mineral in that fraction relative to the total weight of the fraction. (In this particular study, the "fraction" includes only the heavy minerals in the fraction. Other studies may include the light minerals, or more commonly, may consider only the non-opaque heavy minerals.) When a slide is prepared from a single size fraction of a sample and the minerals on that slide are identified, the resulting mineral percentages are concentrations.

Note that these definitions have been limited to consideration of a particular size fraction. The "overall concentration" of a mineral in the sample is the total weight of the mineral in the sample relative to the total weight of the heavy minerals in the sample. It is generally the overall concentration which is of interest in stratigraphic correlation and studies of provenance involving heavy minerals.

Figure 3 may help clarify these definitions. In Figure 3A, the fine fraction has both a greater abundance and a greater concentration of the heavy minerals than does the coarse fraction. No confusion is

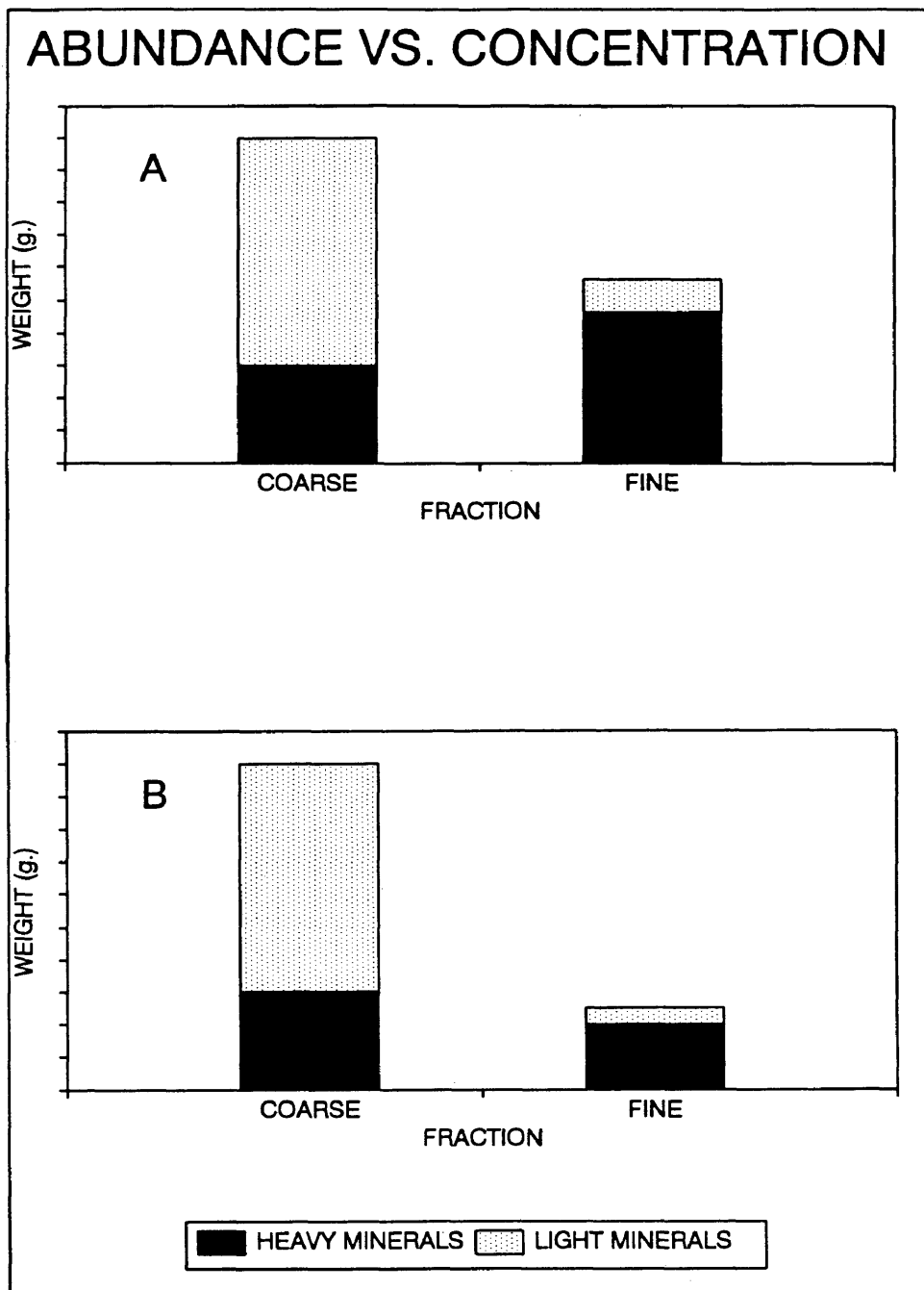


Fig. 3. Illustration of the concepts of abundance and concentration. In graph A, the heavy minerals (dark shading) increase in both abundance and concentration in the fine fraction (as compared to the coarse). In graph B, however, the heavy minerals decrease in abundance but increase in concentration in going from the coarse to the fine fraction.

possible here. In Figure 3B, although the abundance of both the light and heavy minerals is less in the fine fraction, the concentration of the heavy minerals is greater in this fraction. (The heavy minerals make up only 30% of the coarse fraction, but 80% of the fine.) As a further illustration, Figure 4A shows the size distribution of zircon for sample 34 (abundance data); Figure 4B shows zircon concentrations for the same sample.

This distinction can also be stated in another way. Consider the matrix of mineral weights shown in Table 4. Each column represents a different fraction, and each row a different mineral. Row-normalization, so that each row (mineral) sums to 100 percent, gives abundance data (Table 5). Column-normalization yields concentration data (Table 6).

Unfortunately, the differences among abundance, concentration, and overall concentration, as defined here, have not always been clearly understood. Hubbard (1977), for example, went to the trouble of obtaining the data necessary to calculate the size distributions of the heavy minerals for six of his samples. But he interpreted his data on mineral concentrations as if they were mineral abundances. He further chose to examine only a single size fraction from the remainder of his samples, making no attempt to correct for size dependencies in his data. Similarly, Briggs (1965) used the heavy mineral concentrations from a single size fraction for his provenance study, even though he had already determined the size distributions of the minerals and done some work on hydraulic equivalence. Trask and

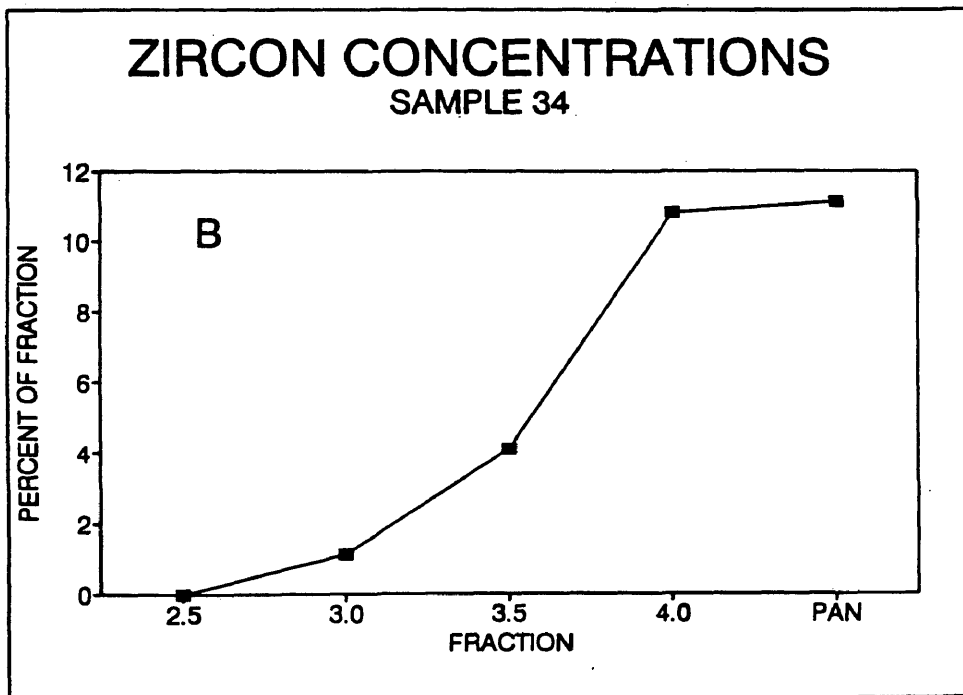
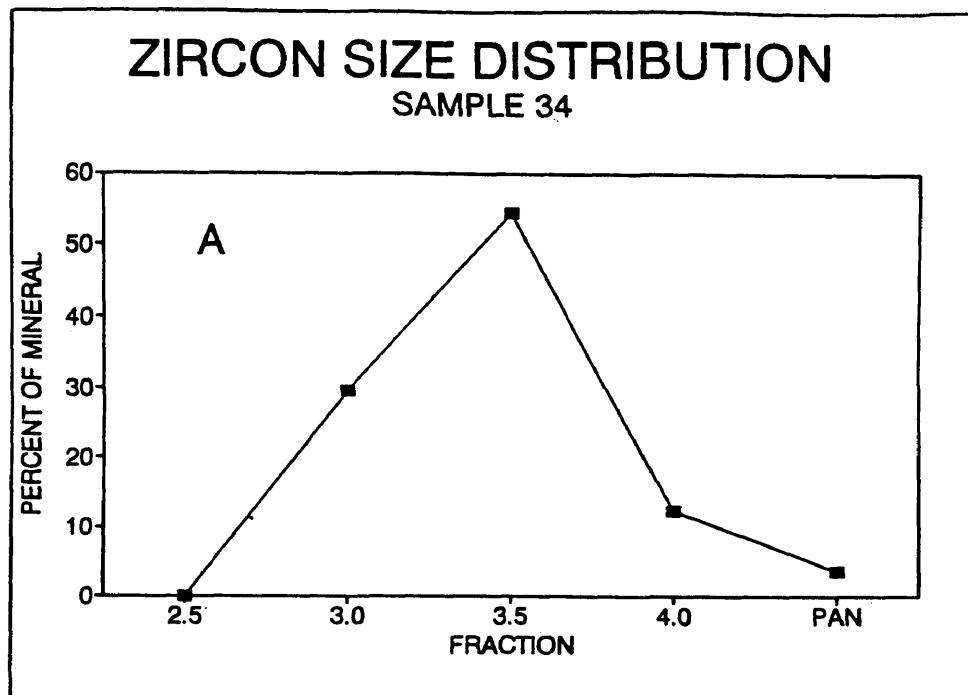


Fig. 4. Comparison of zircon abundances (graph A) and concentrations (graph B) for sample 34.

Table 4. Matrix of mineral weights (in grams) for sample H12, with the total fraction weights (final row) and total mineral weights (final column) added on. Normalization of this matrix by row gives mineral abundances (Table 5); column-normalization gives concentrations (Table 6). Overall concentrations may be found by normalization of the final column (total mineral weights).

SAMPLE H12	FRACTION					TOTAL
	2.5	3.0	3.5	4.0	Pan	
Magnetite/Ilmen	0.01	0.13	0.54	1.63	0.51	2.82
Leucoxene	0.00	0.03	0.04	0.01	0.00	0.08
Garnet	0.02	0.13	0.52	0.52	0.06	1.25
Epidote	0.00	0.02	0.10	0.01	0.00	0.13
Staurolite	0.00	0.01	0.01	0.00	0.00	0.02
Amphibole Grp	0.02	0.25	1.01	0.69	0.02	1.99
Augite/Diopside	0.00	0.03	0.16	0.06	0.00	0.25
Hypersth/Enstat	0.00	0.03	0.17	0.17	0.01	0.38
Apatite	0.00	0.01	0.07	0.06	0.00	0.14
Sillimanite	0.00	0.01	0.02	0.02	0.00	0.05
Kyanite	0.00	0.00	0.00	0.00	0.00	0.00
Andalusite	0.00	0.01	0.04	0.01	0.00	0.06
Rutile	0.00	0.00	0.02	0.03	0.01	0.06
Tourmaline	0.00	0.00	0.00	0.00	0.00	0.00
Zircon	0.00	0.01	0.06	0.13	0.13	0.33
Other	0.01	0.07	0.28	0.27	0.02	0.65
TOTAL	0.06	0.74	3.04	3.61	0.76	8.21

Table 5. Mineral abundances for sample H12 (in weight percent), obtained by row-normalization of the mineral weights given in Table 4. Each row of this matrix gives the size distribution for one of the heavy minerals.

SAMPLE H12	FRACTION					TOTAL
	2.5	3.0	3.5	4.0	Pan	
Magnetite/Ilmen	0.4	4.6	19.1	57.8	18.1	100.0
Leucoxene	0.0	37.5	50.0	12.5	0.0	100.0
Garnet	1.6	10.4	41.6	41.6	4.8	100.0
Epidote	0.0	15.4	76.9	7.7	0.0	100.0
Staurolite	0.0	50.0	50.0	0.0	0.0	100.0
Amphibole Grp	1.0	12.6	50.7	34.7	1.0	100.0
Augite/Diopside	0.0	12.0	64.0	24.0	0.0	100.0
Hypersth/Enstat	0.0	7.9	44.8	44.7	2.6	100.0
Apatite	0.0	7.1	50.0	42.9	0.0	100.0
Sillimanite	0.0	20.0	40.0	40.0	0.0	100.0
Kyanite	0.0	0.0	0.0	0.0	0.0	0.0
Andalusite	0.0	16.7	66.7	16.6	0.0	100.0
Rutile	0.0	0.0	33.3	50.0	16.7	100.0
Tourmaline	0.0	0.0	0.0	0.0	0.0	0.0
Zircon	0.0	3.0	18.2	39.4	39.4	100.0
Other	1.5	10.8	43.1	41.5	3.1	100.0
Total Heavy Minerals	0.7	9.0	37.0	44.0	9.3	100.0

Hand (1985) examined "trends in abundance ratios ... within a particular fall-velocity fraction," claiming that the overall grain size and sorting of the samples should not affect these ratios. However, this would be true only if the shapes of the distributions, and the sorting in particular, were the same for both the light and heavy minerals in a sample and if these minerals were also in settling equivalence.

Other authors have approached the problem of a relationship between mineral concentration and sample grain size by making scatter plots of these two variables. Firek et al. (1977) found, for the 3- to 4-phi fraction, that mineral percentages were "largely independent" of mean grain size for four of their minerals. Swift et al. (1971) and Kelling et al. (1975) found significant relationships between concentration and median grain size for several minerals, including amphibole and garnet, and used linear regression to account for and remove the effect of grain-size variations on mineral concentration. Swift et al. examined the 2.5- to 3.5-phi fraction; Kelling et al. used 1- to 4-phi. All three examined only a limited size range, using concentration data to approximate values of overall concentration. The trends in heavy-mineral concentrations that were found, except for the "anomalous behavior" of amphibole noted by Swift et al., all make sense in the context of Rubey's (1933) paper; they can be explained as apparent trends due only to hydraulic sorting. However, a trend (or the lack of one) in concentration within a given fraction does not necessarily reflect a similar trend in overall concentration. Figure

5 shows, for the 3.5- to 4.0-phi fraction, a trend of decreasing zircon concentration with a decrease in grain size, yet there is essentially no correlation between the overall concentration of zircon and sample grain size. Conversely, Figure 6 shows, for the same size fraction, little correlation between sillimanite concentration and sample grain size, but exhibits a clear trend in the overall concentration of sillimanite. It is clear that the relationship between the overall concentration of a mineral and the sample grain size cannot always be predicted from the concentration data for a limited size range.

As mentioned above, any relationship between the mineral concentration and the sample grain size may be an apparent one due to sorting, or there may be actual differences in overall mineral concentration among the samples (Rubey, 1933). An apparent relationship due to sorting alone should result in a relatively high correlation when the concentration for a single size fraction is plotted against the sample grain size, and in a low correlation when the overall concentration is used (e.g., see Fig. 5). However, actual differences among samples will show up in the overall concentration, and may or may not be reflected in the concentration for a single fraction (Fig. 6). Actual differences in overall mineral concentration may result from differential abrasion of the various minerals or from source differences. The effect of abrasion is to increase the overall concentration of the heavier and softer minerals in fine-grained deposits, opposing the effect of sorting for a given

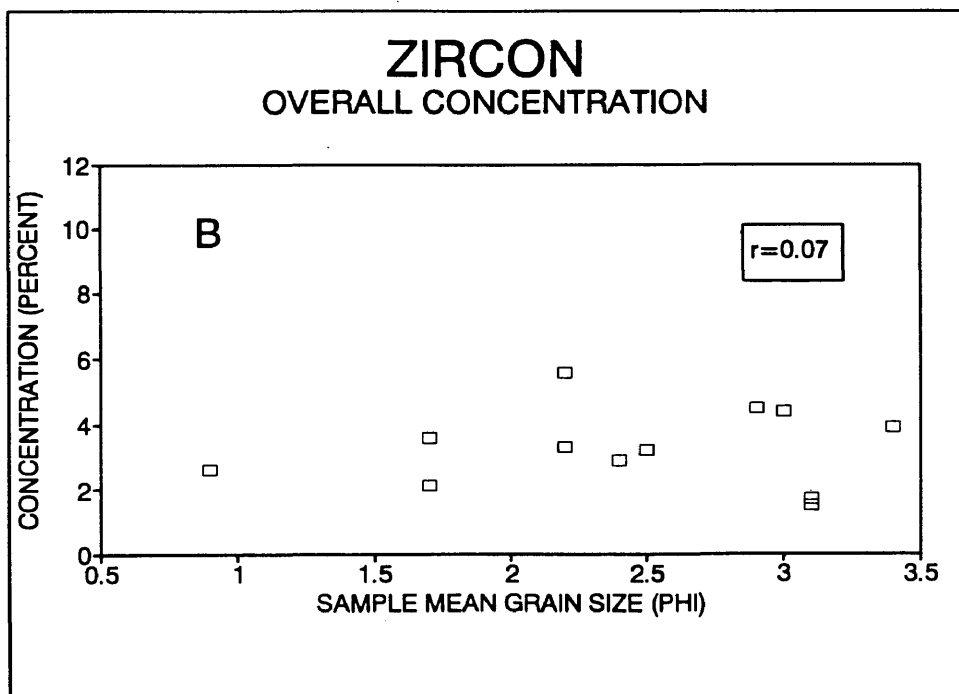
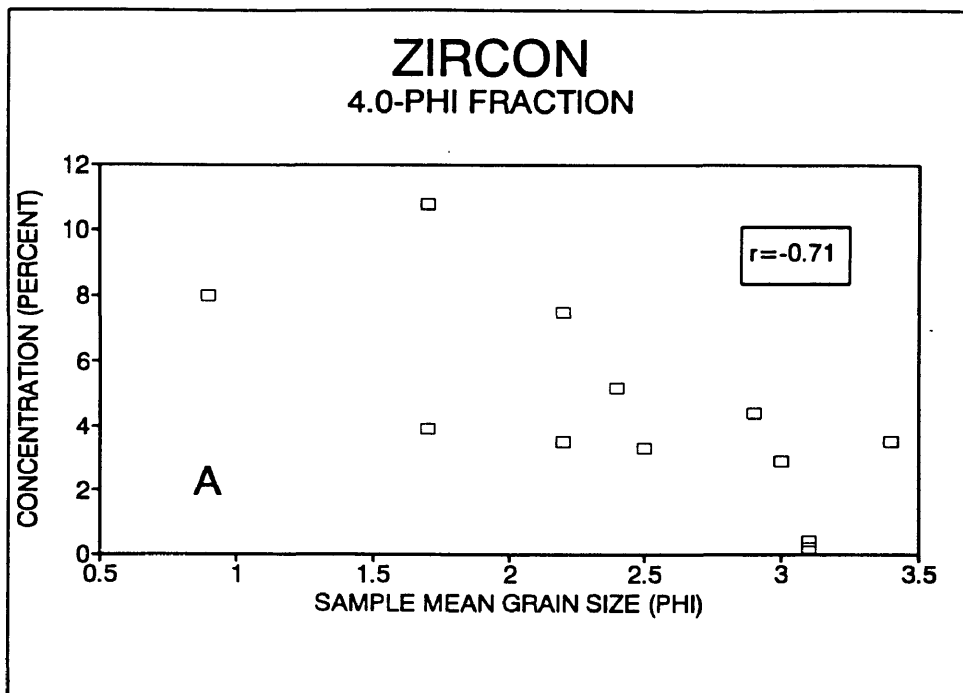


Fig. 5. Comparison of zircon concentrations in the 4.0-phi fraction with overall zircon concentrations. The correlation coefficients for the two plots are also shown.

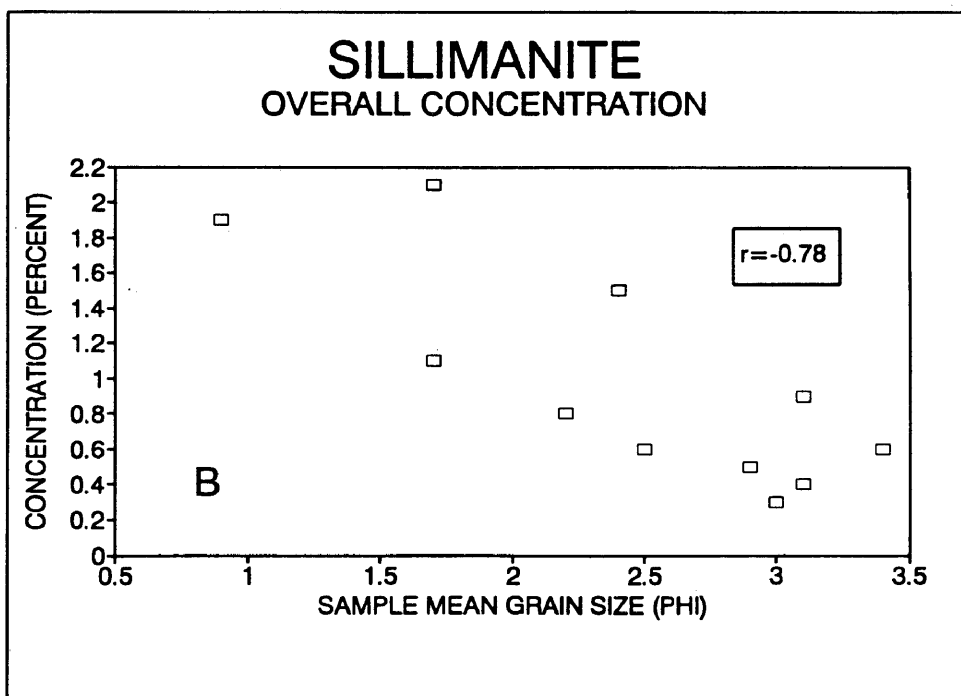
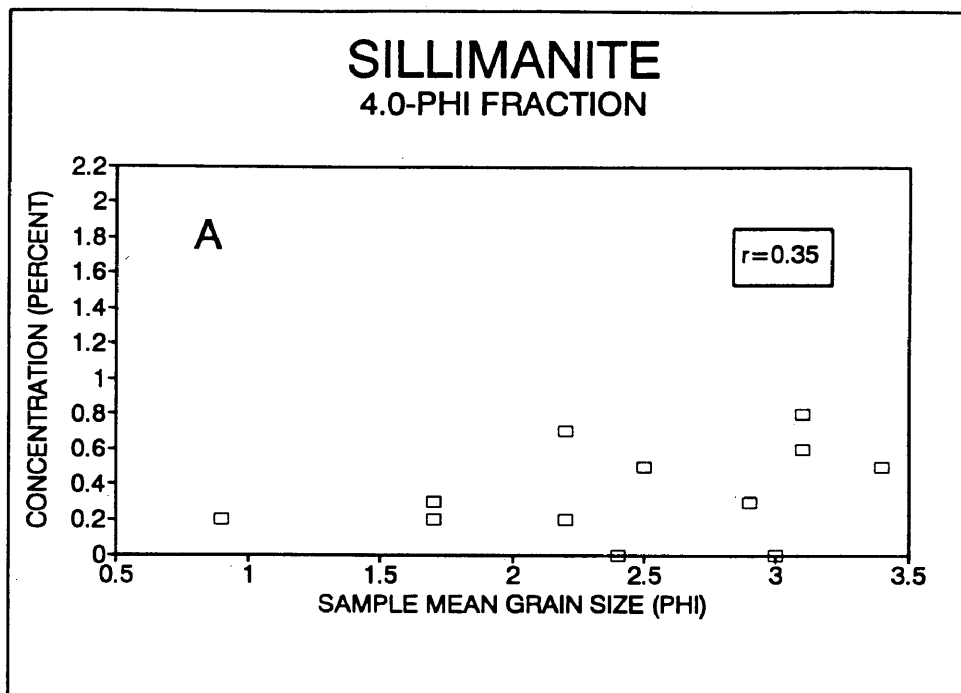


Fig. 6. Comparison of sillimanite concentrations in the 4.0-phi fraction with overall sillimanite concentrations. Again, the correlation coefficients are shown for reference.

size fraction (Rubey, 1933). Since abrasion itself is affected by distance from the source, it would seem that any actual variations in the overall concentration of a mineral would be relevant to studies of provenance, and should not be overlooked or confounded by apparent differences.

Berquist (1986) also examined heavy minerals from a limited size range, the 3- to 4-phi fraction. However, he sampled only fine sand, so his original samples are all of approximately the same grain size. Assuming that the degree of sorting also did not vary significantly among samples, his concentration data can be used legitimately for comparisons among samples within his own study. There should be no size-dependent trends in his data because his samples did not vary in grain size; therefore, his concentration data should accurately reflect changes in overall concentration. Since the overall concentrations of the minerals in his samples are unknown, however, his samples cannot be compared with those of other studies, unless they also were taken from fine sand with a similar degree of sorting, and with the heavy minerals separated from the 3- to 4-phi fraction.

Berquist and Hobbs (1988a, 1988b; Berquist *et al.*, 1990) did not divide their samples into separate size fractions, but identified minerals from the entire sample using the area method of point counting. This method avoids the bias toward larger grains which is inherent in the line method whenever grains of unequal size are present (Galehouse, 1971). Although identifying the entire sample gives data on the overall concentration, the area method of point

counting does make identification more problematic. For this reason, it may not be the most appropriate method to use for a particular study.

The methods used by Berquist (1986) and Berquist and Hobbs (1988a, 1988b; Berquist et al., 1990) both alleviate the problem of misinterpretation which can result from apparent size dependencies in the data. The method of Firek et al. (1977), Swift et al. (1971), and Kelling et al. (1975) does not. Any study involving heavy minerals should be approached with a clear understanding of the relationship between grain size and mineral percentages, especially as this relates to the method used for mineral identification.

Results of this Study

Effect of location. --- The size distributions of the heavy minerals result from the interaction of many factors, including the grain size of the sample (expressed in terms of the median grain size), the sample location, and the particular mineral of interest. The results of the hierarchical log-linear tests of independence indicated that none of these variables is independent of the others, and that even the 3-way interaction among them is significant. This means that changes in the value (or class) of one variable alters the degree of association between the other two variables (Sokal and Rohlf, 1969).

Differences in the heavy-mineral size distributions between the two sample locations may reflect differences in source, distance of transport, or local hydrodynamic processes. Hobbs (1990a), noting differences in the abundance of titanium minerals and total heavies, suggested that the two areas may have different sources and that sediment transport between them may be prevented by the channel topography and the circulation at the mouth of the Chesapeake Bay. The results of this study support the idea that at least the immediate (local) sources of sediment to Smith Island shoals and False Cape are different.

Overall heavy-mineral concentrations vs. sample grain size. ---

The overall concentrations of many of the minerals show a significant correlation with sample mean grain size (Table 7; overall concentrations are given in Appendix C; sample mean grain sizes are listed in Appendix D). These trends appear to be unrelated to the relative densities of the minerals. Amphibole, the pyroxenes, and apatite increase in overall concentration in the finer samples (Figs. 7 and 8). This is the result that would be expected when the mineral grains have undergone a significant amount of abrasion (see discussion above and Rubey, 1933). A mineral's susceptibility to abrasion is a function of its effective density, hardness, cleavage, brittleness, rate of decomposition, and other factors (Dietz, 1973; Rubey, 1933). Amphibole, the pyroxenes, and apatite are all lower in hardness than the other minerals studied, and apatite is both easily crushed and subject to dissolution within the sediment (Parfenoff et al., 1970).

Table 7. Correlation coefficients, measuring the degree of association between the overall concentration of a heavy mineral and sample mean grain size. Correlation coefficients which have an absolute value greater than 0.576 are significant at the 5% level (values marked by a single asterisk); those with an absolute value above 0.708 are significant at the 1% level (values indicated by a double asterisk).

MINERAL	CORRELATION COEFFICIENT
Amphibole	0.62 *
Pyroxenes:	
Augite	0.60 *
Hypersthene	0.76 **
Apatite	0.75 **
Garnet	0.34
Staurolite	-0.85 **
Kyanite	-0.77 **
Sillimanite	-0.78 **
Tourmaline	-0.64 *
Magnetite/ Ilmenite	-0.42
Zircon	0.07
Andalusite	-0.02

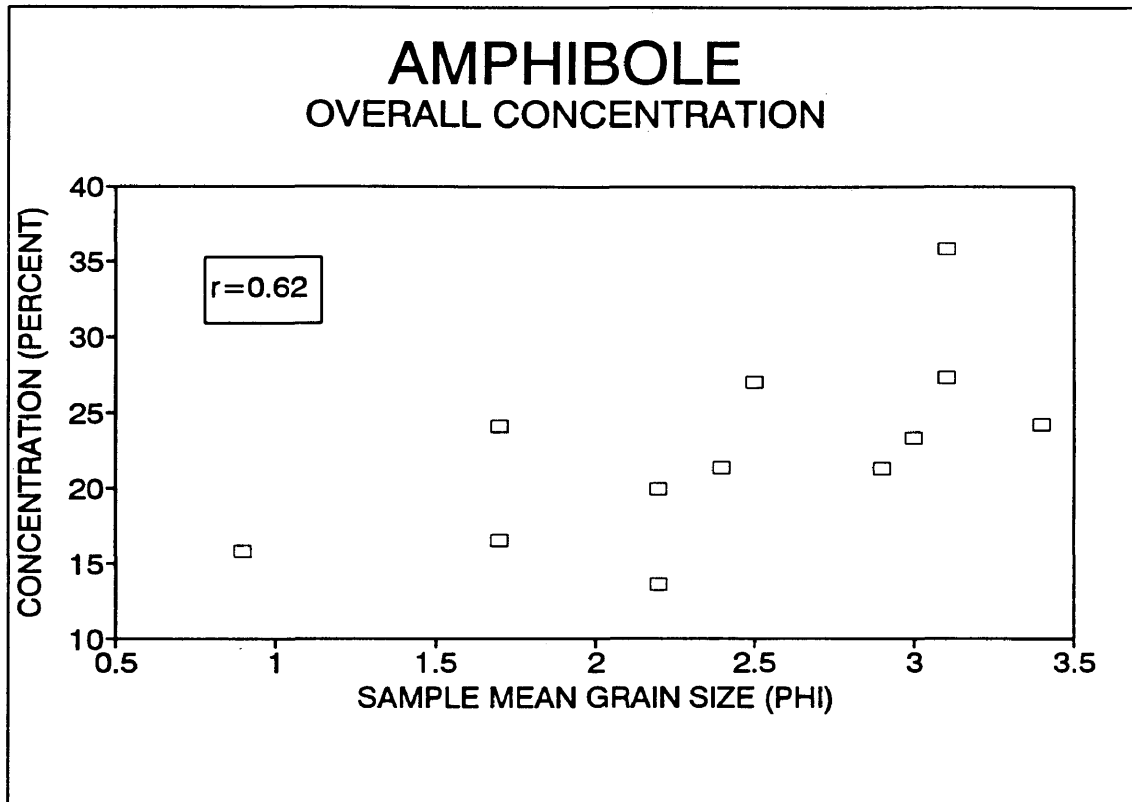


Fig. 7. Relationship between the overall concentration of amphibole and sample mean grain size. The correlation coefficient is significant at the 5% level.

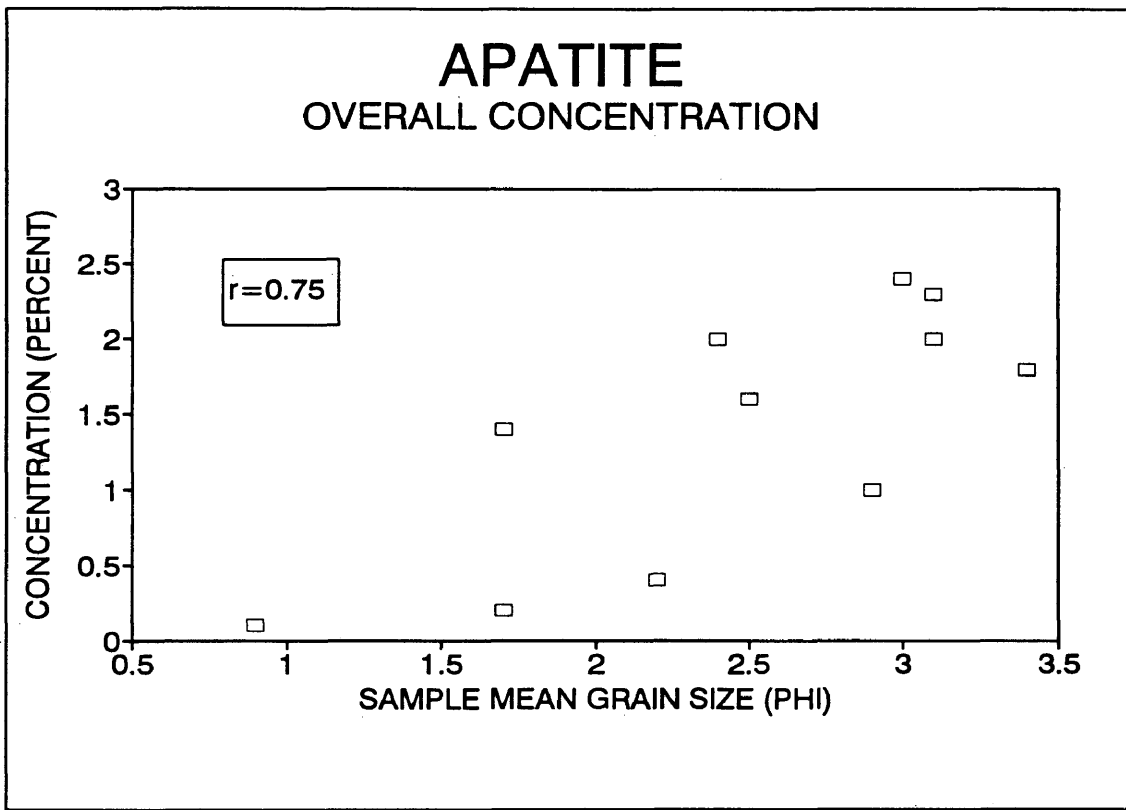


Fig. 8. Relationship between the overall concentration of apatite and sample mean grain size. The correlation coefficient is significant at the 1% level.

It is reasonable, therefore, to conclude that these minerals have undergone substantial abrasion. Garnet also, to some extent, increases in overall concentration in the finer samples (Fig. 9), although its graph shows more scatter than the others, and the correlation coefficient is not significant at the 5% level. This is not surprising, since garnet has a greater hardness and is "fairly resistant to abrasion and to chemical attack" (Deer et al., 1966). It seems likely that garnet has also been affected by abrasion, though to a lesser extent than have the other minerals.

Staurolite, kyanite, sillimanite, and tourmaline have greater overall concentrations in the coarser samples (Fig. 6B). The size distributions of these minerals show that they also tend, to varying degrees, to be coarser than the other heavy minerals in a given sample. In addition, they are likely to be concentrated in the coarser size fractions of the sample. Although the overall concentrations of minerals among samples will not necessarily follow the trends exhibited by those minerals for abundance and concentration within samples, it appears that they do for these four minerals. Magnetite/ilmenite is also somewhat more concentrated in the coarser samples (Fig. 10), but its correlation coefficient is not significant at the 5% level. The wide range in density of magnetite/ilmenite (due to the range in the amount of titanium it contains) may account for some of the scatter shown by this graph. Magnetite is a relatively dense and "soft" mineral, and therefore might be expected to be easily abraded (Rubey, 1933) and to increase in overall concentration in the

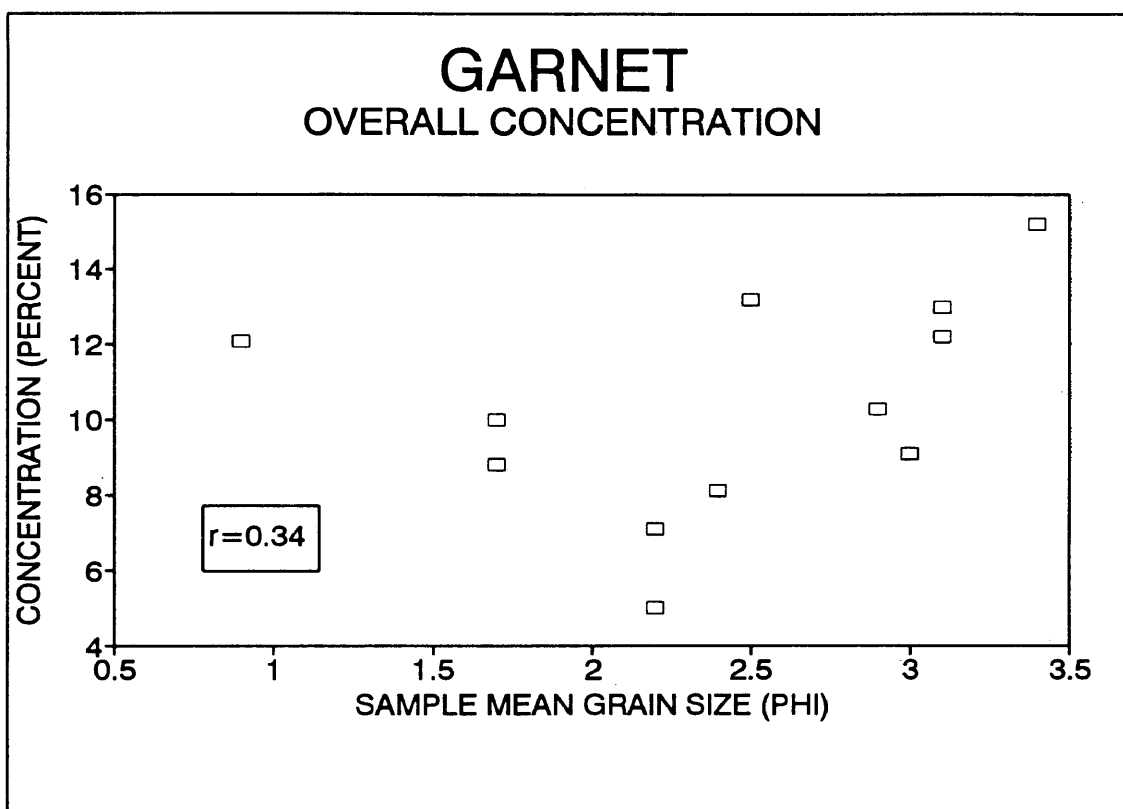


Fig. 9. Relationship between the overall concentration of garnet and sample mean grain size. The correlation coefficient is not significant (at the 5% level).

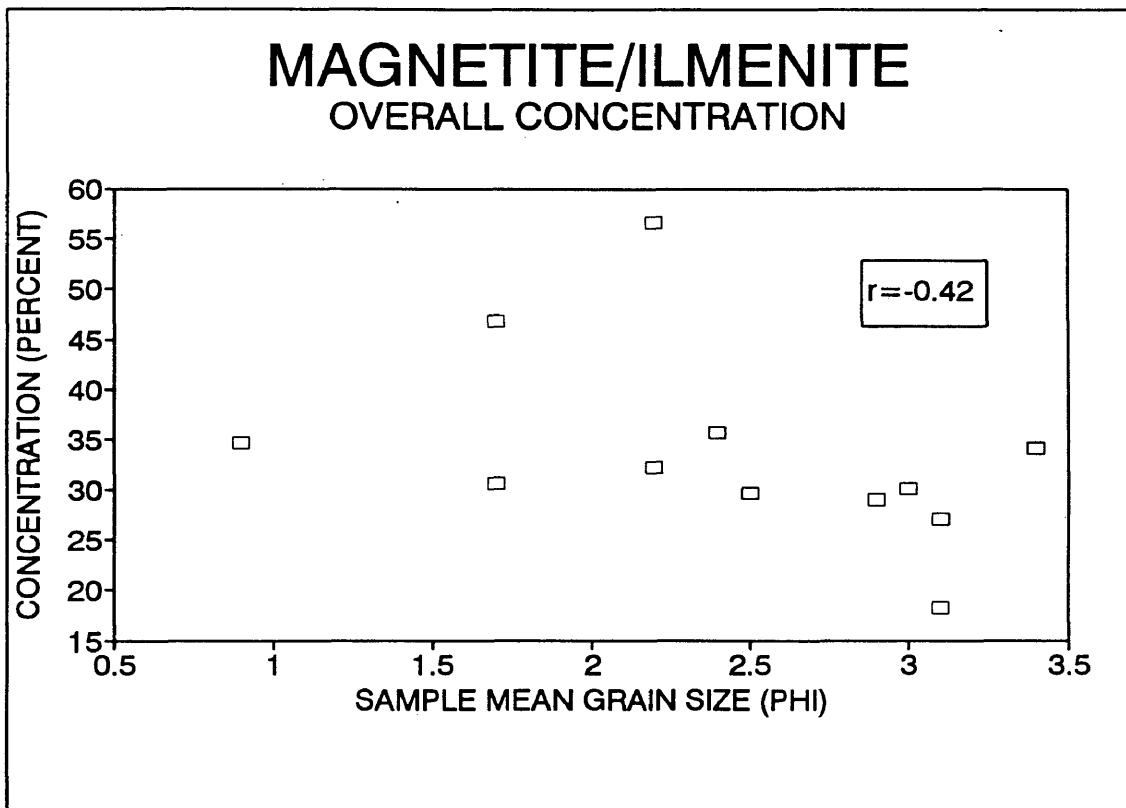


Fig. 10. Relationship between the overall concentration of magnetite/ilmenite and sample mean grain size. The correlation coefficient is not significant (at the 5% level).

finer samples.

The overall concentrations of zircon and andalusite are independent of sample mean grain size (Fig. 5B). For this reason, these minerals could be useful in determining the relative contributions of different sources and transport pathways in the area. Zircon would be a better choice than andalusite for this purpose because it is more resistant, is easier to identify, and may have distinctive (i.e., source-specific) varieties or inclusions (Folk, 1980). It is important, however, that the overall concentration of zircon be determined, and not merely its concentration within a single size fraction (see discussion above and Fig. 5).

Relative size and sorting of light and heavy minerals. --- The heavy minerals in the samples studied are generally finer than the light minerals with which they are associated, and also tend to be better sorted (e.g., see Fig. 11). Zircon and, to some extent, magnetite/ilmenite are somewhat finer than the other heavy minerals, whereas tourmaline, staurolite, and perhaps kyanite tend to be coarser.

The mean grain sizes of the garnet plotted against those of the light minerals are shown in Figure 12. Lines S and E on the graph show the size relationships predicted for settling and entrainment equivalence, respectively; selective entrainment resulting in a lag deposit of equal-size grains is represented by line L. (Dispersive equivalence would be represented by a line between those for equal grain size and settling equivalence.) Considering, for a moment, only

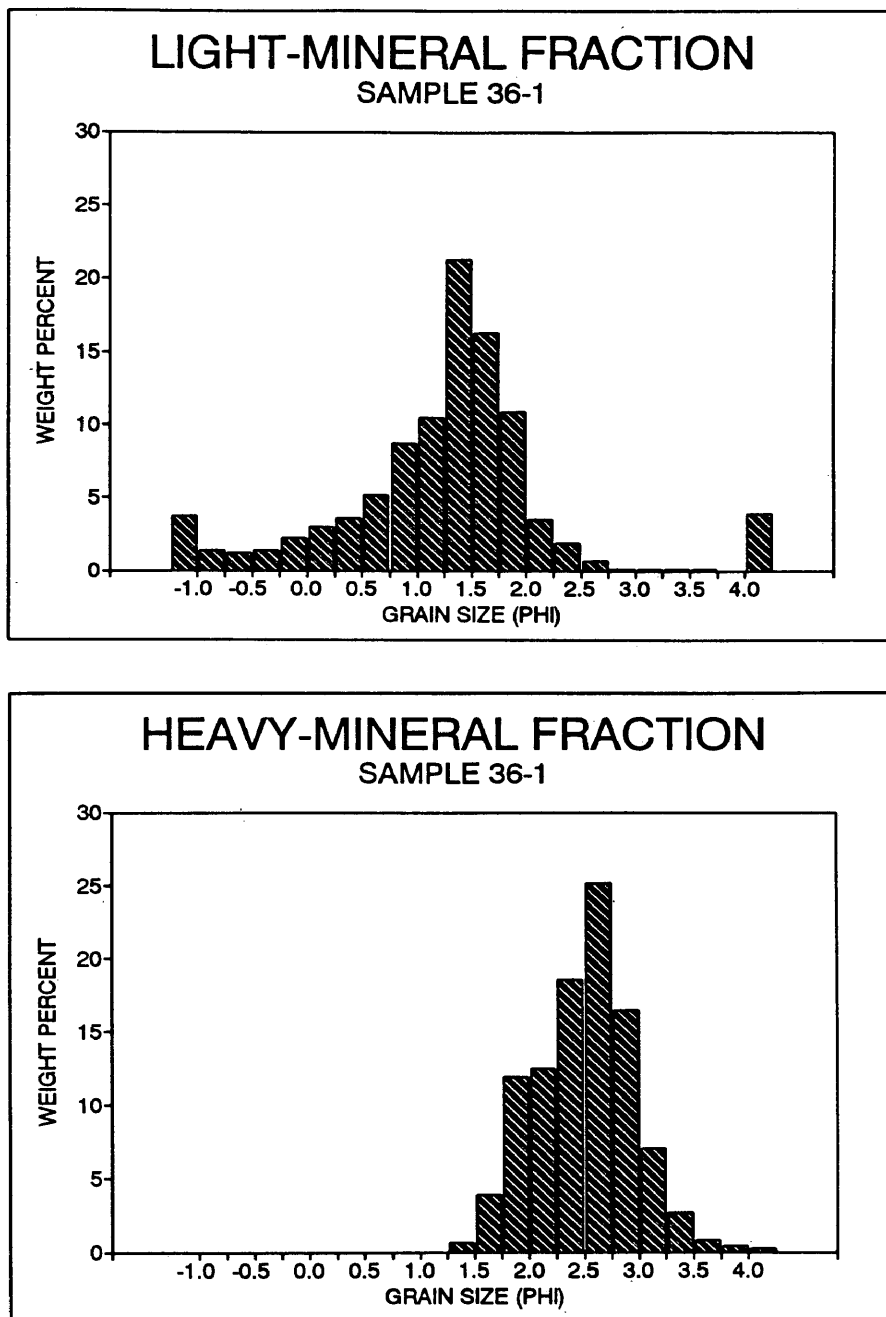


Fig. 11. Comparison of the size distributions of the light- and heavy-mineral fractions for sample 36. The heavy minerals are both finer and better sorted than the light minerals. (Note that the size fractions at the two extremes of the graph are not 1/4-phi fractions--one includes all the gravel; the other consists of the silt and clay.)

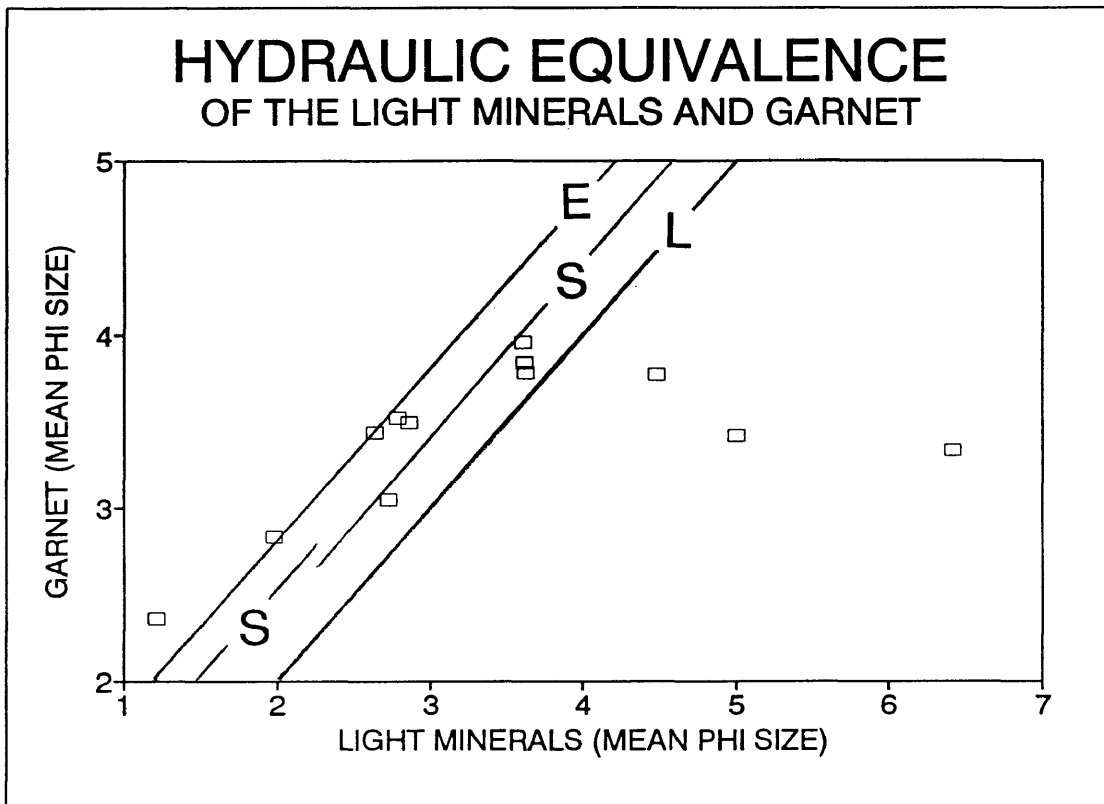


Fig. 12. Relative grain sizes of the light minerals and garnet, showing the size relationships predicted for settling and entrainment equivalence (lines S and E, respectively), and for selective entrainment resulting in a lag deposit of equal-size grains (line L). Two equations were used to calculate settling equivalence (one for grains finer than 2.25 phi, the other for coarser grains; see Table 2), resulting in the two line segments shown above.

the sandy samples (those for which the mean grain size of the lights is less than 4 phi---i.e., coarser than 4 phi), notice that the plotted points do not correspond to any one of the predicted relationships represented by lines A, S, and E. Instead, the trend defined by the points crosses these lines at an angle, possibly indicating an increasing effect of entrainment with increasing mean grain size. This is plausible, as an increase in mean grain size should correspond to an increase in the proportion of the sediment which is carried in the bedload. Because bedload transport generally entails frequent re-entrainment of sediment, an increase in the relative amount of deposition from bedload should result in the increasing influence of entrainment on the size relationships of the light and heavy minerals. As noted above, White and Williams (1967) were able to relate a similar trend (expressed as an increase in modal separation) to an increase in the percent of deposition from traction.

The three muddy samples do not follow the trend exhibited by the sandy samples in Figure 12. In the muddy samples, the heavy minerals are coarser than expected, coarser than the light minerals. It is likely that the character of the muddy sediments has altered the usual size relationships in two ways. First, flocculation of clay particles increases their settling velocity, so that, in order to be in settling equivalence with them, the heavy minerals must be larger than would normally be expected from the size of the individual clay particles. Second, the cohesiveness of the finer sediments makes them more difficult to entrain than non-cohesive sediments, although it is hard

to tell exactly how this would affect the size of the associated heavy minerals. Possibly, following a line of reasoning similar to that of Hand (1967, see above), the heavy minerals would have to be larger than expected in order to be in entrainment equivalence with the light minerals. In a deposit where the heavy minerals were in settling equivalence with the lights, they would be coarser than the lights as a result of the flocculation of the clay particles, but they would be easier to entrain because they would protrude above the clay layer. A small increase in the size of the heavies would increase their cross-sectional area only slightly while significantly increasing their weight, and therefore would make them more difficult to entrain, and equivalent to the lights. (This argument assumes, of course, that the cohesiveness of the light clay particles does not affect the larger heavy minerals, or vice versa.) In general, with an increase in the proportion of clay in the sample, seen as a decrease in the mean grain size of the light minerals, the effects of flocculation and sediment cohesiveness should increase, and the heavy minerals should become coarser relative to the lights. This seems to be the case for the three muddy samples in this study.

Similar plots for magnetite/ilmenite, amphibole, sillimanite, and zircon show size relationships which are essentially the same as those described above for garnet.

The average sorting of the light minerals is 1.2 phi (poorly sorted), of the light minerals excluding the three muddy samples is 0.6 phi (moderately well sorted), and of the heavy minerals for which

the sorting was determined is 0.4 phi (well sorted). (There appears to be no relationship between sample mean grain size and sorting for any of these minerals, except that the sorting of the light minerals is much poorer in the muddy samples.) In every sample, the light minerals are less well sorted than their associated heavies.

Mineral concentration within samples. --- The concentrations of many minerals vary significantly among the different size fractions. Zircon, for example, is highly concentrated in the finer fractions and absent from the coarser ones (Fig. 13), whereas sillimanite and kyanite are concentrated in the coarser fractions (Fig. 14). Leucoxene tends to be most concentrated in about the 3.0-phi fraction (Fig. 15). Magnetite/ilmenite also varies in concentration among the different fractions, but the pattern of variation is less well defined.

Concentration of a mineral within certain size fractions sometimes results from an increase in the abundance of that mineral within those fractions. However, it is often due, at least in part, to a relatively large decrease in the abundance of other minerals (see Fig. 3). This is especially true for those minerals, such as sillimanite, kyanite, and zircon, which tend to be highly concentrated in the coarsest or finest fraction.

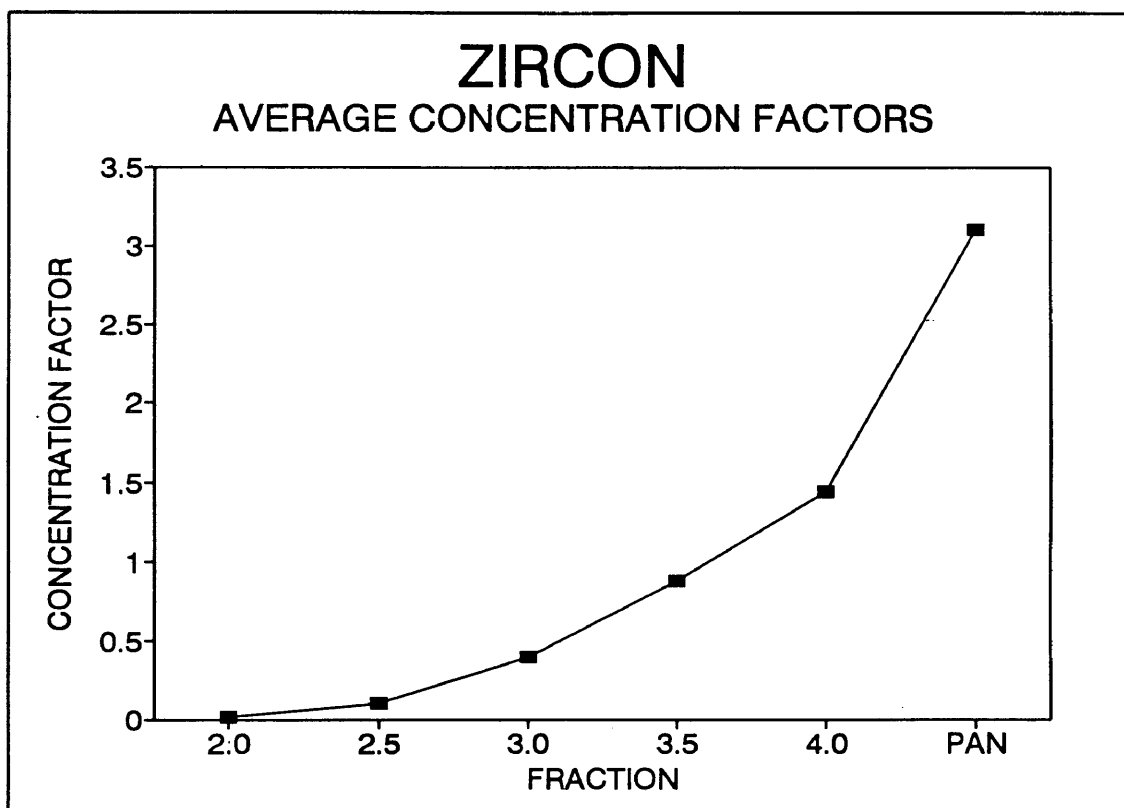


Fig. 13. Average concentration factors for zircon, showing the increase in the concentration of zircon in the finer fractions.

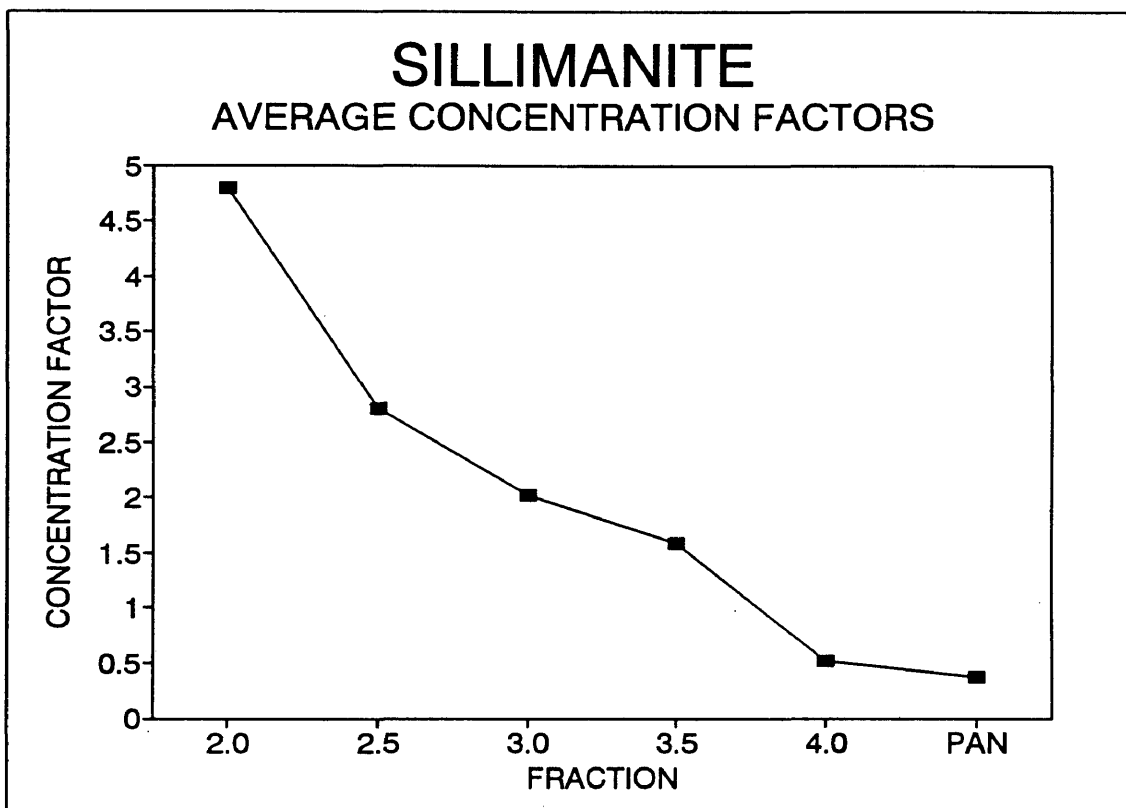


Fig. 14. Average concentration factors for sillimanite, showing the decrease in the concentration of sillimanite in the finer fractions.

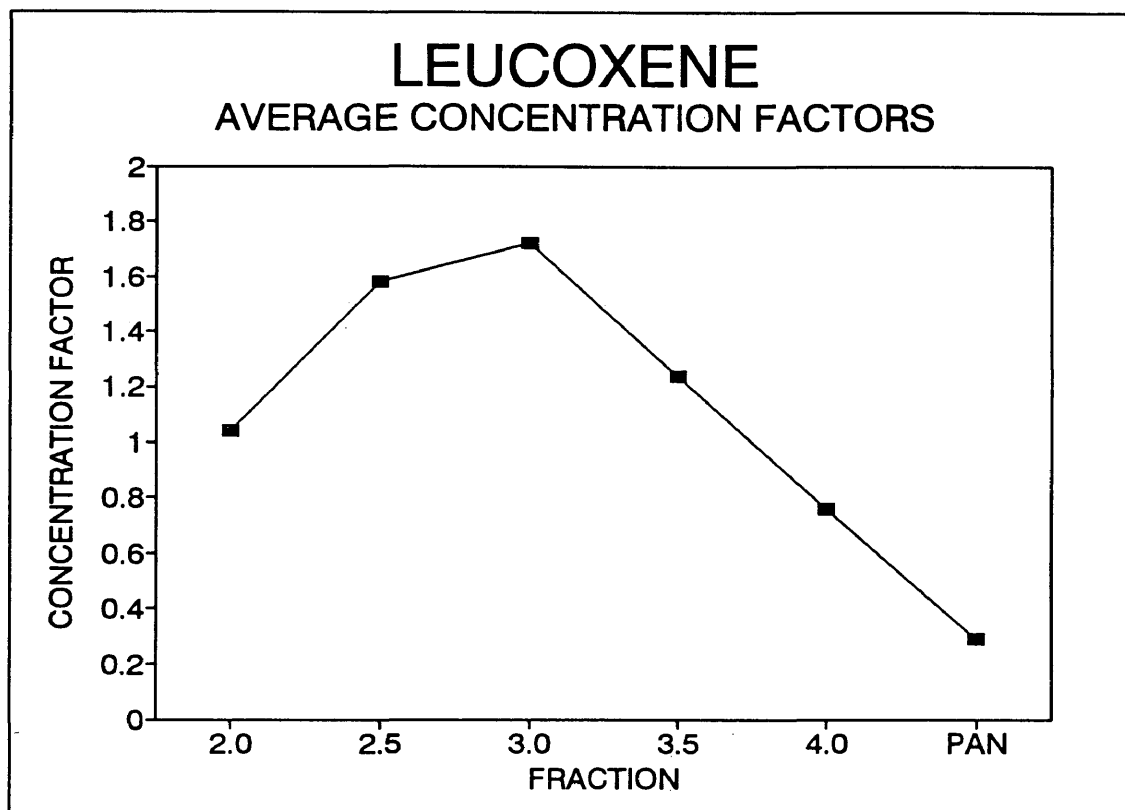


Fig. 15. Average concentration factors for leucoxene, showing the variation in the concentration of leucoxene among the different size fractions.

SUMMARY AND CONCLUSIONS

The three objectives of this study concern the relationships between overall heavy-mineral concentrations and sample grain size, the relative size distributions of the light and heavy minerals, and the concentration of heavy minerals within samples. These objectives deal, respectively, with the concepts of overall concentration, abundance (or size distribution), and concentration within a given size fraction. In this section, the results detailed in the previous sections will be summarized, with an emphasis on the relationships among the patterns of overall concentration, abundance, and concentration within samples which are shown by the various heavy minerals of this study.

As expected, the heavy minerals in the samples studied were found to be both finer and better sorted than the light minerals associated with them. Among the heavy minerals, staurolite, kyanite, sillimanite, and tourmaline are generally somewhat coarser than the others. Within samples, these minerals are concentrated in the coarser size fractions; their overall concentrations also increase in the coarser samples. In contrast, zircon, which tends to be finer than the other heavy minerals and is concentrated in the finer size fractions within samples, nevertheless does not increase in overall

concentration in the finer samples. Clearly, trends in abundance or concentration of heavy minerals within samples cannot be used to predict similar trends in the overall concentrations of those minerals.

Magnetite/ilmenite, which, like zircon, has a high density, and therefore tends to be finer than the other heavy minerals, presents something of an enigma. Its pattern of concentration among the various size fractions, if indeed there is a pattern, is difficult to discern because of the wide variation among samples. Leucoxene, an alteration product of ilmenite, shows a clear pattern of increasing, then decreasing, concentration, with the highest concentration in about the 2.5- to 3.0-phi fraction. Some of the samples show a similar pattern for magnetite/ ilmenite. In addition, magnetite/ilmenite shows an unexpected increase in overall concentration in the coarser samples; but the corresponding correlation coefficient is not significant, perhaps because of the wide range in density of these minerals. In some of the False Cape samples, there appear to be two populations of magnetite/ilmenite, one coarser and well rounded, the other finer and more angular, which suggests the possibility of two distinct sources for these minerals. However, most of the samples did not indicate this. Because magnetite/ilmenite is present in relatively large amounts, with its overall concentration ranging from 18 to 57 percent, and because ilmenite is of economic interest, further research on the relationship between the concentration and grain size, including any effects caused

by variation in density, as well as on the source (or sources) of magnetite and ilmenite should be of value. Perhaps zircon, which has an overall concentration that is independent of sample mean grain size, could be useful in helping to determine the source(s) and patterns of transport for magnetite and ilmenite in this region.

Several of the heavy minerals studied, including amphibole, the pyroxenes, apatite, and probably garnet, have undergone substantial abrasion. This is indicated by their greater overall concentrations in the finer samples.

The hydraulic equivalence of the light and heavy minerals, for the five heavy minerals examined, does not correspond to any one of the theoretical equivalence relationships (settling, entrainment, and dispersive), nor do their relative sizes correspond to those expected for a lag deposit where heavy minerals are concentrated. Instead, for the sandy samples, it seems that the hydraulic equivalence is a function of both settling and entrainment; the increasing effect of entrainment is seen with an increase in the mean grain size of the sample. For the muddy samples, the effects of flocculation and cohesion alter the usual hydraulic-equivalence relationships, resulting in the association of fine-grained light minerals with coarser heavy minerals. Hydraulic-equivalent size is the result of several different processes, and these processes may not have affected all grain sizes in a deposit equally.

In general, the relationships between the overall concentrations of the heavy minerals and sample mean grain size seem to reflect

mineral availability (in terms of size) rather than the effects of hydraulic sorting. The relative size distributions of the light and heavy minerals may depend upon hydraulic equivalence relationships, which are determined by differences in mineral density. Overall concentrations, however, appear to be affected not as much by the concentrating processes which operate through selective entrainment, as by the overall size of the minerals in the source (for the "coarse" minerals), the effects of abrasion (for minerals concentrated in the finer samples), and resistance to wear (in the case of zircon). In other words, local hydraulic processes do not seem to be working to concentrate these minerals; instead, their patterns of overall concentration depend more upon the influence of source and the effects of transport upon the different minerals.

As explained earlier, the relationship between the overall concentration of a heavy mineral and the sample grain size cannot always be predicted from the concentration data for a limited size range. Although this was demonstrated by Rubey as early as 1933, subsequent authors often have either ignored or misunderstood this concept. Unfortunately, although many of their conclusions are likely to be unaffected by this mistake, it is impossible to tell just which ones are reliable, and which are not, without knowing the overall concentrations of the minerals in the samples they studied. Future studies involving heavy minerals should be designed in such a way that this problem is avoided.

APPENDIX A

SAMPLE LOCATIONS AND CORE LOGS

Water depth, latitude, and longitude are from Berquist and Hobbs (1988b; also in Berquist et al., 1990). Core descriptions were taken from the original core logs, and also have been published in those same reports.

CORE	WATER DEPTH (ft.)	LATITUDE deg. min.	LONGITUDE deg. min.
H04	38	37 05.50	75 46.58
H06	37	37 03.94	75 46.03
H08	30	37 04.89	75 46.98
H12	29	37 05.77	75 47.31
C26	47	36 33.97	75 48.14
C27	45	36 34.26	75 49.56
C29	37	36 33.18	75 48.62
C30	33	36 34.70	75 51.73
C33	37	36 33.59	75 50.66
C34	31	36 33.52	75 50.43
C35	41	36 33.38	75 49.68
C36	25	36 33.31	75 49.05

Depth (meters)

CORE H04-1

Fine to very fine sand, massive, olive gray (5Y 4/2). ----- 0-1.09
 Clay, plastic, massive, very wet. ----- 1.09-1.18
 Very fine silty sand, massive. ----- 1.18-1.33

CORE H06-1

Fine to very fine sand, micaceous, massive, scattered shell fragments up to 3 cm., very dark gray (5Y 3/1); oyster and clam shell fragments up to 7 cm. at 0.72-0.82 m. ----- 0-0.82
 Clayey silt, slightly sandy, slightly plastic, massive, bone (?) fragment 3 cm. long at 1.49 m. ----- 0.82-1.66

CORE H08-1

Fine sand, micaceous, massive, shell fragments, grayish brown (2.5Y 5/2). ----- 0-0.17
 Medium to fine sand, shell fragments up to 0.5 cm. ----- 0.17-0.25
 Fine sand, micaceous, massive, shell fragments up to 4 cm., dark gray (2.5Y 4/0); oyster shell fragment 4 cm. long at 1.00 m.; interrupted by layer of coarse sand with shell fragments up to 2 cm. at 1.18-1.22 m.; scallop shell 2.5 cm. long near bottom of interval; grades into fine to very fine silty sand below. ----- 0.25-1.34

CORE H12-1

Medium to coarse sand, abundant shell fragments. ----- 0-0.19
 Medium sand, abundant shell fragments up to 1 cm., dark gray (5Y 4/1) to very dark gray (5Y 3/1); grades into layer below. ----- 0.19-1.00
 Very fine to fine sand, micaceous, shell fragments. ----- 1.00-1.17

CORE 26-1

Fine to very fine sand, micaceous, olive gray (5Y 5/2); fine sand with shell hash (fragments up to 1 cm.) at 1.10-1.14 m. and 1.26-1.28 m.; laminations of silty fine sand 1 cm. thick at 1.20-1.25 m.; layer of silty clay at 1.60-1.64 m.; color changes to dark gray (5Y 4/1) at 1.24 m. ----- 0-1.71

CORE 27-1

Very coarse to coarse sand, scattered shell fragments, dark gray (5Y 4/1). ----- 0-0.12
 Fine sand, micaceous, dark gray (5Y 4/1); lamination of silty clay at 0.23 m. ----- 0.12-0.25
 Coarse to medium sand; sandy shell hash with shell fragments up to 3 cm. at 0.32-0.38 m. ----- 0.25-0.45
 Very fine sand, micaceous, scattered shell fragments. ----- 0.45-0.53
 Silty clay, dark gray (2.5Y 4/1); shelly, coarse to medium sand at 0.61-0.64 m.; pods of silty sand at 0.65-0.70 m. and 0.96-0.98 m. ----- 0.53-1.73

CORE 29-1

Medium to fine sand, some silt, scattered shell fragments up to 2 mm., olive gray (5Y 5/2); concentration of

shell fragments at 0.98-1.02 m.; shell fragments up to
3 cm. at 0.95-1.45 m.; color changes to dark gray
(5Y 4/1) at 1.50 m. ----- 0-1.93

CORE 30-1

Silty clay, scattered shell fragments under 1 mm., dark
gray (5Y 4/1); layer of fine sandy silt 3 cm. thick at
a 45 deg. angle at 0.20 m. ----- 0-0.34
Silty fine sand, shell fragments up to 3 cm.; piece of wood
2 cm. long at 0.42 m. ----- 0.34-0.78
Silty clay with interlayers of silty fine sand (clay layers
4-5 cm. thick, sand layers 15-20 cm. thick), scattered
shell fragments up to 1 mm., dark gray (5Y 4/1). ----- 0.78-1.34
Silty clay, dark gray (5Y 4/1). ----- 1.34-1.48
Silty fine sand, scattered shell fragments up to 1 mm. ----- 1.48-1.77

CORE 33-1

Silty fine sand, widely scattered shell fragments, black
(2.5Y 6/0); interlayers of silty clay 0.5-6.0 cm.
thick at 0.0-0.95 m.; layers of silty clay at 0.32-
0.38 m., 0.45-0.48 m. (with 0.5-cm. layer of coarser
sand below), and 0.64-0.67 m.; layer of silty medium
to fine sand at 0.50-0.57 m.; medium sand and some
silt with shell fragments up to 4 cm. at 0.68-
0.73 m.; color changes to dark gray (2.5Y 4/0) at
0.48 m. ----- 0-1.54

CORE 34-1

Medium sand, traces of coarse and fine sand, widely
scattered shell fragments, olive gray (5Y 5/2). ----- 0-1.71

CORE 35-1

Medium sand in mud matrix, shell fragments up to 4 cm.,
very dark gray (5Y 3/1). ----- 0-0.08
Clay, very dark gray (5Y 3/1); occasional pods and
discontinuous laminations of fine sand; pods towards
surface contain medium sand and mud; scattered
fragments of wood at 1.15-1.20 m. and 1.35-1.56 m.;
color changes to dark gray (5Y 4/1) at 0.80 m. ----- 0.08-1.56

CORE 36-1

Coarse to medium sand, abundant shell fragments up to
5 cm., olive (5Y 5/3); grades into layer below. ----- 0-0.72
Medium to fine sand, occasional coarse sand, olive
(5Y 4/2). ----- 0.72-1.25

APPENDIX B

CRITERIA USED IN MINERAL IDENTIFICATION

MAGNETITE/ILMENITE: Opaque, black, usually granular texture. This category includes an occasional grain of hematite, which is opaque and red.

LEUCOXENE: Opaque, white to brown, porcelaneous texture.

PYRITE: Opaque, brass yellow, in flakes or botryoidal aggregates, often seen as replacement for micro-organisms.

GARNET: Colorless to pink/orange, high relief, isotropic.

EPIDOTE: Pleochroic colorless to yellow-green, high birefringence, oblique extinction.

STAUROLITE: Pleochroic straw yellow to orange, moderate birefringence, rounded grains with weathered inclusions ("Swiss cheese" texture).

AMPHIBOLE GROUP (Hornblende): Pleochroic in shades of brownish green (occasionally colorless), elongate grains, low to moderate birefringence, oblique extinction ($12-34^{\circ}$). Metamorphic hornblende and riebeckite are pleochroic in shades of greenish yellow to blue-green or blue, and riebeckite has a lower extinction angle ($3-21^{\circ}$).

AUGITE/DIOPSIDE: Colorless to pale green or brown (weakly pleochroic, if at all), high birefringence, oblique extinction ($>38^{\circ}$). Many grains have dentate ends.

HYPERSTHENE/ENSTATITE: Pleochroic green to pink, usually elongate, often with dentate ends, low to moderate birefringence, parallel extinction, positive elongation.

APATITE: Colorless (pale bluish cast), generally rounded grains, very low birefringence.

SILLIMANITE: Clear, colorless, finely striated, moderately high birefringence, parallel extinction.

KYANITE: Colorless, elongate, right angle cleavage, moderate birefringence, 30° extinction angle.

ANDALUSITE: Colorless to pale green or pink (may be pleochroic), often equant and somewhat weathered, low birefringence, parallel extinction, negative elongation.

RUTILE: Deep red to opaque, usually elongate, very high relief, very high birefringence, parallel extinction.

TOURMALINE: Highly pleochroic (inverse pleochroism), yellow or pink to dark brown, often elongate, high birefringence, parallel extinction.

ZIRCON: Colorless, often elongate, high relief, adamantine luster, may have inclusions, high birefringence, parallel extinction.

OTHER: Includes weathered grains and others that could not be identified, as well as some recognizable, but uncommon, minerals.

LIGHT MINERALS (Quartz): Colorless, often "dirty" and irregular, very low relief, low birefringence. Calcite has a relief that changes with rotation, very high birefringence, and oblique extinction.

APPENDIX C

OVERALL CONCENTRATIONS OF HEAVY MINERALS
(given as a percentage of the heavy-mineral fraction)

MINERAL	SPECIFIC GRAVITY	SAMPLE				
		H04-1	H06-1	H08-1	H12-1	26-1
Magnetite/Ilmen	4.85	27.0	18.2	29.7	34.1	35.8
Leucoxene	4.00	2.2	1.9	2.5	1.1	4.8
Garnet	3.90	12.2	13.0	13.2	15.2	8.1
Epidote	3.44	1.4	3.3	2.3	1.6	3.4
Staurolite	3.75	0.0	0.0	0.2	0.2	0.8
Amphibole Grp	3.25	27.3	35.8	27.0	24.2	21.4
Augite/Diopside	3.30	5.3	3.9	3.1	3.1	2.0
Hypersth/Enstat	3.50	6.4	5.1	5.0	4.6	2.1
Apatite	3.20	2.3	2.0	1.6	1.8	2.0
Sillimanite	3.25	0.9	0.4	0.6	0.6	1.5
Kyanite	3.60	0.5	0.2	0.1	0.0	0.3
Andalusite	3.15	0.8	1.2	1.1	0.7	2.0
Rutile	4.20	0.6	0.3	0.1	0.8	1.0
Tourmaline	3.10	0.3	0.2	0.2	0.1	0.5
Zircon	4.60	1.5	1.7	3.2	3.9	2.9
Other	3.40	11.4	12.7	10.0	7.9	11.4

MINERAL	SAMPLE						
	27-1	29-1	30-1	33-1	34-1	35-1	36-1
Magnetite/Ilmen	30.6	56.7	29.0	30.1	46.9	32.2	34.7
Leucoxene	3.4	2.8	7.0	3.6	4.2	5.4	5.0
Garnet	10.0	7.1	10.3	9.1	8.8	5.0	12.1
Epidote	2.2	1.9	1.8	1.8	5.0	1.8	6.8
Staurolite	1.5	0.7	0.7	0.7	2.2	0.9	5.9
Amphibole Grp	24.1	13.6	21.3	23.3	16.5	19.9	15.8
Augite/Diopside	3.2	0.7	2.5	3.0	1.7	1.8	1.5
Hypersth/Enstat	2.9	1.3	3.4	4.1	1.2	2.9	1.5
Apatite	1.4	0.4	1.0	2.4	0.2	0.4	0.1
Sillimanite	1.1	0.8	0.5	0.3	2.1	0.8	1.9
Kyanite	0.4	0.1	0.1	0.0	1.0	0.1	2.0
Andalusite	1.5	1.2	1.4	1.1	0.9	1.6	0.7
Rutile	0.3	0.6	1.0	0.3	1.2	1.2	0.3
Tourmaline	0.6	0.5	0.4	0.5	0.3	0.6	0.6
Zircon	3.6	3.3	4.5	4.4	2.1	5.6	2.6
Other	13.1	8.1	15.1	15.1	5.6	19.9	8.7

APPENDIX D

SAMPLE CHARACTERISTICS

The weight percent of total heavy minerals in each sample is from Berquist and Hobbs (1988b; also in Berquist et al., 1990). The size classes used for the median grain size correspond to the following phi sizes: medium sand, 1.0 to 2.0 phi; fine sand, 2.0 to 3.0 phi; very fine sand, 3.0 to 4.0 phi; mud, finer than 4.0 phi (Folk, 1980). The mean grain size was determined using the RSA, i.e., only the sand fraction was considered (see discussion in text).

SAMPLE	TOTAL HEAVY MINERALS (wt. %)	MEDIAN GRAIN- SIZE CLASS	MEAN GRAIN SIZE (phi)
H04-1	3.06	Very Fine Sand	3.1
H06-1	3.13	Very Fine Sand	3.1
H08-1	5.52	Fine Sand	2.5
H12-1	6.88	Fine Sand	3.4
26-1	3.53	Fine Sand	2.4
27-1	2.28	Mud	1.7
29-1	4.53	Fine Sand	2.2
30-1	2.96	Very Fine Sand	2.9
33-1	1.95	Very Fine Sand	3.0
34-1	1.08	Medium Sand	1.7
35-1	1.78	Mud	2.2
36-1	0.62	Medium Sand	0.9

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