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A Procedure for Assessing Heavy Mineral Resources Potential

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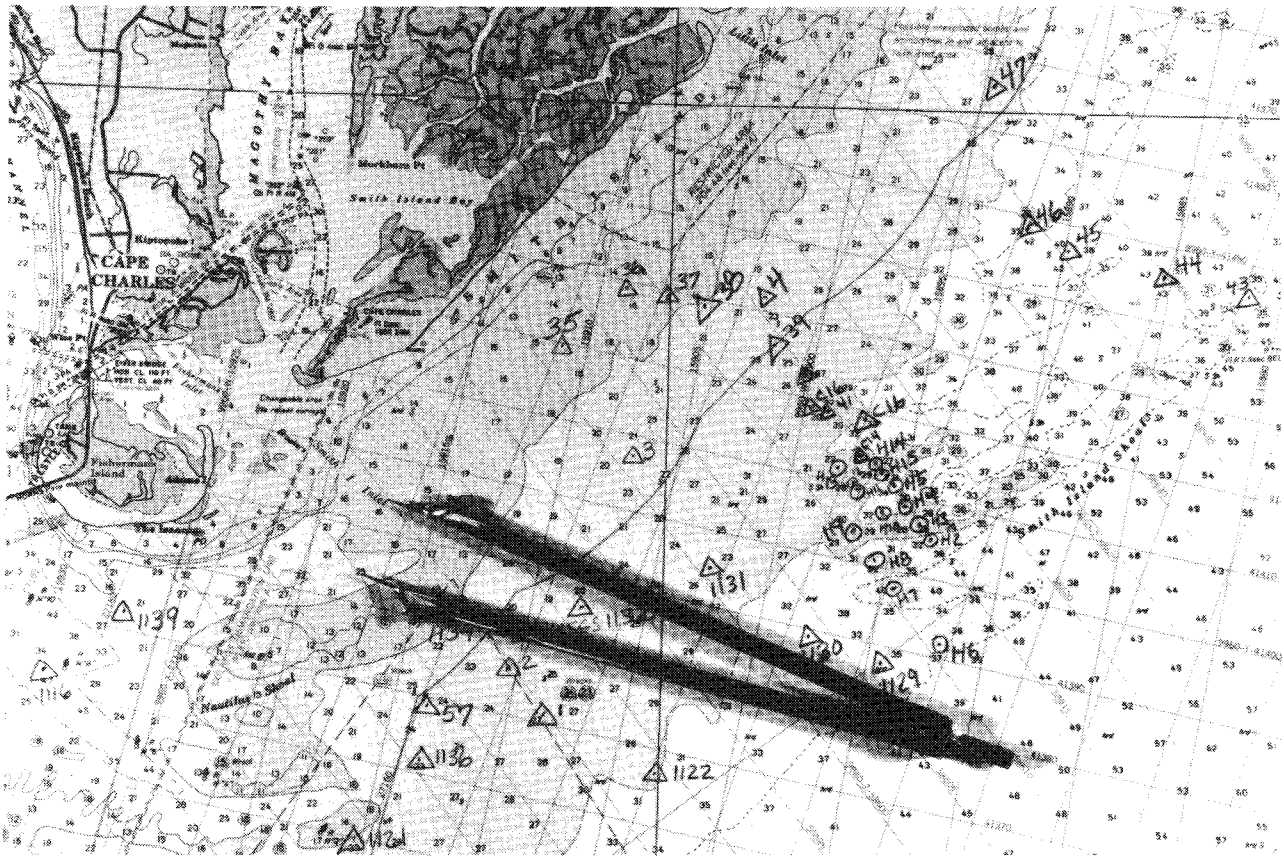
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HEAVY-MINERAL STUDIES — VIRGINIA INNER CONTINENTAL SHELF

C.R. Berquist, Jr., Editor



COMMONWEALTH OF VIRGINIA

DEPARTMENT OF MINES, MINERALS AND ENERGY
DIVISION OF MINERAL RESOURCES
Robert C. Milici, State Geologist

CHARLOTTESVILLE, VIRGINIA
1990

A PROCEDURE FOR ASSESSING HEAVY-MINERAL RESOURCES POTENTIAL OF CONTINENTAL SHELF SEDIMENTS*

Andrew E. Grosz¹, C.R. Berquist, Jr.², and C.T. Fischler³

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* Any use of trade names is for descriptive purposes only and does not imply endorsement by the USGS.

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ABSTRACT

Supplies of placer heavy minerals, such as ilmenite, rutile, zircon, and monazite, are anticipated to be in short supply by early in the next century. The depletion of conventional onshore deposits coupled with the declaration of the Exclusive Economic Zone in 1983 have provided the impetus to assess the resource potential of heavy-mineral concentrations in U.S. Continental Shelf sediments as future sources for these mineral commodities.

Mineralogically imprecise assessments of placer resources result from analyses of concentrates derived from small-volume samples because of the particle-sparsity effect. The overall low grade of heavy minerals in Atlantic Continental Shelf sediments require the analysis of mineral concentrates from large volumes of bulk sample.

A set of procedures to extract and analyze heavy minerals from large-volume samples is presented. These procedures were designed for general application to reconnaissance surveys; the Virginia study is given as an example. Resulting data are appropriate for both basic research needs and for industry's requirements for information on offshore mineral grades and distribution.

The recovery of heavy minerals was a two-stage process using a modified spiral concentrator followed by heavy-liquid separation procedures. The mineral concentrate derived from heavy-liquid separation was magnetically fractionated to reduce the number of mineral species so that mineral identification and quantification could be facilitated. Reflected and transmitted light microscopes were used for mineral identification and quantification. The overall heavy-mineral composition of samples was determined by combining the percentages of heavy-mineral species distributed across the magnetic fractions by use of a computerized database.

BACKGROUND

The United States is dependent on imports from Australia, South Africa, and a number of other countries for about 80 percent of its ilmenite, about 60 percent of its rutile, and virtually all its zircon and monazite (Lynd, 1985). These minerals are commonly mined from heavy-mineral deposits that are subaerially exposed in modern and ancient beach-complex sediments (including beach, dune, inlet, washover fan, and barrier environments). A global-class beach-complex placer deposit of the titanium minerals ilmenite, altered ilmenite, and rutile (including monazite, zircon, and others) may be up to tens of kilometers in length, up to 2 km in width, and 10 or more m in thickness. Ore grades are variable, averaging 3 to 6 percent total heavy minerals, which typically has about a 50 percent economically valuable (ilmenite, altered ilmenite, rutile, zircon, and monazite) component.

Uses for heavy minerals and the elements they contain are being developed at a faster rate than new deposits are being discovered, and, consequently, it is not known how demand will continue to be met at current costs (Fantel and others, 1986; Shepherd, 1986). According to Fantel and others (1986), the production of rutile concentrates will likely decline significantly after 2000 as many mines, particularly

those in Australia, deplete their demonstrated reserves. They concluded that within the coming decade, there could be a shortage of high-grade, low-cost rutile. Inactive mines that could come into production might act as a temporary replacement source for a limited time, but this would be at substantially higher costs. Production of rutile might be maintained longer if new resources were found at operating mine sites or if inferred reserves became demonstrated. Because of limited rutile availability over the long term, the production of synthetic rutile from ilmenite deposits is seen as the likely source for future high-grade titanium concentrates.

In many chemical plants, where about 95 percent of the world's annual production of titanium minerals is used for pigment manufacturing (Lynd, 1985), both synthetic rutile and high-titanium slags are suitable alternatives to rutile. Because placer reserves are being depleted and the demand is high, the titanium industry is in a state of flux and could use any of the following sources of TiO_2 : lateritic anatase from Brazil, eclogitic rutile from Italy, high- TiO_2 slag from Canada and South Africa, fine-grained placers from Western Tennessee, perovskite from Colorado, synthetic rutile from magmatic ilmenites, and offshore placers.

The declaration of the U.S. Exclusive Economic Zone (EEZ) in 1983 provided an impetus to define the mineral resources contained within ocean-floor sediments and rocks. The declaration amplified the potential importance of placer deposits of heavy minerals in continental shelf sediments as future sources for strategic and critical mineral commodities.

The Atlantic Continental Shelf (ACS) of the United States has an area of about $3.9 \times 10^{11} \text{ m}^2$ and contains an estimated $8.3 \times 10^{11} \text{ m}^3$ of sand and gravel, assuming a 5-m average thickness (U.S. Department of the Interior, 1979). Most sand and gravel deposits, however, are 10 m or more thick. Heavy-mineral sand of variable composition and grade on the ACS is estimated to have a volume of about $1.3 \times 10^9 \text{ m}^3$, which is 0.16 percent of the estimated sand and gravel volume. Recent studies by Grosz (1987), however, showed that this value may be underestimated.

Until recently, published reports on the economic importance of detrital heavy-mineral concentrations within sediments of the ACS were often speculative and provided inadequate data for a rigorous assessment of resources. In most of the literature heavy-mineral data is only used to clarify geologic or stratigraphic problems. The analyses commonly discuss "opaques" as a component forming 20 to 60 percent of the heavy-mineral assemblage. Because most of the heavy minerals of economic value are opaque (ilmenite, altered ilmenite, and frequently rutile), an assessment of the economic potential on this previously published literature cannot be mineralogically precise. Another factor that precludes the usefulness of most published heavy-mineral analyses for resource estimation is the bias caused by analysis of a narrow size-fraction (commonly a 2-to 3-phi, 0.250-to 0.125-mm, size interval) that commonly contains comparatively high heavy-mineral values, and reporting those elevated values as representative of the heavy-mineral grades (Arthur and others, 1986). A few published studies on the economic aspects of heavy minerals in ACS sediments are known (Drucker, 1983; Goodwin and Thomas, 1973), but inconsistencies within these reports limit their usefulness. None of the data from

offshore industrial exploration programs on the ACS have been published.

A larger effort is being undertaken jointly by the U.S. Geological Survey (USGS), the Atlantic coastal state geological surveys, the universities, and industry to assess the hard-mineral resources potential (including sand, gravel, phosphate, and heavy minerals) of the ACS. The Virginia Division of Mineral Resources and the Virginia Institute of Marine Science (VIMS) of the College of William and Mary collected and analyzed vibracore and grab samples from 1986 (Berquist and Hobbs, 1986) through 1988 (Berquist and Hobbs, 1988a, 1988b) on the inner ACS (<40-m isobath) offshore of Virginia.

The studies were initiated in response to high values of heavy-mineral concentrations reported by Nichols (1972), Goodwin and Thomas (1973), and Grosz and Escowitz (1983). Additional samples from the mouth of the Chesapeake Bay area were made available when the USGS acquired approximately 1300 vibracores from the U.S. Army Corps of Engineers. In addition, about 23,000 km of high-resolution seismic reflection profiles were acquired from the Corps of Engineers on the inner ACS from Maine to Florida. These cores and profiles were originally collected to identify potential borrow areas for beach nourishment and reclamation projects. From this collection, 36 vibracores were used in addition to the 77 vibracores and 106 grab samples that were collected and analyzed for the study detailed in other sections of this publication.

SAMPLE PREPARATION

RATIONALE

The rationale for the sample processing scheme presented here is based on a number of factors, some are specific to the samples obtained from the Corps of Engineers, and others are specific to the objective of characterization of the resource potential of a large area in a timely manner. The methods and procedures used here were designed to insure uniformity of resultant databases produced by all users of core samples, to offset particle-sparsity biases, to produce rapid reconnaissance-level information without sacrificing the detail necessary for follow-up detailed studies, and to provide economic geologic information for industry.

The type and the size of the sample to be used for mineral separation depends largely on the analytical goals of the study. Heavy minerals commonly constitute less than 1 percent by weight of sediments; therefore, it may take a sample of up to several tens of kilograms, depending on the amount of heavy-mineral concentrate needed. Preliminary microscopic examination to determine the approximate heavy-mineral percentage and to establish the approximate grain sizes of the minerals will help in establishing the appropriate procedures for maximizing the efficiency of mineral recovery. The end-product of separation processes in terms of mass of sample required for complete analysis is a function of the types of analyses anticipated (textural, mineralogic, wet chemical, geophysical, microprobe, X-ray fluorescence, and so forth) and the accuracy being sought from each analytical

procedure.

The heavy-mineral processing scheme for the analysis of samples from the ACS (specifically for the samples contained within the Corps of Engineers vibracores) was designed to be flexible enough to accommodate a variety of current and anticipated analytical needs and to act as a guide for studies on other continental shelves where grades and compositions of heavy-mineral assemblages differ from those found in ACS sediments. The principal objective is to assemble a regional reconnaissance database that shall show grades, compositions, and areal/vertical distribution patterns of heavy minerals in ACS sediments. Studies of the economic geology of surficial sediments based on grab samples (Grosz and Escowitz, 1983; Grosz and others, 1986; Grosz and Nelson, 1989) show high regional and local variability; studies of vibracore samples also show high variability in grade and composition with depth in the sedimentary column (Grosz and others, 1989a, 1989b). In the past, most of the advances in laboratory-scale detrital mineral separation and identification have been made by sedimentary petrologists who sought to resolve stratigraphic and sedimentologic problems. For these purposes, relatively small amounts (usually on the order of tens of grams) of bulk sample were considered appropriate. Because the initial sample size was small and most studies sought to analyze a narrow size fraction (usually the 2- to 3-phi, 0.250- to 0.125-mm, less often the 3- to 4-phi, 0.125 to 0.0625-mm, size interval as well) for their heavy-mineral content, particle-sparsity biases (Clifton and others, 1969) precluded an accurate characterization of the full heavy-mineral assemblage present in sediment samples. Methods of separation utilized in such studies relied on initial screening to isolate the size fraction of interest and subsequently processing the recovered size fraction by sink-float methods (generally by use of bromoform having a specific gravity of 2.85) to recover the heavy-mineral component. Volume percentages of individual mineral species were then determined by methods utilizing 300 to 500 point-counted grains from slide mounts. This (and modifications of this) method appears to have worked satisfactorily for the resolution of stratigraphic and sedimentologic problems; however, the problems confronting the economic geologist in assessing the resource potential of heavy-mineral concentrations in continental shelf sediments necessitated a series of modifications in sample processing and analytical methods.

The freshly collected vibracores contain wet sediment in which the sedimentary structures are usually retained intact or are only slightly disturbed. During the 10- to 20-year period over which the Corps of Engineers' vibracores were processed for information, stored first at Fort Belvoir, Virginia, then shipped to the University of Texas at Arlington for storage, and finally shipped to the USGS in Virginia, they have dried completely. The dry nature of the contained sediments, the repeated shipping, and the removal of samples either by splitting the cores lengthwise or by drilling through the core liner, have, in many instances, disrupted the vibracores to the extent where sedimentary structures are not recognizable. Furthermore, most of the sediment contained within these vibracores is unconsolidated sand. These characteristics made the vibracores of little use to small-scale studies of sedimentary textures and mineral distribution pat-

terns. However, because of the large volumes of sediment in these vibracores, infrequently occurring heavy-mineral species within the heavy-mineral assemblages were identified. Although large-volume samples for these studies are considered to be critically important, particularly in reconnaissance phases, retention of intact portions of fresh (wet) vibracores is equally important.

The sample processing and analysis procedure discussed in the following sections is shown schematically in Figure 1. Processing of vibracore samples begins with lengthwise splitting of the plastic core liner (7.6- to 10.2-cm inner diameter; 0.64-cm wall thickness) either by use of a router (Figure 2) or by other suitable means, such as a static blade cutter (Figure 3). Care should be taken not to introduce plastic shards into the sediment because they are soluble in the heavy liquids used and in acetone. The top half of the split core is removed, and the bottom half is scraped clean by using a spatula to expose a flat surface for examination. Sedimentary structures, color (if wet), texture, composition, and fauna are noted. The opened core is photographed (Figure 4) in 30-cm increments that have approximately 3-cm overlaps between sequential photographs.

Samples from the vibracores were selected on the basis of textural criteria; from vibracores that have one sedimentary texture, they averaged about 1.5 m in length, and, from those that have more than one sedimentary texture, they varied in length. After removal of materials used in age dating (shells and peat), the sediment was weighed. All vibracores used in this study were channel sampled along the length of each sample; 300 to 500 g of bulk sediment were removed for archival and grain-size analysis purposes. The balance of the sediment from the Corps of Engineers' vibracores was processed for heavy-mineral content as described in following sections. Half of each core collected between 1986 and 1988 was processed for heavy minerals, and the other half was archived.

Because the cores ranged up to 6.5 m in length, sample identification numbers consisted of the unique core number followed by "-1", "-2", and so forth, where "-1" refers to the sample from the upper portion of the core (that is, from the water-sediment interface to some specified depth), "-2" refers to the next interval down, and so on to account for the entire length of the core. Each sample was placed in a 20-liter plastic bucket to determine the net sediment weight on a dry basis. For wet sediments, the dry-weight was based on weighing, drying, and reweighing 50 to 10- to 100-g aliquots of homogenized sediment. All weight calculations referred to in this report are on a dry-weight basis.

SAMPLE CONCENTRATION

Dividing the vibracores into discrete samples yielded an average of about 7 kg of sediment and ranged from 1 to 20 kg. To determine the gravel fraction, the sample was wet-sieved through a 10-mesh (2.00-mm opening) U.S. Standard stainless steel sieve. An undetermined, but generally small, amount of predominantly clay- and a lesser amount of silt-sized material was lost from the samples during this procedure. Modifications to the process can be made to recover

these fine-grained fractions if future studies require their analysis. The mass of sediment available for the recovery of heavy minerals after this step averaged 4.9 kg and ranged from 0.8 to 19.7 kg.

Efficiency and consistency of heavy-mineral recovery, ease of operation, clean-up time between sample runs, and cost resulted in the selection of a Humphreys three-turn spiral concentrator with molded rubber lining (Figure 5) for preconcentration. The selection of this equipment does not imply that others would not have performed satisfactorily. The sediments obtained from the vibracores (predominantly sand) made the spiral concentrator best suited for the task.

The operation of the spiral concentrator requires a constant water flow of about 20 L/min which carries approximately 20 percent solids (sediment). The sample is introduced into the hopper at the top of the spiral concentrator and carried down the spiral trough by the flowing water. The light minerals (predominantly quartz, feldspar, and shell fragments) are centrifugally thrown to the outside edge of the trough whereas the heavy minerals lag within a few centimeters of the inner edge of the spiral trough because of their higher density (Figure 6). An adjustable splitter placed at the lower end of the spiral concentrator separates the light minerals from the heavy minerals and routes them into separate containers. The light fraction was passed through the spiral concentrator several times to assure maximum recovery of heavy minerals. The heavy-mineral concentrate (spiral heavies) was also passed through the spiral as many as three times to remove as much of the light-mineral fraction as possible. For the Virginia study, this procedure recovered an average of 55 percent of the heavy minerals from the bulk sample (the range was between 5 and 95 percent) and resulted in a concentrate averaging 320 g, which represented approximately 5 percent of the bulk sample weight. Similar procedures on samples from offshore of Cape May, New Jersey, resulted in an average of 87 percent recovery; from offshore of central Florida, in an average of 75 percent recovery; and from Long Island Sound, New York, in an average of 82 percent recovery. Poor recovery is usually associated with muddy samples, poorly sorted samples, or samples containing significant carbonate (shell fragment) components. Because the size, the shape, and the composition of clastic grains impart different hydrodynamic properties to individual samples that affect their susceptibility to recovery by differing methods of separation, a 250- to 350-g aliquot of homogenized sediment was grab sampled from the material rejected by the spiral (spiral lights) for control purposes. The spiral concentrator was thoroughly washed between samples to reduce cross-sample contamination. The heavy-mineral concentrate and the aliquot of rejected material were dried, weighed, and then processed by heavy-liquid separation techniques.

HEAVY-LIQUID SEPARATION

As pointed out by Krumbein and Pettijohn (1938), a heavy liquid should have the following attributes to be effective: inexpensive, easily prepared or purchased, transparent, liquid at ordinary temperature, noncorrosive, chemically inert towards most minerals, odorless, fluid rather than viscous, to

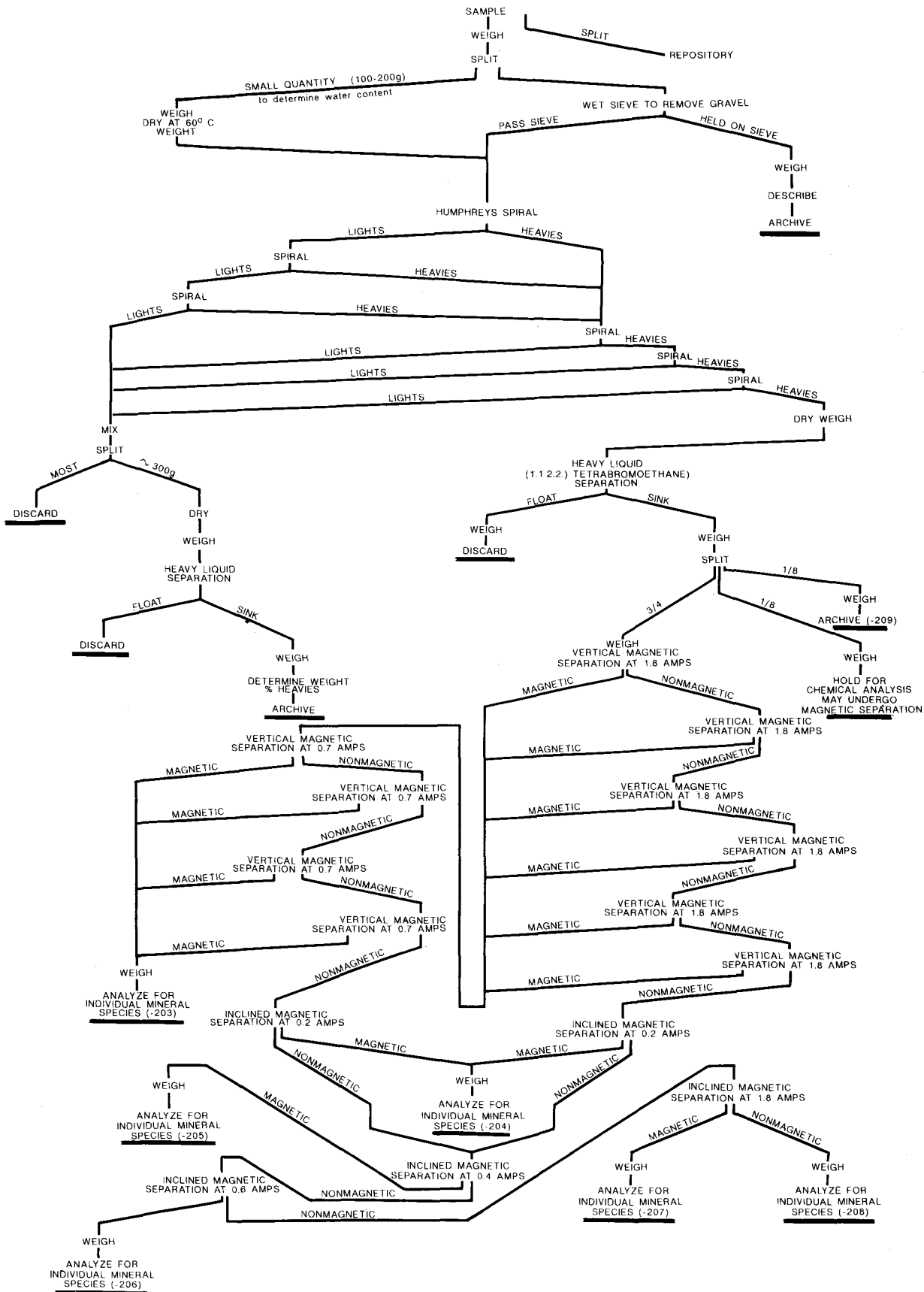


Figure 1. Flowchart showing the scheme of sample processing and analysis.



Figure 2. Photograph showing router apparatus utilized to split vibracores lengthwise.

and easily diluted and recovered. None of the heavy liquids now in use have all these qualities; however, some have been proven to be better than others. For the purposes of this, and other parallel studies on the ACS, acetylene tetrabromide ($C_2H_2Br_4$), which has a specific gravity of 2.96, was used. In laboratories where heavy liquids are used extensively it is necessary to standardize procedures as much as possible. Because the original investment in large quantities of heavy liquids is comparatively high and they are toxic, efforts should be made to recover the maximum amount of the liquid.

Complete recovery is very seldom realized. However, it is possible to keep the loss of most liquids under about 1 percent on any one separation. When using the volatile liquids in large volumes, all operations should be carried out under well-ventilated hoods. The transfer of liquids from stock bottles to separatory funnels should be done in comparatively small volumes so that loss by dropping or spilling can be kept to a minimum.

The simplest and most widely used method for heavy-mineral separation is the use of liquids in separatory funnels (Figure 7). The heavy liquid and the mineral grains are introduced into the funnel and agitated by using a glass stirring rod. The mixture is allowed to stand until the light minerals float, the heavy minerals sink, and the two fractions are completely separated. The light minerals should be agitated several times to allow all the trapped heavy minerals

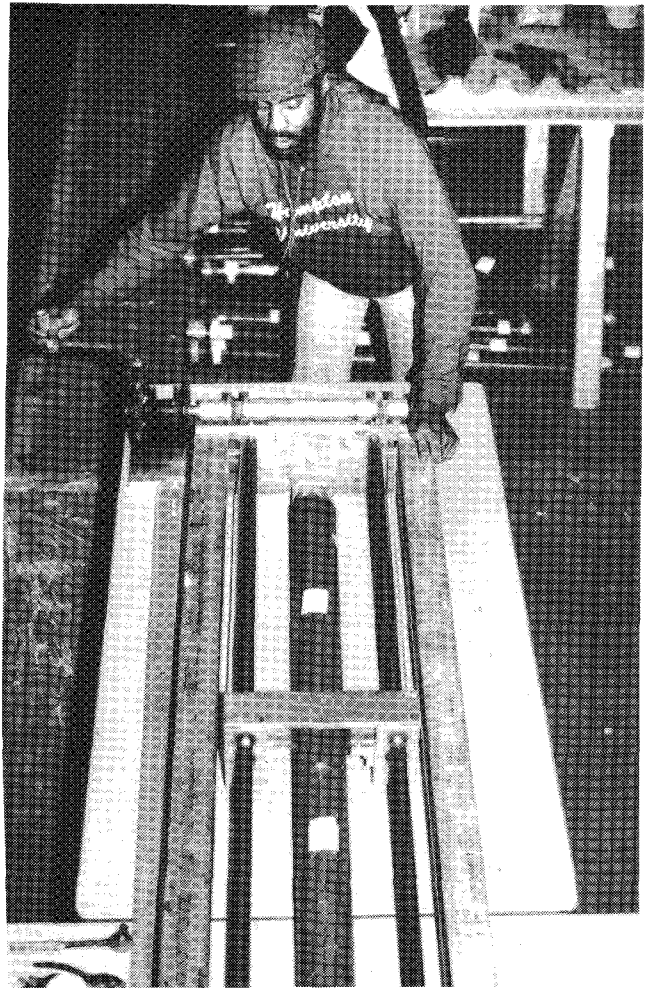


Figure 3. Photograph showing static blade cutter apparatus utilized to split vibracores lengthwise.

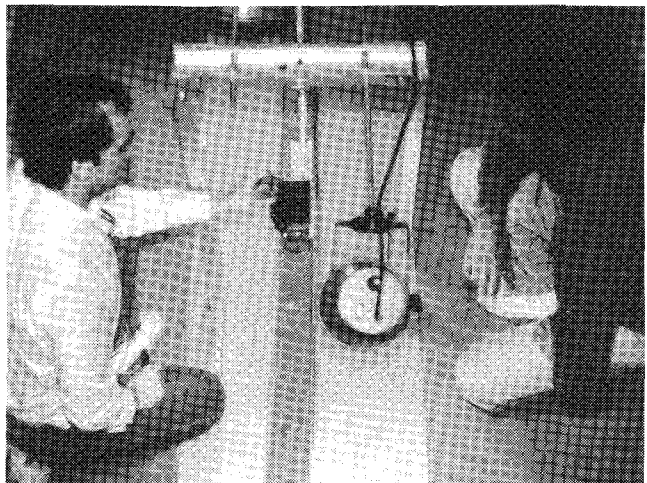


Figure 4. Photograph showing setup of equipment utilized to photograph split vibracores.



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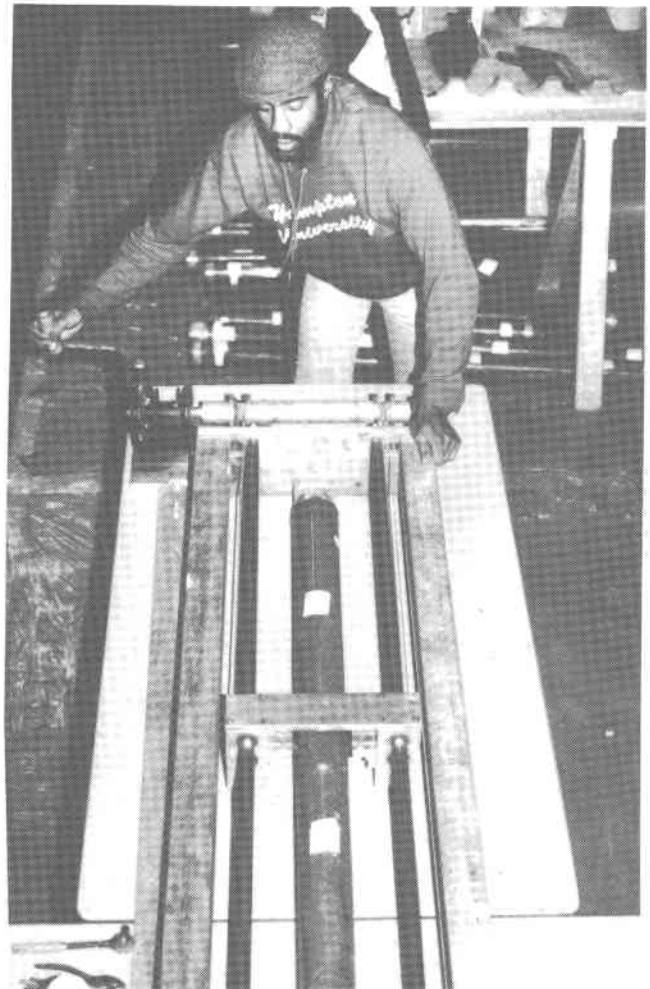


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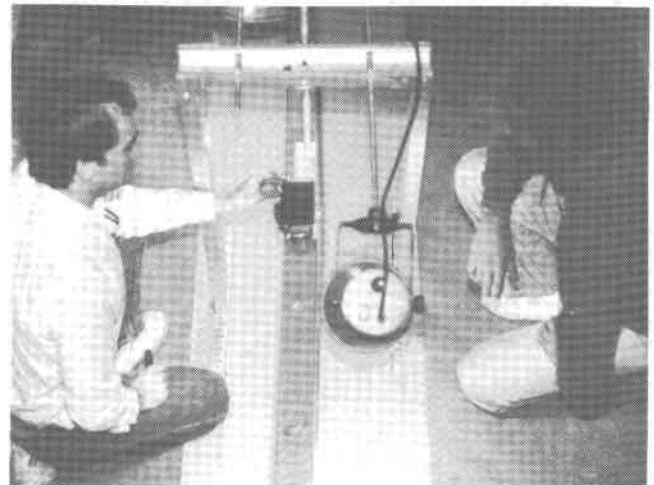


Figure 4. Photograph showing setup of equipment utilized to photograph split vibracores.

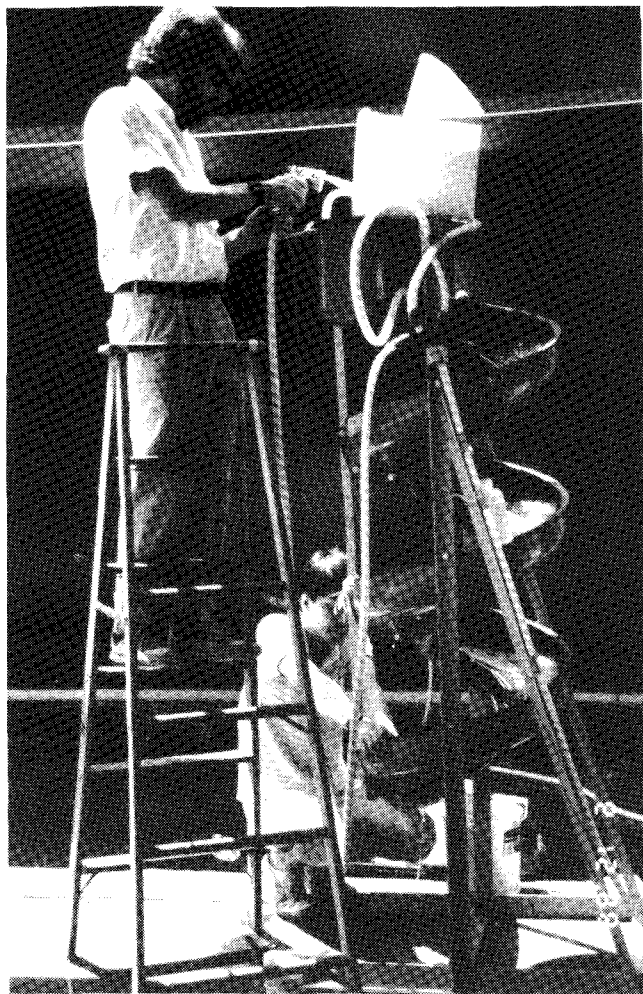


Figure 5. Photograph of three-turn spiral concentrator.

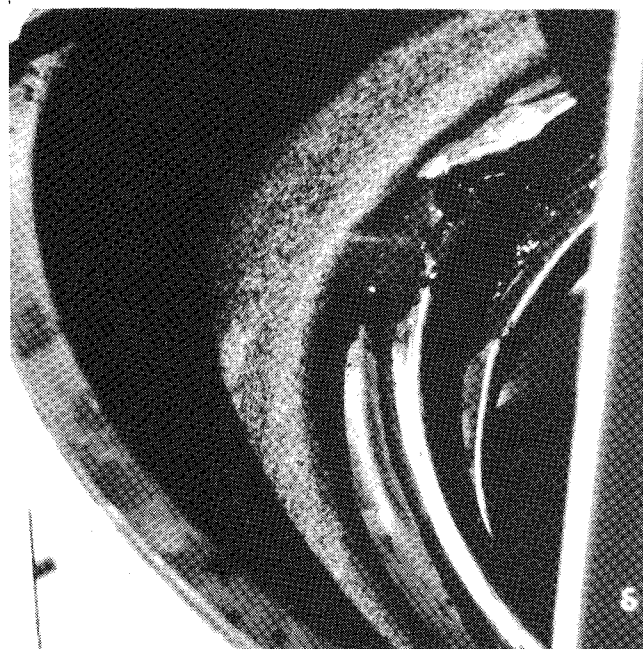


Figure 6. Close-up photograph showing separation of heavy (right) from light (left) minerals in the spiral trough.

sink. The heavy fractions are tapped by turning the stopcock and are allowed to pass through to a filter setup. Fine-grained material has a tendency to clot because the heavy minerals drag down some of the light minerals. A slow introduction of the sample into the separatory funnel along with frequent gentle agitation reduces, but does not completely eliminate, the clotting problem. After all the heavy minerals are tapped and the grains are filtered from the liquid, a new filter setup is made, and the remaining liquid and light minerals are tapped. A filtering process done under vacuum saves time and recovers a greater volume of the heavy liquid. The filters containing the light and the heavy minerals are washed liberally with acetone. The heavy liquid is recovered from the acetone washings by either using a water-wash process or by bubbling air through the washings until the specific gravity is determined to be acceptable.

The methods described above are not completely satisfactory for producing pure heavy-mineral separates, particularly if fine-grained material is present. Furthermore, the large volumes of heavy liquid that are needed for these samples result in a loss of more heavy liquid with each separation. Centrifuging overcomes both of these problems, but the use of the centrifuge precludes the rapid processing of large-volume samples.

The spiral heavies and the spiral lights were processed to obtain their "pure" heavy-mineral content by the method described above. Weights of all fractions were recorded. The heavy minerals recovered from the spiral heavies comprise the recovered heavy-mineral (RHM) fraction. The total heavy-mineral (THM) content of the bulk samples was approximated by methods described in the section "Mineral Database." The RHM fraction averaged approximately 100 g and ranged from 8.8 to 1227 g; the THM content averaged 229 g for the Virginia samples.

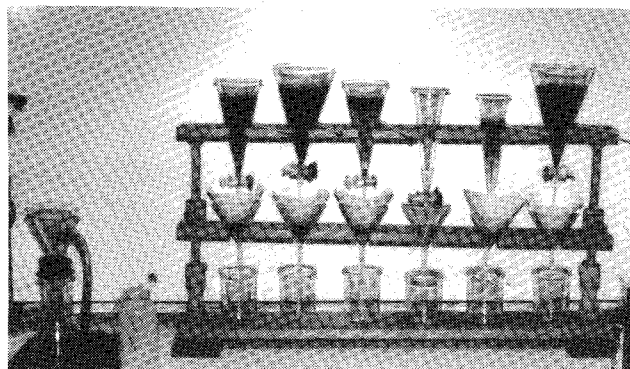


Figure 7. Photograph showing apparatus utilized for sink-float separation of heavy from light minerals in heavy liquid.

MAGNETIC MINERAL SEPARATION

The volumes of heavy minerals recovered by the (Humphreys) spiral and the heavy-liquid processing were large enough for archival and mineralogic determinations and chemical analysis. Archived samples are necessary for grain size distribution, magnetic susceptibility, gamma-ray suscep-



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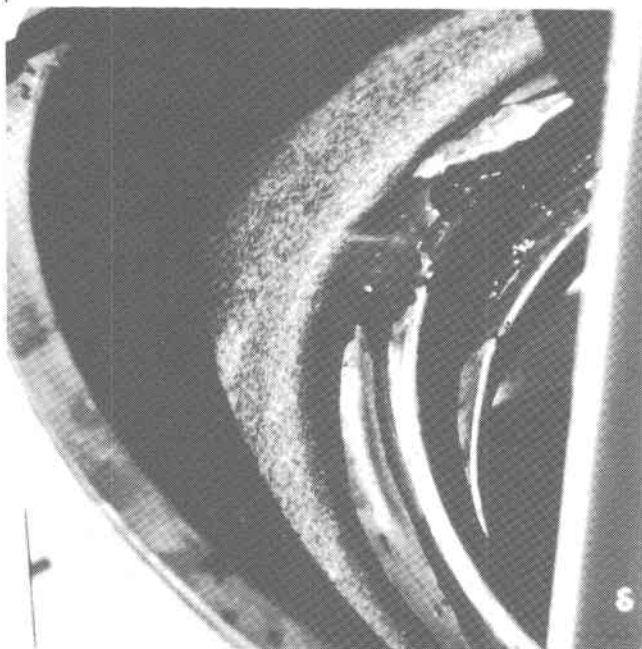


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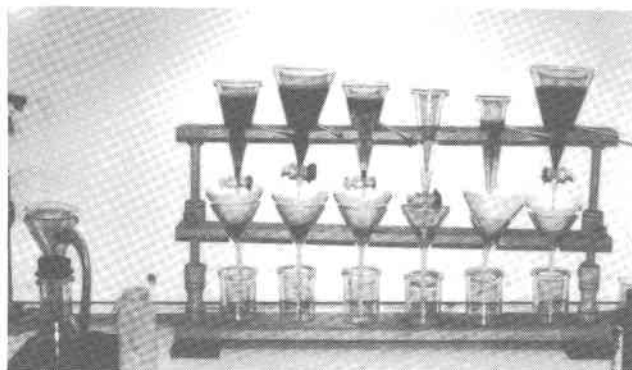


Figure 7. Photograph showing apparatus utilized for sink-float separation of heavy from light minerals in heavy liquid.

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tibility, density, and induced polarization susceptibility measurements. A Jones splitter was used to obtain the three portions consisting of 12.5 volume percent for archiving, 12.5 volume percent for chemical analysis, and 75.0 volume percent for optical mineralogy. As the immediate objective of these studies is to reconnoiter heavy-mineral concentrations, detailed mineralogy on a large number of samples is too time consuming. Multi-element chemical analyses of the magnetic fractions from one portion of the RHM assemblage were planned to help identify mineral species that are difficult to resolve by the mineral identification methods discussed in the next section. Another portion of the RHM assemblage was retained for mineralogic analyses by optical methods. This was done to ensure that high-value, low-frequency mineral species, such as monazite, rutile, xenotime, cassiterite, and gold, had a significant chance to be identified and quantified in this reconnaissance study.

The splits retained for mineralogic determinations were separated into magnetic fractions by using a Frantz Magnetic Barrier Laboratory Separator (MBLS). This fractionation was done to reduce the number of mineral species in each magnetic fraction and to facilitate mineral identification and quantification. This procedure also should be followed with the split for chemical analyses to reduce inter-elemental interferences associated with polymineralic assemblages; this was not followed for the Virginia samples.

The Frantz Isodynamic Magnetic Separator (FIMS) is a versatile instrument and can produce excellent concentrates of many minerals. Substantial literature has been published on the subject of mineral separations performed with the FIMS (McAndrew, 1957; Gaudin and Spedden, 1943; Flinter, 1959; Hess, 1966; Nessel and Finch, 1980).

The MBLS has a significant advantage over the FIMS in the ratio of magnetic force to field intensity. Material is visible as it enters the field and undergoes separation at the magnetic barrier. These conditions result in better control, superior sensitivity, and greatly reduced processing time. A FIMS can be converted to an MBLS by using retrofit equipment. Much of the information in the literature about the FIMS is useful for operating the MBLS.

As the result of differences in design, the direction of magnetic force in the working space of the MBLS is the reverse of that in the FIMS, and the side slopes used in separating minerals according to their magnetic susceptibilities, therefore, also are reversed. For the FIMS, the magnetic force moves particles against a component of gravitational force, whereas, for the MBLS, gravitational force is used to move particles against a magnetic force. The range of field intensity provided by the two separators is substantially the same (0 to 20,000 Gauss). At any field intensity selected, however, the effective force provided by the MBLS is about 3 times greater than the effective force provided by the FIMS. A small adjustment of current to the MBLS results in a substantially greater change in the effective force than does the adjustment of current to the FIMS. Separation of materials that differ slightly in magnetic susceptibility is improved when the MBLS is used. The number of minerals that respond to magnetic force sufficiently for separation also is extended. At high magnetic force field intensities, the barrier field of the MBLS is sufficient to separate paramagnetic and weakly

diamagnetic materials that cannot be separated by using the FIMS.

A sample consisting of minerals that differ in magnetic susceptibility is usually processed by separating the most strongly magnetic component first, and then separating of the other components in order of declining susceptibility. Separation of mineral mixtures that have susceptibilities ranging from ferromagnetic to diamagnetic is expedited by the initial removal of ferromagnetic minerals. Otherwise, the most magnetic minerals tend to be held by the pole pieces or on the chute surface inside the gap and thus divert other minerals from their normal paths.

The methods of removing ferromagnetic particles from heavy-mineral assemblages before paramagnetic separation include the use of hand-held magnets passed over the concentrate, the use of low current settings (10 to 20 mA) on the MBLS, and various configurations of the electromagnet that offer large surface areas over which the concentrates can be passed. These three methods offer individual advantages; however, in processing large-volume samples, a more rapid, replicable, and consistent method is necessary. For our processing, the magnetic poles of the MBLS were rotated into a vertical position and then the tops of the poles were inclined toward the operator. A 1.125-in. diameter, 0.225-in.-thick wall, glass tube was fastened to the pole pieces straddling the gap to provide a conduit for a flowing stream of concentrate containing ferromagnetic minerals. Then the magnetic field strength is set at the maximum (about 2.0 A; at this current setting, the magnetic field strength tends to decay as the magnet's coils heat up), the sample is introduced into the glass tube. As the grains fall through the tube, the more magnetic minerals are preferentially pulled against the inner side of the tube near the pole pieces (Figure 8); the minerals that are less magnetic fall through the length of the tube into a container. After the initial pass, an empty container is placed at the bottom of the glass tube, the current is turned off, and the magnetic minerals are collected. This procedure is rapid, and repeated passes through this setup are recommended for the nonmagnetic minerals, especially for the fine-grained mineral assemblages.

The ferromagnetic minerals were processed through the same setup by using a lower current setting (0.5 to 0.7 A, depending on the mineral assemblage) to concentrate those minerals that have paramagnetic properties and those minerals that have magnetic inclusions, such as zircon, staurolite, aluminosilicates, garnet, amphibole group, and others. This process was effective in removing ferromagnetic minerals in about 10 minutes for 300 g of bulk concentrate sample.

The nonmagnetic-mineral fraction derived from the free-fall separation was processed through the MBLS in sequential passes at increasing current strengths. The factory-provided ammeter on the MBLS was shunted to a digital ammeter for increased accuracy (a digital ammeter-equipped power controller is highly recommended for maintenance of current settings). Five mineral groups were thus generated at current settings of 0.2, 0.4, 0.6, 1.8 A, and nonmagnetic at 1.8 A. Each mineral group was weighed, bottled, and labeled.

General procedures for the determination of current and slope settings for the MBLS are provided by the manufacturer; optimal settings for any mineral assemblage must be

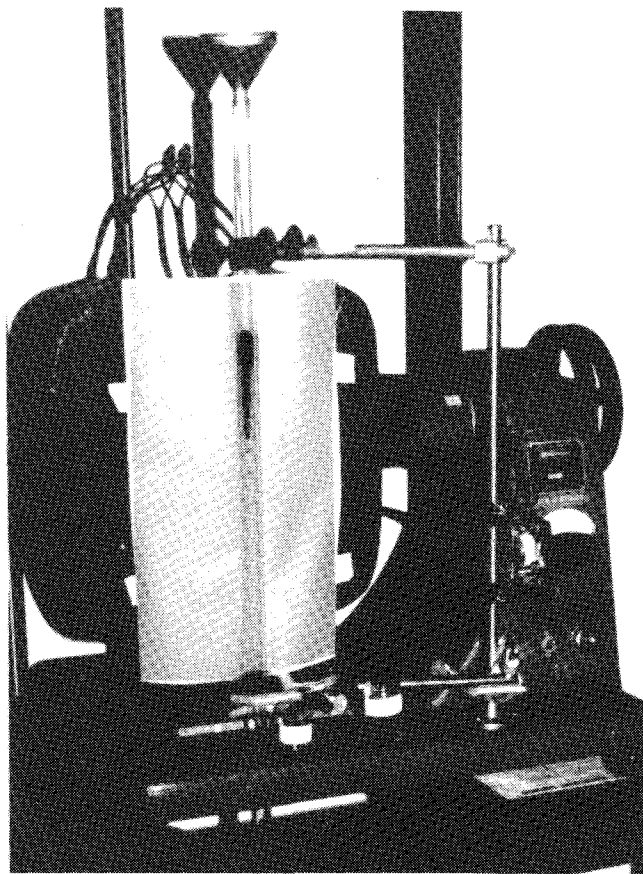


Figure 8. Photograph of magnet configuration utilized to separate ferromagnetic minerals from bulk heavy-mineral concentrates.

determined by the user. Forward and side slopes of the MBLs ranged from 15° to 20° and 15° to 25°, respectively. The current and the slope settings defined above were appropriate for the heavy-mineral assemblages found offshore of Virginia; however, for heavy-mineral assemblages elsewhere on the ACS higher current settings and steeper side slopes (up to 35° to 45°) provide cleaner and more rapidly processed separates. For our reconnaissance work, the emphasis was on processing many large samples in a short period of time.

A consequence of the time constraint is less-than-pure concentrates that have a scatter of given mineral species across a number of magnetic fractions because of variations in mineral composition and the presence of polymineralic grains. Because many heavy minerals have a wide range of possible compositions that results in a wide range of possible magnetic susceptibilities for a particular mineral, optimal current settings for extraction must be determined empirically for each suite. The mineralogy of the resultant magnetic fractions is discussed in the section "Mineral Identification and Quantification."

Geochemical data can be used to indicate the presence of potentially economic mineral species not distinguishable by rapid optical mineralogical analyses. The 12.5 volume percent split of the RHM fraction generated for chemical analyses also can be magnetically separated into three fractions. The first magnetic fraction should be derived in a manner identical

to that utilized for the ferromagnetic-mineral fraction. The second magnetic fraction should be generated at a current setting of 0.6 A, and the third magnetic fraction is the nonmagnetic minerals at 0.6 A. The geochemical data from these three magnetic fractions can then be used to indicate the presence of mineral species not easily identified by petrographic procedures; for example, high tin (Sn) values in the nonmagnetic mineral fraction may signal the presence of cassiterite.

MINERAL IDENTIFICATION AND QUANTIFICATION

To estimate mineral abundances, each magnetic-mineral fraction was examined by using reflected and transmitted light microscopes. Estimation was easy because only a few mineral species were present in each fraction. Comparison charts for visual estimation of percentage composition (Folk, 1951; Terry and Chillingar, 1955; Reid, 1985) and point-counting were used for this purpose. In addition to petrographic methods, X-ray diffraction analyses were used to identify some minerals; however, because of the reconnaissance nature of the work, all the mineral species were not identified. An "Others" category was estimated and included quartz, unidentified opaques, unidentified non-opaques, polymineralic grains, and clay balls. The identification of zircon and monazite was aided by the use of ultraviolet light. The principal criteria for identification were magnetic susceptibility, grain shape, color, physical properties (that is, cleavage), streak, fluorescence, solubility in acids, and optical properties.

The estimated percentage abundances of each mineral species was multiplied by the weight of each fraction. The total percentage for each mineral was calculated by summing their weights across the magnetic fractions in which the mineral occurred. Because the average of specific gravities of all species in each magnetic fraction are generally similar, differences in specific gravities of the mineral species were ignored in the calculations. Although the calculated percentages are not true weight percentages, the differences are probably small. An example of the observations and calculations used to determine the weight percentages of minerals for a sample are given in Appendix I.

Because silt- and clay-rich sediments are difficult to separate and identify, the amounts of ferromagnesian micas and lighter heavy minerals (specific gravity <3.50) are probably underestimated in the analytical table, and higher density minerals such as garnet and zircon may be overestimated.

The ferromagnetic-mineral fraction commonly is comprised of minerals containing magnetite mineral inclusions that should be in fractions separated by low magnetic field strength. X-ray fluorescence analyses of this fraction in two samples from offshore Virginia indicated titanium values in excess of what one would expect of magnetite. The excess could be explained by the presence of approximately 40 percent titanomagnetite (Oliver Fordham, Virginia Division of Mineral Resources, oral communication, 1988). This combination of magnetite and ilmenite is confirmed by geochemical analyses given elsewhere in this publication. Because optical identification of different opaque minerals in the

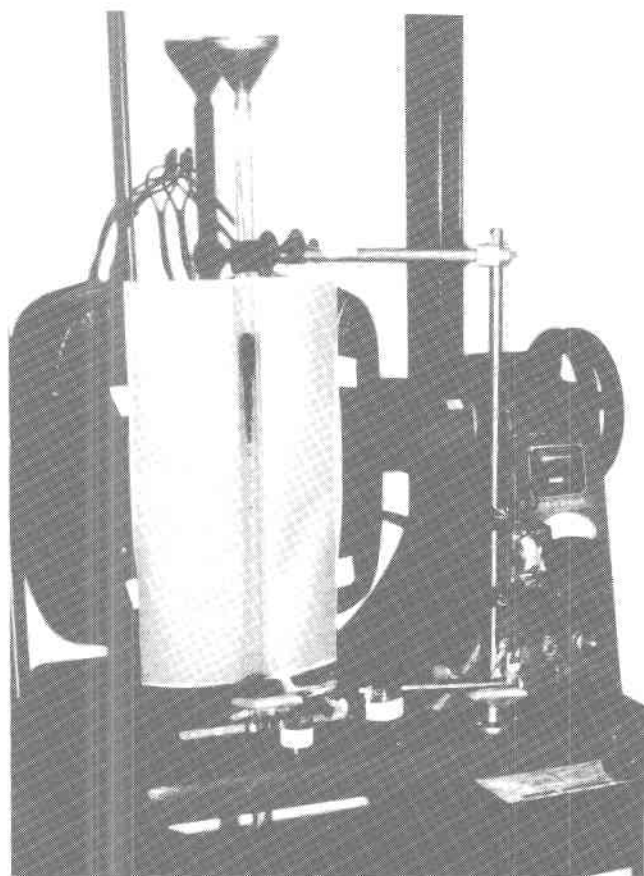


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ferromagnetic-mineral fraction is difficult without the use of polished grain mounts and the mass is small, the entire fraction is labeled "magnetite."

In addition to petrographic techniques, the paramagnetic-mineral fractions were examined using ultraviolet illumination. This technique aided the identification of monazite which had green fluorescence, and zircon which had yellow to orange fluorescence. Not all zircons fluoresce, for example, metamict zircons. Because quartz was often found in the non-magnetic at 1.8 A magnetic fraction, its weight was included in the heavy-mineral fraction. For the Virginia samples, a correction was made to the weight percentage of the total heavy minerals by subtracting the weight of quartz and is included in the calculation of data under column 151 in Appendix I. The decrease in the weight of the heavy minerals ranged from 2 to 18 percent of the uncorrected value and averaged about 3 percent for Virginia samples.

DATABASE

Ideally, an offshore mineral-resource database should contain all the variables generated by direct measurements as well as those derived by calculation. Because the formulae for calculating a number of derivative variables are discussed in detail later in this section, only the directly measured variables are discussed here. The variables that should be entered into a database and their units of measure are as follows:

<u>VARIABLE</u>	<u>UNIT OF MEASURE</u>
Sample number	
Latitude.....	Degrees and fractions of a degree
Longitude.....	Degrees and fractions of a degree
Water depth.....	Meters
Section length (vibracore).....	Centimeters
Bulk sample weight.....	Grams
Weight of:	
Gravel fraction.....	Grams
Sand-size fraction.....	Grams
Clay-size fraction.....	Grams
CaCO ₃ component.....	Grams
Mean grain size on a:	
+CaCO ₃ basis.....	Grams
-CaCO ₃ basis.....	Millimeters
Sorting on a:	
+CaCO ₃ basis.....	Millimeters
-CaCO ₃ basis.....	Millimeters
Skewness on a:	
+CaCO ₃ basis.....	Millimeters
-CaCO ₃ basis.....	Millimeters
Kurtosis on a:	
+CaCO ₃ basis.....	Millimeters
-CaCO ₃ basis.....	Millimeters
Weight of:	
spiral derived HM conc.....	Grams
spiral gangue subsample.....	Grams
HM in spiral gangue.....	Grams
Composition of:	
gravel fraction.....	Percentage of shell, rock, quartz, and so forth
HM fraction.....	Percentage of minerals

For the samples from Virginia, several databases were used. One of these contains location data and core (sample) length, and two others hold measured weights, observed mineral compositions, and calculated or derived values.

The original concept and the outline for the database presented here were the efforts of the senior author; modifications of calculation formulae for the 20/20 spreadsheet program available on the VIMS Prime computer were made by C.R. Berquist and C.T. Fischler. Other collaborating institutions on the Atlantic seaboard utilized the *Lotus 1-2-3* spreadsheet program. The database (Appendix I) that has values for two samples is shown as an example. Each row contains the data for one sample. The column headers (variables) are generally self-explanatory; however, they are discussed briefly in the following section. Column data originates from observation, measurement, or calculation. The calculation formulae (Appendix II) follow the database (Appendix I).

DISCUSSION OF COLUMN HEADERS

Values in column 11 were calculated by determining the amount of water in a 50- to 100-g subsample and correcting the initial bulk sample weight. Because not all samples were wet (USGS vibracores were dry when received), some columns in the final database contain 0 or "ERR" (where, in fact, there is no error). The weight of sediment greater than 2.00 mm in diameter after wet sieving is given in column 12. Column 13 gives the weight of a subsample from the spiral light (SL) fraction; column 14 gives the weight of the portion which sank in heavy liquid (spiral lights tetrabromoethane sink). Column 15 is the final spiral concentrate; column 16 gives the weight of the spiral heavy, tetrabromoethane sink fraction. Column 17 is a check for gross errors in weighing sample fractions (see formulae in Appendix II). Column 18 is the percentage of heavy minerals in the spiral light fraction and approximates the amount of heavy minerals lost during the spiral concentration procedure to the spiral lights fraction (column 19). Column 20 gives the percentage of the heavy minerals recovered by the spiral concentration procedure from the calculated total amount of heavy minerals in the sample and is a measure of the efficiency of the spiral concentrator in recovering heavy minerals from a given sample. Column 21 is the calculated total amount of heavy minerals in the sample based on the recovered and the lost heavy minerals during the spiral concentrating procedure. Column 22 is the weight percentage of the heavy minerals recovered in the spiral concentrate and subsequent heavy-liquid procedure.

The mud (silt and clay), gravel (>2.00 mm), and sand size distributions were determined for some samples by using a split of the repository sample; columns 23 to 28 give these data. The mean size of the sand fraction of some samples (column 30) were determined by using a Rapid Sediment Analyzer.

The weights of the magnetic fractions derived by use of the free-fall and MBLS magnetic separators are shown in columns 31 to 36; "203" is the most magnetic fraction, and "208" is the least magnetic fraction. The sum of these weights are given in column 37. Columns 38 to 40 show the weights

of the splits of the RHM reserved for archive (-209; 12.5 volume percent of the RHM fraction), geochemical analyses (-200, -201, and -202; 12.5 volume percent of the RHM fraction), and optical analyses (-203, -204, -205, -206, -207, and -208; 75.0 volume percent of the RHM fraction). For the Virginia samples, no magnetic separation of the geochemical split was made, and the entire weight is reported in column 39. Gross weighing errors are checked in column 41. Observed amounts of individual heavy-minerals in each magnetic fraction (203 to 208) are shown in columns 42 to 116; summation columns insure that the compositions add up to 100 percent.

Columns 117 to 131 show the gram-equivalent weight of an observed mineral for an entire sample (fractions 203 to 208) calculated by summing the gram equivalent of the visually estimated frequency of the mineral in each magnetic fraction. By using these data, the weight percentage of the observed minerals in the RHM fraction is calculated and shown in columns 132 to 147. Column 147 is the sum of ilmenite + leucosene + rutile + zircon + monazite + aluminosilicates (sillimanite, kyanite, and andalusite).

Columns 148 and 150 are copied from columns 22 and 21, respectively. "CORR" in columns 149 and 151 correct columns 148 and 150 by removing the amount of quartz observed in the 208 fraction from the mass of RHM and THM. Column 152 is a check where THM should be always greater than RHM. In column 153 the weight percentages of the observed minerals are added and checked to be certain that they total to 100 percent.

With respect to the entire bulk sample (as opposed to the concentrate), the concentrations of heavy minerals are shown in columns 154 to 169; the sum is shown in column 170. These values were calculated by multiplying the mineral abundance in the concentrate by column 151. Column 171 is a check that the sum of the mineral percentages (columns 154 to 168) and the corrected THM are the same.

APPROXIMATE TIME REQUIREMENTS FOR ANALYSIS OF AN OFFSHORE VIRGINIA SAMPLE

The sample analysis procedure that we have described requires numerous labor-intensive tasks. Based on the experience that we have gained during this study, the average times required to perform the various tasks are as follows:

TASK	TIME PER SAMPLE (in minutes)
Cut, describe, and photograph core.....	45
Wet sieve gravel fraction.....	15
Spiral concentrate sand-sized fraction.....	30
Dry and weigh spiral fractions.....	15
Heavy-liquid separation.....	45
Remove ferromagnetics (-203 fraction).....	10
Magnetic fractionation (-204 to -208 fractions).	120
Mineral identification/quantification.....	180
Data entry.....	30
Total.....	490 (about 8 hr20 min)

The volume, texture, heavy-mineral content and composition,

heavy-liquid separation funnel capacity, balance capacities, and other variables have significant and highly variable effects on the time required to analyze each sample.

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Appendix I.

Example of the observations and calculations used to determine the weight percentages of heavy minerals in a sample. This Appendix shows column titles and data for two core samples in one of the Virginia spreadsheet files. Column 0 contains the sample number; columns numbered 1 to 171 contain measured or observed values and derived values (by use of formulae; see Appendix II) for each sample. Each row represents an individual sample.

The original database allowed for observed concentrations of amphibole and pyroxene group minerals but was converted later so that pyroboles (undifferentiated pyroxene and amphibole group minerals) assumed the positions of the amphiboles columns. The columns (55, 64, 77, 92, 107, 123, 138, 160) ordinarily used for pyroxenes, therefore, are not used.

Abbreviations, and their explanations are: WT, weight; g, grams; SP, spiral; SLTBS, spiral lights, tetrabromoethane sink fraction; SHTBS, spiral heavies tetrabromoethane sink fraction; arc, 12.5 percent volumetric split of the SHTBS for archival purposes; anal, 12.5 percent volumetric split of the SHTBS for chemical analyses; THM, total heavy minerals; RHM, recovered heavy minerals; EHM, economic heavy minerals; SIK, undifferentiated aluminosilicates (sillimanite, kyanite, andalusite); ND, not determined.

0	1	2	3	4	5	6	7	8	9	10	11			
SAMPLE NUMBER	WT (g)	WT BUCKET & SAMPLE (g)	NET WT SAMPLE (g)	BEAKER WT (g)	WET WT & BEAKER (g)	DRY WT & BEAKER (g)	WET WT SAMPLE (g)	DRY WT SAMPLE (g)	WATER IN SAMPLE (g)	WATER WT (g)	DRY WT SAMPLE (g)			
1-1	950	8300	7350	66.15	188.91	177.41	122.76	111.26	11.50	9.37	6661			
1-2	951	8300	7349	62.77	188.54	171.14	125.77	108.37	17.40	13.83	6332			
12	13	14	15	16	17	18	19	20	21	22	23			
WT. > -1.0 PHI (g)	SPLIGHTS SUBSAMPLE (g)	SLTBS (g)	SPIRAL HEAVIES (g)	WT SHTBS (g)	WT SHTBS- (arc+anal+ 75% split)	% HM IN SPIRAL LIGHTS	WT HM IN SPIRAL LIGHTS	% RECOVERY BY SPIRAL	WT % THM	WT % RHM	WT MUD (g)			
205.83	373.04	1.81	330.92	115.16	-0.06	0.49	30.72	78.94	2.19	1.73	0.90			
48.30	298.70	2.51	575.85	155.06	0.11	0.84	48.37	76.22	3.21	2.45	2.22			
24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
WT SAND (g)	WT GRAVEL (g)	WT % SAND	WT % MUD	WT % GRAVEL	SUM WT % GRAVEL+SAND +MUD	MEAN SAND SIZE (PHI)	WT (g)	WT (g)	WT (g)	WT (g)	WT (g)	WT (g)	WT (g)	WT (g)
39.71	1.42	94.50	2.10	3.40	100.00	ND	0.25	16.95	48.55	1.77	10.32	7.21	85.05	14.76
33.48	0.28	93.00	6.20	0.80	100.00	2.31	0.83	39.10	59.73	2.86	5.49	8.04	116.05	19.10

39	40	41	42	43	44	45	46	47	48	49	50		
WT 12.5 % ANALYTIC (g)	WT 75.0 % MINERALOGY (g)	DIFF 75.0% -SUM WT (g)	203 % MAGNETITE	203 % ILMENITE	203 % GARNET	203 % EPIDOTE	203 % PYROBOLES	203 % OTHERS	SUM %	204 % ILMENITE	204 % GARNET		
15.21	85.25	0.20	97	0	3	0	0	0	100	86	6		
19.57	116.28	0.23	94	0	2	1	1	2	100	38	22		
51	52	53	54	55	56	57	58	59	60	61	62		
204 % EPIDOTE	204 % STAUROLITE	204 % PYROBOLES	204 % TOURMALINE	COLUMN NOT USED	204 % LEUCOXENE	204 % OTHERS	SUM %	205 % ILMENITE	205 % GARNET	205 % EPIDOTE	205 % STAUROLITE		
1	0	5	0	2	2	0	100	21	35	7	1		
1	0	35	0	1	1	3	100	9	15	10	15		
63	64	65	66	67	68	69	70	71	72	73	74	75	
205 % PYROBOLES	COLUMN NOT USED	205 % SPHENE	205 % TOURMALINE	205 % LEUCOXENE	205 % ZIRCON	205 % OTHERS	SUM %	206 % ILMENITE	206 % GARNET	206 % EPIDOTE	206 % STAUROLITE		
16	0	0	8	4	0	8	100	10	20	5	25		
40	0	0	7	1	0	3	100	0	5	2	0		
76	77	78	79	80	81	82	83	84	85	86	87	88	89
206 % PYROBOLES	COLUMN NOT USED	206 % RUTILE	206 % SIK	206 % SPHENE	206 % TOURMALINE	206 % LEUCOXENE	206 % MONAZITE	206 % ZIRCON	206 % OTHERS	SUM %	207 % ILMENITE	207 % GARNET	207 % EPIDOTE
30	0	0	0	1	0	0	1	0	8	100	5	8	8
45	0	0	0	2	14	12	0	0	20	100	0	4	0

90	91	92	93	94	95	96	97	98	99	100	101	102	103
207 % STAUROLITE	207 % PYROBOLES	207 % USED	207 % RUTILE	207 % SIK	207 % SPHENE	207 % TOURMALINE	207 % LEUCOXENE	207 % MONAZITE	207 % ZIRCON	207 % OTHERS	207 % ILMENITE	208 % GARNET	208 % GARNET
0	0	0	0	5	0	0	10	0	0	44	100	0	0
0	1	18	36	3	1	5	0	0	7	25	100	0	0
104	105	106	107	108	109	110	111	112	113	114	115	116	117
208 % EPIDOTE	208 % STAUROLITE	208 % PYROBOLES	208 % USED	208 % RUTILE	208 % SIK	208 % SPHENE	208 % TOURMALINE	208 % LEUCOXENE	208 % MONAZITE	208 % ZIRCON	208 % OTHERS	208 % MAGNETITE	208 % MAGNETITE
1	0	0	8	30	0	0	0	1	0	50	10	100	0.24
0	0	0	9	24	0	0	0	1	0	37	29	100	0.78
118	119	120	121	122	123	124	125	126	127	128	129	130	131
SUM WT (g)	SUM WT (g)	SUM WT (g)	SUM WT (g)	SUM WT (g)	SUM WT (g)	SUM WT (g)	SUM WT (g)	SUM WT (g)	SUM WT (g)	SUM WT (g)	SUM WT (g)	SUM WT (g)	SUM WT (g)
25.47	19.20	4.55	2.99	9.15	0.58	2.68	3.88	3.39	3.88	3.39	0.02	3.60	9.29
20.23	17.94	6.43	8.96	38.93	1.71	3.91	4.64	1.69	4.64	1.69	0.00	3.36	7.26
132	133	134	135	136	137	138	139	140	141	142	143	144	145
WT %	WT %	WT %	WT %	WT %	WT %	COLUMN NOT	WT %	WT %	WT %	WT %	WT %	WT %	WT %
0.29	29.94	22.57	5.35	3.52	10.75	0.68	3.15	0.02	4.57	3.98	0.02	0.02	4.24
0.67	17.44	15.46	5.54	7.72	33.54	1.48	3.37	0.19	4.00	1.45	0.00	0.00	2.89

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146	147	148	149	150	151	152	153	154	155	156	157	158	159
WT % OTHERS	WT % EHM	WT % RHM	WT % RHM	WT % THM	WT % THM	DIFFERENCE THM % - RHM %	SUM OF MINERAL PERCENTAGES	MAGNETITE % IN BULK SAMPLE	ILMENITE % IN BULK SAMPLE	GARNET % IN BULK SAMPLE	EPIDOTE % IN BULK SAMPLE	STAUROLITE % IN BULK SAMPLE	PYROBOLES % IN BULK SAMPLE
10.92	42.01	1.73	1.72	2.19	2.18	0.00	100	0.01	0.65	0.49	0.12	0.08	0.23
6.25	26.62	2.45	2.42	3.21	3.18	0.01	100	0.02	0.55	0.49	0.18	0.25	1.07
160	161	162	163	164	165	166	167	168	169	170	171		
COLUMN NOT USED	RUTILE % IN BULK SAMPLE	SIK % IN BULK SAMPLE	SPHENE % IN BULK SAMPLE	TOURMALINE % IN BULK SAMPLE	LEUCOXENE % IN BULK SAMPLE	MONAZITE % IN BULK SAMPLE	ZIRCON % IN BULK SAMPLE	OTHER % IN BULK SAMPLE	EHM % IN BULK SAMPLE	SUM % HM IN BULK SAMPLE	CORR % HM IN BULK SAMPLE	WT % THM OF BULK	
	0.01	0.07	0.00	0.10	0.09	0.00	0.09	0.24	0.92	2.18	0.00		
	0.05	0.11	0.01	0.13	0.05	0.00	0.09	0.20	0.85	3.18	0.00		

Appendix II.

The formulae used in calculating the described variables are based on the column numbers in Appendix I.

COLUMN DESCRIPTION NUMBER	FORMULA IN TERMS OF COLUMN NUMBER [IN BRACKETS]
3 NET WEIGHT OF SAMPLE	[2]-[1]
7 WET WEIGHT OF SAMPLE	[5]-[4]
8 DRY WEIGHT OF SAMPLE	[6]-[4]
9 WATER WEIGHT IN SAMPLE	[7]-[8]
10 WEIGHT PERCENT WATER	[9]/[7]*100
11 DRY WEIGHT OF BULK SAMPLE	[3]-[3]*([10]/100)
17 WEIGHT LOSS DUE TO SPLITTING	[16]-([38]+[39]+[40])
18 WEIGHT % HM IN SPIRAL LIGHTS	([14]/[13])*100
19 WEIGHT HM IN SPIRAL LIGHTS	([18]/100)*([11]-[15])
20 % OF HM RECOVERED BY THE SPIRAL	100*[16]/([16]+[19])
21 WEIGHT % TOTAL HM IN SAMPLE	([19]+[16])*100/[11]
22 WEIGHT % RECOVERED HM	100*[16]/[11]
26 WEIGHT % SAND	([24]/([23]+[24]+[25]))*100
27 WEIGHT % MUD	([23]/([23]+[24]+[25]))*100
28 WEIGHT PERCENT GRAVEL	([25]/([23]+[24]+[25]))*100
29 SUM OF SAND, MUD AND GRAVEL %	SUM([26..28])
37 SUM OF MAGNETIC FRACTIONS	SUM([31..36])
41 WEIGHT LOSS DUE TO MAGNETIC FRACTIONATION	[40]-[37]
48 SUM OF % MINERAL SPECIES IN 203 FRACTION	SUM([42..47])
58 SUM OF % MINERAL SPECIES IN 204 FRACTION	SUM([49..57])
71 SUM OF % MINERAL SPECIES IN 205 FRACTION	SUM([59..70])
86 SUM OF % MINERAL SPECIES IN 206 FRACTION	SUM([72..85])
101 SUM OF % MINERAL SPECIES IN 207 FRACTION	SUM([87..100])
116 SUM OF % MINERAL SPECIES IN 208 FRACTION	SUM([102..115])
117 MAGNETITE (g) IN ALL MAGNETIC FRACTIONS	[31]*[42]
118 ILMENITE (g) IN ALL MAGNETIC FRACTIONS	[31]*[43]+[32]*[49]+[33]*[59] +[34]*[72]+[35]*[87]+[36]*[102]
119 GARNET (g) IN ALL MAGNETIC FRACTIONS	[44]*[31]+[50]*[32]+[60]*[33] +[73]*[34]+[88]*[35]+[103]*[36]
120 EPIDOTE (g) IN ALL MAGNETIC FRACTIONS	[51]*[32]+[61]*[33]+[74]*[34] +[45]*[31]+[35]*[89]+[36]*[104]
121 STAUROLITE (g) IN ALL MAGNETIC FRACTIONS	[52]*[32]+[62]*[33]+[75]*[34] +[90]*[35]+[105]*[36]
122 PYROBOLES (g) IN ALL MAGNETIC FRACTIONS	[53]*[32]+[63]*[33]+[76]*[34] +[91]*[35]+[106]*[36]+[46]*[31]
123 COLUMN NOT USED IN VIRGINIA STUDY	[55]*[32]+[64]*[33]+[77]*[34] +[92,8]*[35,8]+[107,8]*[36,8]
124 RUTILE (g) IN ALL MAGNETIC FRACTIONS	[78]*[34]+[93]*[35]+[108]*[36]
125 ALUMINOSILICATES (g) IN ALL MAGNETIC FRACTIONS	[79]*[34]+[94]*[35]+[109]*[36]+[65]*[33]
126 SPHENE (g) IN ALL MAGNETIC FRACTIONS	[66]*[33]+[80]*[34]+[95]*[35]+[110]*[36]
127 TOURMALINE (g) IN ALL MAGNETIC FRACTIONS	[67]*[33]+[81]*[34]+[96]*[35] +[111]*[36]+[54]*[32]
128 LEUCOXENE (g) IN ALL MAGNETIC FRACTIONS	[82]*[34]+[97]*[35]+[112]*[36]+[68]*[33]+[56]*[32]
129 MONAZITE (g) IN ALL MAGNETIC FRACTIONS	[83]*[34]+[98]*[35]+[36]*[113]
130 ZIRCON (g) IN ALL MAGNETIC FRACTIONS	[99]*[35]+[114]*[36]+[69]*[33]+[84]*[34]
131 OTHERS (g) IN ALL MAGNETIC FRACTIONS	[47]*[31]+[57]*[32]+[70]*[33]+ [85]*[34]+[100]*[35]+[115]*[36]

132	WEIGHT PERCENT MAGNETITE IN HM FRACTION	[117]/[37]
133	WEIGHT PERCENT ILMENITE IN HM FRACTION	[118]/[37]
134	WEIGHT PERCENT GARNET IN HM FRACTION	[119]/[37]
135	WEIGHT PERCENT EPIDOTE IN HM FRACTION	[120]/[37]
136	WEIGHT PERCENT STAUROLITE IN HM FRACTION	[121]/[37]
137	WEIGHT PERCENT PYROBOLES IN HM FRACTION	[122]/[37]
138	COLUMN NOT USED IN VIRGINIA STUDY	[123]/[37]
139	WEIGHT PERCENT RUTILE IN HM FRACTION	[124]/[37]
140	WEIGHT PERCENT ALUMINOSILICATES IN HM FRACTION	[125]/[37]
141	WEIGHT PERCENT SPHENE IN HM FRACTION	[126]/[37]
142	WEIGHT PERCENT TOURMALINE IN HM FRACTION	[127]/[37]
143	WEIGHT PERCENT LEUCOXENE IN HM FRACTION	[128]/[37]
144	WEIGHT PERCENT MONAZITE IN HM FRACTION	[129]/[37]
145	WEIGHT PERCENT ZIRCON IN HM FRACTION	[130]/[37]
146	WEIGHT PERCENT OTHERS IN HM FRACTION	[131]/[37]
147	WEIGHT PERCENT EHM	SUM([133],[139],[140],[143..145])
148	WEIGHT PERCENT RHM	100*[16]/[11]
149	CORRECTED WEIGHT PERCENT RHM	([16]-[36]*([115]*0.9))/[11]
150	WEIGHT PERCENT THM	([19]+[16])*100/[11]
151	CORRECTED WEIGHT PERCENT THM	([16]+[19]-([36]*[115]*0.9))/[11]
152	THM % - RHM %	[151]-[149]
153	SUM OF MINERAL PERCENTAGES	SUM([132..146])
154	MAGNETITE AS A WEIGHT PERCENTAGE OF THE BULK SAMPLE	[132]*[151]
155	ILMENITE AS A WEIGHT PERCENTAGE OF THE BULK SAMPLE	[133]*[151]
156	GARNET AS A WEIGHT PERCENTAGE OF THE BULK SAMPLE	[134]*[151]
157	EPIDOTE AS A WEIGHT PERCENTAGE OF THE BULK SAMPLE	[135]*[151]
158	STAUROLITE AS A WEIGHT PERCENTAGE OF THE BULK SAMPLE	[136]*[151]
159	PYROBOLES AS A WEIGHT PERCENTAGE OF THE BULK SAMPLE	[137]*[151]
160	COLUMN NOT USED IN VIRGINIA STUDY	[138]*[151]
161	RUTILE AS A WEIGHT PERCENTAGE OF THE BULK SAMPLE	[139]*[151]
162	ALUMINOSILICATES AS A WEIGHT PERCENTAGE OF THE BULK SAMPLE	[140]*[151]
163	SPHENE AS A WEIGHT PERCENTAGE OF THE BULK SAMPLE	[141]*[151]
164	TOURMALINE AS A WEIGHT PERCENTAGE OF THE BULK SAMPLE	[142]*[151]
165	LEUCOXENE AS A WEIGHT PERCENTAGE OF THE BULK SAMPLE	[143]*[151]
166	MONAZITE AS A WEIGHT PERCENTAGE OF THE BULK SAMPLE	[144]*[151]
167	ZIRCON AS A WEIGHT PERCENTAGE OF THE BULK SAMPLE	[145]*[151]
168	OTHERS AS A WEIGHT PERCENTAGE OF THE BULK SAMPLE	[146]*[151]
169	EHM AS A WEIGHT PERCENTAGE OF THE BULK SAMPLE	[147]*[151]
170	SUM WEIGHT PERCENTAGE OF HEAVY MINERALS IN THE BULK SAMPLE	SUM([154..168])
171	CORRECTED WT % THM - SUM % HM OF BULK SAMPLE	[151]-[170]