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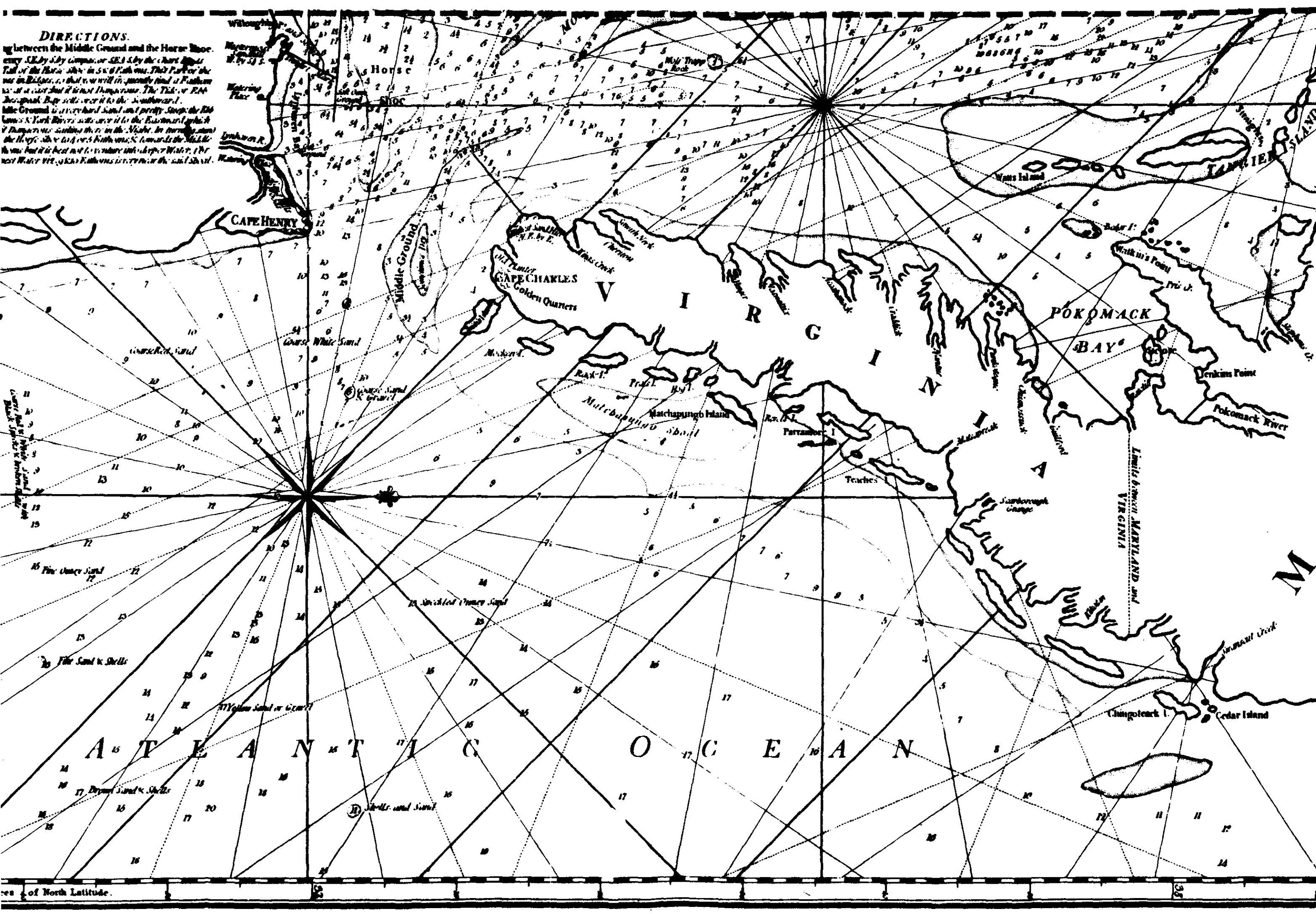
III. HEAVY MINERALS



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Cover: Portion of an early English navigation chart dated 1776 displaying bottom sediment notations used to navigate into the Chesapeake Entrance. Chart oriented as printed for use in approaching the entrance; north is to the right. This is the oldest source of information showing sediment distributions off the Chesapeake Bay.

ABSTRACT

The heavy minerals in the sand sized fraction of 112 grab samples collected off the Virginia coast were analyzed for their variations in mineralogy. The main purpose was to characterize the heavy mineral suite and to delineate potentially important economic areas.

The heavy minerals comprise between 0 and 18 weight percent of the total samples averaging $5.3 \pm 3.8\%$. Dominant heavy minerals are garnet, magnetite-ilmenite, hornblende and epidote. Less abundant are kyanite, sillimanite, andalusite, apatite, tourmaline, rutile and zircon. Occasionally phosphatic shell fragments dominate not only the heavy mineral suite but the total sample. In general weight percent of the heavy mineral fraction varies inversely with the mean grain size. Potentially economic concentrations of zircon, rutile and ilmenite occur along the 60-foot isobath off Wachapreague Inlet. Garnet, Hornblende and the opaques dominate the coarser fractions.

Distribution of the total heavy mineral assemblage indicates concentrations parallel the present-day shore-line in water depths of between 30 and 60 feet because of hydraulic fractionation. Based on heavy mineral suites and concentration variations, two major sources are hypothesized: a dominant contribution from Chesapeake Bay and its tributaries, and a secondary addition from the vicinity of the Delaware River. The possible ancient strand line concentrations suggested by surface samples may yield economic deposits but their true economic potential must be determined by sampling at depth.

CONTENTS

INTRODUCTION

The purpose of this study is twofold: (1) to evaluate the economic potential of the sands, specifically the heavy mineral fraction and (2) to relate mineralogic variations to changes in bottom topography for a portion of the Continental Shelf off the Eastern Shore of Virginia. This report presents our data concerning the composition and concentration of heavy minerals in bottom sediments of the study area as part of a larger study of the shelf environment aimed at defining the distribution of sediment properties. Resulting data reported here should expand our knowledge of heavy minerals as potential mineral resources. Tentative geologic interpretations and inferences based on our data provide a better knowledge of the economic potential of Virginia's Continental Shelf.

PREVIOUS WORK

Though there has been extensive study of the continental shelf sediments, and some work on heavy minerals within the sediments, north (Ross, 1970) and south (Pilkey, 1963) of the Eastern Shore of Virginia, little work has included this area. Nichols (1972) and Thompson and Nichols (1973) discussed the grain size and composition of the sediments in this study area but did not delve into the heavy minerals. The most detailed nearby studies of heavy minerals are by Ryan (1953), who investigated the sediments of Chesapeake Bay; and by Swift, Dill, and McHone (1971), who studied the heavy minerals in a narrow band extending seaward for 8 km from the beaches between Cape Hatteras and Cape Henry. Broad-spectrum studies by Stetson (1938, 1939), Milliman (1972), and Milliman, Pilkey, and Ross (1972) encompass the area of this report but lack detail. Emery (1965) indicated the economic potential of these sediments when he sampled the area on a ten mile grid and Milliman (1970) studied the area using sampling on a 50 mile grid. Sediments in the adjacent Chesapeake Bay entrance and the James River have been described by Meisburger (1972) and Moncure and Nichols (1968). The conomic potential of sands on adjacent beaches and on the chelf has been investigated by Kuster (1959) and Manheim (1972).

SAMPLING PLAN

Most of the samples were taken during five cruises in 1961, 1962, 1963, 1967, and 1972. In general, samples were collected on a grid consisting of stations at 2 mile (3.22 km) intervals along traverses 4 miles (6.44 km) apart parallel to lines of latitude. Additionally, three traverses extend across the entire shelf with stations at 3- to 10- mile (4.8 to 16.1 km) intervals. The last two cruises yielded more closely spaced samples in selected localities over ridges and swales to evaluate local sedimentologic variations related to topography.

Stations are designated by a number in which the first group of three digits is taken from the degrees and minutes north of 30°00' (e.g. 37°00') and the second group of two digits, following a hyphen, is taken from the distance in miles east of the 76°00' W longitude through Chesapeake Bay entrance. The samples include a range of different sediment types from various water depths and different morphologic features. The heavy mineral content of 112 of these samples provide the basis of this report and do not include all local changes because the sediment properties are so variable. The location of sampling stations analyzed for heavy minerals is given in Fig. 1. Continued studies utilizing more samples will undoubtedly reveal more detail than is reported here.

FIELD PROCEDURES

Samples were collected from the R/V Pathfinder, a 55-foot (16.5m) oceanographic research vessel, from the Seabreeze, a 87-foot (26.5m) fishing trawler, and from the R/V Ridgley Warfield, a 105-foot (32.0m) oceanographic research vessel. Stations were positioned mainly by Loran bearings but also by ranging on bouys wherever possible. Accuracy of the positions is estimated to be better than 0.8 km (0.5 mi).

Most of the bottom samples were taken with a Van Veen grab which "bites" a 0.17 m^2 surface area and penetrates to a depth of 2 to 16 cms depending on the sediment type. In very coarse material and hard bottom, samples were obtained with an orange peel grab which "bites" a surface area of about 0.10 m^2. Subsamples of about 40 cc were obtained from the grabs by punching a 5 cm diameter core tube into the surface sediment and slicing off the top 2 cm. By these procedures it was possible to obtain more or less equal area and equal volume samples, though the sediment was usually subjected to some degree of washing during retrieval from the bottom.

LABORATORY PROCEDURES

Samples were initially washed through 0.062, 1.0 and 2.0 mm mesh sieves. The fraction between 0.062 and 1.0 mm was split, if necessary, by a Sepor microsplitter to portions weighing approximately 5 grams. After weighing a sample, separation of heavy minerals from the remainder of the sample was accomplished by means of density separation in bromoform (S.G. = 2.87). Heavy minerals withdrawn from the separatory apparatus were washed with acetone, dried, and weighed. Grain mounts of the heavy mineral fraction were then prepared utilizing Lakeside 70 thermoplastic cement (n = 1.54) as a mounting medium. Identification of heavy minerals was made by petrographic microscope as were grain counts. For each slide two hundred grains were identified and counted in order to determine the percentage of each mineral within the sample. The counts were made by conducting successive traverses across the slide and counting each grain which came into the field of view. Visual observations were also made on the average grain size and morphology of the grains in each slide.

The major method employed to analyze the data was to plot the percentage of individual heavy minerals at each sampling station on a map. These percentages were then contoured so that variations in abundance of individual minerals could be readily compared to variations in bottom relief topography and possible sediment source areas.

RESULTS AND DISCUSSION

Grain count analyses and the weight percent of heavy minerals in the 0.062 to 1.0 mm grain size fraction of the 112 samples analyzed are given in Appendix II. The heavy mineral fraction comprises between 0 and 18 weight percent of the total samples, averaging $5.3 \pm 3.8\%$. A contoured plot of the weight percent of heavy minerals is shown in Fig. 2 and clearly delineates a strong concentration paralleling the present-day shoreline in water depths between 30 and 60 feet. The largest concentration here is just south of Wachapreague Inlet and appears to be related to bottom topography lying just inshore of the ridge and swale system suggesting a relict shoreline. This area definitely contains the coarser heavy minerals. A second, smaller but equally intense concentration of heavy minerals occurs further offshore opposite the mouth of

Wachapreague Inlet in water depths of between 60 and 90 feet. Heavy mineral concentrations in excess of 5% are most abundant in the southern half of the study area and are confined to a band within twenty miles of the present coast. No concentrations in excess of 15% were found more than fourteen miles offshore, though there may be such concentrations not sampled.

Dominant heavy minerals are garnet, magnetite-ilmenite, hornblende and epidote. Less abundant are kyanite, sillimanite andalusite, apatite, tourmaline, rutile and zircon. Trace amounts of sphene, pyrite and hematite were also noted. Occasionally phosphatic shell fragments dominate not only the heavy mineral suite but the total sample. In general, weight percent of the heavy mineral fraction varies inversely with the mean grain size. Garnet, hornblende and the opaques dominate the coarser fractions. Diagnostic characteristics of heavy minerals are given in Appendix I. For purposes of analyzing the distribution of particular heavy minerals, contoured plots of grain percent of the total heavy mineral fraction were prepared for the black opaque minerals, magnetite-ilmenite (Fig. 3), hornblende (Fig. 4), garnet (Fig. 5), epidote (Fig. 6), kyanite (Fig. 7), apatite (Fig. 8), and the potentially-economic minerals zircon, rutile, and ilmenite combined (Fig. 9).

Black opaque minerals shown in Figure 3 include magnetite, ilmenite and traces of pyrite. Magnetite attains a maximum grain percent of 41.0, ilmenite a maximum of 17.5 percent, and pyrite a maximum of 2.0 percent although it is frequently absent. The black opaque minerals present a random distribution but the greatest concentrations generally occur in the northern and southern portions of the area. This suggests two probable sources of black opaques: (1) recent incorporation from nearby coastal areas possibly contributed by outflow from Chesapeake Bay; and (2) sediments swept down the coast from the Delaware Estuary. Some of the concentration may be derived from relict marine sediments as the black opaques are characteristically more abundant in the coarser grain sizes which are typically rounded to well rounded grains and most common in samples furthest offshore.

Hornblende (Fig. 4) has a maximum grain percent of 55.0 and commonly comprises more than 30 percent of the heavy minerals. Its highest concentrations are in areas where the black opaques are less abundant. A linear concentration paralleling and adjacent to the coast suggests that wave action on the present beaches has caused it to concentrate at shallow depths offshore. Additional concentrations in the northern and southern portions of the area once again suggest an influx of this mineral from Chesapeake Bay and the region of the Delaware Estuary. We conclude that this mineral is both reworked (relict) and recent in origin.

Garnet (Fig. 5) with a maximum grain percent of 45.0 makes up more than 10 percent of the heavy mineral assemblage over most of the area and not uncommonly occurs in excess of 15 percent. This high percentage of garnet is quite striking but is not surprising in light of the metamorphic terrain of the piedmont which likely served as the original source of these sediments. Although ubiquitous, the major concentrations to the north and to the south suggest the Chesapeake Bay and Delaware Estuary influences. Maximum concentrations, and the greater concentrations in general occur offshore in deeper water. This is due at least in part to hydraulic fractionation by wave action since it is one of the coarser-sized heavy minerals.

Epidote (Fig. 6) is never present in high concentrations, reaching a maximum grain percent of 15.5 but it is almost always present and makes up more than 6 percent of the heavy minerals over broad areas. A strong concentration to the south suggests Chesapeake Bay inflow. A second area of concentration occurs offshore from Parramore Island and extends north of that region possibly representing relict concentration from an older drainage system.

Kyanite (Fig. 7) along with epidote is an excellent indicator of an original Piedmont source for much of the heavy mineral suite. Rarely comprising more than 4 percent of the heavy minerals and attaining a maximum concentration of 11.5 grain percent, its greatest abundance occurs immediately adjacent to the mouth of Chesapeake Bay pinpointing the Bay as an avenue of transport. A secondary source off Wachapreague Inlet closely resembles the data for epidote. The possibility of an older drainage system in the vicinity of Wachapreague Inlet is strongly suggested by the concentrations of epidote and kyanite in that area.

Apatite (Fig. 8) is never abundant, with a maximum grain percent of 9.5, most commonly comprises less than 2 percent of the heavy minerals and only occurs in an abundance of greater than 4 percent in a very limited area. Its major area of concentration is in a narrow belt a short distance seaward of and paralleling the 60 foot submarine contour extending northward from the central part of the area. In general it occurs in abundance only shoreward from a water depth of 70 to 80 feet. Some of the apatite is undoubtedly derived from disintegrated skeletal material.

For convenience the heavy minerals of major economic importance; zircon, rutile, and ilmenite were grouped together (Fig. 9). Because of the optical similarities between zircon and monazite (a rare earth oxy-phosphate), the percentages of zircon include indeterminate amounts of monazite. The only concentration in excess of 20 grain percent occurs in a narrow belt near Wachapreague Inlet shoreward of and paralleling the 60 foot submarine contour. An ancient source in the vicinity of this inlet is once again suggested. Contribution of these minerals by the Chesapeake Bay and the Delaware Estuary is also suggested by lesser but prominent, concentrations in the southern and northern parts of the area.

The distribution of the preceeding minerals strongly suggests that hydraulic fractionation has played a major role in concentrating particular minerals. In deeper water the heavy mineral suite is simplified to a dominance of black opaques, garnet, and at times, hornblende. Greater diversity occurs in the suite nearer the shore where nearshore currents and tidal ebb and flow influence the concentrations.

Special mention should be made of four samples in which shell fragments comprised more than 78 grain percent of the heavy minerals. Two of these lie adjacent to a 60-foot submarine contour and two are in an area where bottom topography is not clearly defined. All four are from samples dominated by coarse, angular, brown shell fragments of extremely high P_2O_5 content. It is suspected that they represent ancient beach ridge deposits of apatite-secreting mollusks. An abundance of shells in the heavy mineral fraction suggests that the shell material may be highly phosphatic.

As additional samples are processed, the necessity for determining the vertical variation of heavy mineral content in these sediments becomes increasingly imperative if a well-defined assay of the economic potential of these grains is to be determined. With additional heavy mineral concentrates being separated (Thompson and Nichols, 1973), the need for a heavy mineral sedimentation model in the offshore area will be needed.

May (1973) has demonstrated qualitatively a mechanism for hydraulic fractionation of heavy minerals by shoaling waves. Recognizing differences between heavy minerals and less dense clasts (e.g. quartz) as well as the shielding nature large grains have for smaller diameter ones, he demonstrates that heavy minerals will be subjected to a net onshore transport while lighter minerals are more liable to oscillatory motion in water where the ratio of depth to wavelength equals 0.5; his zone of "shoaling waves". In deeper water, heavy mineral concentrates, therefore, are probably relict from periods of lower stillstands of the sea.

SUMMARY

1. Heavy minerals do occur in the shallow coastal waters off Eastern Virginia in concentrations which tend to parallel the present-day coastline.

2. Variations in concentration and mineralogy suggest that a portion of the heavies were derived by longshore transport (Delaware Estuary?) and from onshore (Chesapeake Bay). In the case of the latter, no current measurements at the mouth of the Bay were considered and hence, its source rock contribution is based solely on similarity of heavy mineral suites.

3. Concentrations of zircon + ilmenite + rutile are indicated in percentages greater than 1.5% in relatively shallow water off of Wachapreague Inlet. Potentially economic concentrations for phosphate (shell hash) and abrasives (garnet-magnetite) are also concentrated in bands paralleling the coast.

4. The total lateral and vertical variation in heavy mineral concentrates within the coastal sediment prism, cannot be adequately evaluated without coring. Tidal and nearshore currents are used to explain present fractionation but it is unknown how this varied through time.

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APPENDIX I. Characteristics of heavy mineral components.

The following is a brief description of the most common heavy minerals identified in the grain mounts prepared for this project. More detailed information may be found in optical mineralogy texts such as that by Kerr (1959), or in Krumbein and Pettijohn (1938).

<u>Andalusite</u> - Al_2SiO_5; Orthorhombic. Typically occurs as elongate prisms with parallel extinction and showing pink to colorless pleochroism; negative elongation and moderate relief.

Apatite - $Ca_5(PO_4)_3$ (F, Cl, OH): Hexagonal. Present in subrounded and short prismatic grains which are colorless and exhibit markedly low birefringence and relief. Often show good uniaxial negative figure.

Epidote - $Ca_2(Al,Fe)_3Si_3)_{12}(OH)$; Monoclinic. Ubiquitous in occurrence, grains often rounded, pale green-yellow and exhibit weak green-pale green-greenish yellow pleochroism. High order interference colors, "propeller" interference figures and striations parallel to <u>b</u> helped in identification.

<u>Garnet</u> - $A_3B_2(SiO_4)_3$, where A may be Mg, Fe, Ca or Mn and B is Al, Fe or Cr; isometric. Isotropic mineral with high relief and a variety of colors in plane light; colorless, green, shades of red. Typical occurrence as rounded grains with conchoidal fractures and surface pits; inclusions of bubbles and rutile occasionally noted.

<u>Hematite</u> - Fe_2O_3; Hexagonal. Opaque heavy mineral occurring chiefly as reddish-brown replacements of other minerals such as magnetite. Color in reflected light was diagnostic.

<u>Hornblende</u> - complex hydrated calcium aluminosilicate; Monoclinic. Really a group of minerals exhibiting excellent cleavage parallel to (110) and lesser cleavages parallel to (100) and (010). Varying shades of green but typically pleochroic, colorless to blue-green or yellow to olive-green or light brown to green-brown. Relief moderate with positive elongation typical of the amphibole group. Many grains were seemingly opaque except along thin edges of grains so body color masked pleochroism.

<u>Ilmenite</u> - $FeTiO_3$; Orthorhombic. Grains of ilmenite generally were of two types; opaque grains coated with leucoxene, and heavily abraded grains exhibiting a bluish-black luster in reflected light. Often observed were twinning lamellae in grains intergrown with magnetite. Difficult to confidently separate ilmenite from intergrown magnetite-ilmenite grains.

<u>Kyanite</u> - Al_2SiO_5; Triclinic. Typical grains were slightly elongate with nearly perfect parting (pinacoidal and prismatic) close to 90 degrees. Grains showed occasional weak pleochroism (colorless to pale blue), biaxial negative sign and step-like cleavage.

<u>Magnetite</u> - Fe_3O_4; Isometric. This isotropic opaque mineral showed typical deep blue-black luster, occasional octahedral parting or lineation. Grains in samples most distant from shore exhibited high degrees of rounding and some intergrowth with ilmenite.

<u>Pyrite</u> - FeS_2; Isometric. The few grains present were typically striated and were slightly rounded cubes or octahedra or pyritihedra. Brassy-yellow color was typical and diagnostic.

<u>Pyroxene</u> - Ca, Mg aluminosilicate group; Monoclinic (some Orthorhombic). Present as highly colored (green or dirty green) sub-rounded prisms. Pleochroism is very weak, shades of green. Moderate relief and nearly right angle cleavage (110)($\bar{1}$10) typical.

<u>Rutile</u> - TiO_2; Tetragonal. Easily identified by root beer-brown color and tetragonal prismatic cleavage, positive elongation, parallel extinction and extremely high relief.

<u>Shell Fragments</u> - $Ca_5(PO_4)_3(OH)$?. Fragments varying in opacity, generally tan to light brown; molluscan debris predominant. Wet chemical analysis indicates high P_2O_5 content.

<u>Sillimanite</u> - Al_2SiO_5; Orthorhombic. When present, these grains were typically stubby prisms, colorless and showing striae or partings parallel to (010). Cleavage parallel to (100) was excellent; extinction is parallel.

<u>Sphene</u> - $CaTiSiO_5$; Monoclinic. Grains were typically subhedral, showing excellent (110) cleavage, pale brown or yellow and pleochroic (colorless to reddish-brown), extremely high relief and does not go to extinction but shows color-banding in crossed nicols.

<u>Staurolite</u> - $2Al_2SiO_5 \cdot Fe(OH)_2$; Orthorhombic. When present, these grains were typically a rich yellow or yellowish-brown with some pleochroism (colorless through shades of yellow), cleavage parallel to (010) and an irregular fracture. Bubble-like inclusions quite common and noticeable due to high relief.

<u>Tourmaline</u> - complex Na,Ca, Al hydrated borosilicate; Hexagonal. Grains were either slender prisms or ovoid particles showing marked pleochroism (dark brown to yellow or colorless to green). Prisms showed negative elongation and parallel extinction. Generally free of inclusions, high relief made the few inclusions quite obvious.

<u>Zircon</u> - $ZrSiO_3$; Tetragonal. Occurred either as fractured prismatic crystals or rounded elongate grains. Generally colorless to pale blue with occasional pleochroism (colorless to blue). Grains have extremely high relief, parallel extinction and often show rutile fiber inclusions.

APPENDIX II. Weight percent of total heavy mineral assemblage and grain percent of individual heavy minerals.

Station No.	700-47	702-02	702-04	702-06	702-08	702-10	702-12	702-14	702-16	702-18	702-20
Wt. % Heavies	7.9	-	3.0	7.0	7.0	5.0	9.0	5.0	2.0	7.0	11.0
Andalusite	2.5	0.5	2.0	1.0	-	1.0	1.5	-	4.0	1.0	2.0
Apatite	0.5	0.5	2.0	1.0	-	1.0	1.5	-	4.0	1.0	2.0
Epidote	11.0	4.0	10.5	12.5	10.5	7.5	11.5	15.5	14.0	11.0	9.5
Garnet	15.5	16.5	9.5	23.0	14.5	10.5	19.0	15.0	15.5	16.5	19.5
Hematite	-	-	-	-	-	0.5	-	-	1.0	-	-
Hornblende	48.5	11.0	30.0	26.0	26.0	32.5	23.0	25.0	14.0	25.0	24.5
Ilmenite	1.0	17.5	6.0	3.5	3.5	3.5	3.0	6.5	8.5	5.5	3.5
Kyanite	2.0	1.5	10.0	7.5	11.5	5.0	5.5	7.5	6.5	7.0	5.5
Magnetite	11.5	26.0	15.5	11.5	16.0	16.0	18.0	16.5	18.5	15.0	22.0
Pyrite	-	-	-	-	-	1.5	1.0	1.5	-	-	-
Pyroxene	1.0	1.5	-	-	-	-	-	-	-	-	-
Rutile	1.5	1.5	1.0	2.0	2.0	0.5	1.5	1.0	0.5	1.0	2.0
Shell Fragments	-	-	-	-	-	-	-	-	-	-	-
Sillimanite	2.5	3.5	4.5	0.5	2.0	2.0	1.0	1.5	1.5	1.0	1.0
Sphene	0.5	1.0	0.5	-	0.5	-	-	-	-	1.5	-
Staurolite	-	-	1.0	2.0	3.5	1.5	1.5	3.5	3.0	2.5	1.5
Tourmaline	-	4.0	4.5	4.0	4.0	3.5	5.0	3.0	2.5	5.0	2.0
Zircon	2.0	7.5	2.5	4.0	4.0	6.5	5.0	3.0	2.5	4.5	2.5
Others	-	4.0	2.5	5.5	2.0	8.0	6.0	1.0	7.0	3.0	5.0

Appendix II (Cont'd)

Station No.	702-22	702-24	702-26	702 26.5	702-27	702 27.5	702-28	702-30	702-32	702-48	704-11
Wt. % Heavies	3.0	7.0	3.0	3.0	8.0	11.0	1.0	5.0	3.0	3.0	9.0
Andalusite	-	-	-	-	1.0	-	-	-	-	-	0.5
Apatite	1.0	-	1.5	1.0	1.5	0.5	-	2.0	0.5	2.0	1.0
Epidote	6.0	6.5	5.0	3.0	3.5	1.5	4.0	7.5	8.5	5.5	9.5
Garnet	25.5	18.0	17.5	26.0	20.0	25.5	26.0	9.0	17.5	11.0	19.5
Hematite	-	-	-	-	-	-	2.0	-	-	-	-
Hornblende	10.5	23.5	23.5	11.0	28.5	14.0	9.0	29.0	31.0	34.0	33.0
Ilmenite	6.0	10.5	5.5	7.0	5.0	4.5	4.0	4.5	4.0	1.0	2.0
Kyanite	2.0	3.5	4.5	2.5	2.0	0.5	2.5	4.0	3.5	4.5	-
Magnetite	33.5	21.0	20.5	29.0	21.0	36.5	18.0	14.0	21.0	35.5	25.0
Pyrite	0.5	-	-	-	-	-	-	0.5	-	-	0.5
Pyroxene	-	-	-	-	-	-	-	2.5	-	-	1.0
Rutile	2.0	1.5	1.5	2.0	1.5	2.0	1.0	1.0	1.5	-	-
Shell Fragments	-	-	-	7.5	-	-	19.0	0.5	-	-	-
Sillimanite	1.5	2.5	3.0	1.0	1.5	0.5	1.0	2.5	1.0	1.0	0.5
Sphene	-	-	0.5	-	-	0.5	3.5	-	-	-	0.5
Staurolite	1.5	1.0	1.0	2.0	2.0	1.0	1.5	0.5	1.0	1.0	0.5
Tourmaline	1.5	3.0	4.0	2.0	10.0	1.5	1.5	4.0	2.5	0.5	0.5
Zircon	4.5	5.5	3.5	2.0	4.5	8.5	3.0	13.0	4.5	3.5	5.0
Others	4.0	8.5	8.5	4.0	4.0	3.0	4.0	5.5	3.5	0.5	1.5

Appendix II (Cont'd) .

Station No.	705-11	706-19	706-20	706-22	706-24	706-26	706-28	706-30	706-32	707-10	707-11
Wt. % Heavies	6.0	7.0	10.0	9.0	3.0	5.0	4.0	4.0	6.0	5.5	1.2
Andalusite	0.5	0.5	-	-	-	0.5	1.0	2.0	-	1.5	0.5
Apatite	2.5	-	0.5	-	0.5	1.0	0.5	0.5	0.5	0.5	4.5
Epidote	6.0	9.0	5.0	8.5	5.5	11.0	8.0	5.5	5.0	9.5	7.5
Garnet	13.5	19.5	22.5	14.0	45.0	17.5	16.0	19.0	27.0	25.5	10.0
Hematite	-	0.5	2.5	-	0.5	-	0.5	-	2.0	-	1.0
Hornblende	25.0	27.0	29.0	33.5	7.0	26.5	42.0	31.0	9.5	11.5	13.0
Ilmenite	7.0	3.0	4.5	3.5	4.0	9.0	7.0	5.0	7.5	1.0	3.0
Kyanite	3.5	3.0	2.5	0.5	-	2.0	0.5	4.0	1.0	1.0	0.5
Magnetite	24.5	17.5	14.0	23.0	23.0	19.0	13.5	19.5	30.0	30.5	13.5
Pyrite	-	0.5	-	-	-	1.0	-	0.5	1.0	0.5	-
Pyroxene	-	2.0	3.5	2.5	1.0	2.0	0.5	3.5	2.0	1.0	2.5
Rutile	1.0	2.0	-	1.0	1.5	-	-	0.5	2.5	4.0	-
Shell Fragments	-	0.5	-	-	5.5	-	-	-	-	9.0	30.0
Sillimanite	0.5	1.0	2.0	2.0	-	2.0	2.0	1.0	0.5	0.5	1.5
Sphene	-	-	-	-	-	-	-	-	-	-	0.5
Staurolite	2.5	1.5	2.5	1.5	3.0	-	-	1.5	0.5	2.0	2.5
Tourmaline	2.5	3.0	2.0	1.5	2.0	3.0	3.0	2.0	2.0	1.0	2.5
Zircon	5.0	6.0	4.0	6.5	1.5	2.5	3.5	2.0	5.0	1.0	2.5
Others	5.0	3.5	5.5	4.5	-	3.0	2.0	2.5	4.0	-	4.5

Appendix II (Cont'd)

Station No.	707 11.5	707-16	707 18.5	708-11	708-12	708-13	708 14.5	709-10	712 14.5	712-26	713-26
Wt. % Heavies	3.4	6.3	7.0	5.9	6.7	6.2	15.6	7.3	7.0	4.1	5.3
Andalusite	3.5	1.5	2.5	2.5	2.0	0.5	1.5	2.5	4.0	-	-
Apatite	2.0	6.0	4.5	1.0	-	1.0	2.0	1.0	2.0	-	-
Epidote	9.5	6.0	6.0	5.0	5.0	9.5	12.5	7.5	6.0	-	2.5
Garnet	12.5	7.5	9.5	22.0	23.0	8.0	14.5	21.5	11.5	1.0	4.5
Hematite	-	-	-	-	-	-	-	0.5	-	-	0.5
Hornblende	38.0	38.0	43.0	18.5	18.0	43.0	30.0	24.0	33.5	-	0.5
Ilmenite	5.0	1.0	3.5	2.0	4.5	2.0	3.5	3.0	1.5	-	-
Kyanite	3.5	5.0	4.0	2.5	2.5	4.5	5.0	1.0	1.0	-	-
Magnetite	18.5	16.0	7.5	37.0	34.0	11.0	22.0	22.5	22.5	1.0	3.0
Pyrite	-	-	-	-	-	-	-	2.0	-	-	-
Pyroxene	1.0	4.0	3.0	1.0	3.0	1.0	2.0	3.0	1.0	-	-
Rutile	0.5	1.0	0.5	0.5	1.0	0.5	1.5	0.5	2.0	-	-
Shell Fragments	1.0	0.5	7.5	-	-	9.5	-	-	3.5	97.0	86.5
Sillimanite	1.0	3.5	1.5	1.0	1.0	3.0	1.5	1.0	2.0	-	0.5
Sphene	-	2.0	3.0	1.0	1.0	2.5	-	0.5	2.0	-	-
Staurolite	0.5	1.5	1.5	-	1.0	0.5	-	0.5	2.0	-	0.5
Tourmaline	1.0	-	0.5	2.0	1.0	-	1.0	3.5	-	-	0.5
Zircon	1.5	3.5	2.0	3.0	1.5	2.0	3.0	3.5	2.5	-	0.5
Others	1.0	3.0	0.5	1.0	1.5	1.5	-	1.0	3.0	1.0	0.5

Appendix II (Cont'd)

Station No.	714-21	714 24.5	714-32	715 23.8	716-14	717-14	720-30	722-18	723-26	726-18	726-20
Wt. % Heavies	14.5	6.8	3.0	4.2	8.3	7.4	3.7	11.5	2.8	8.0	18.0
Andalusite	-	2.5	3.5	5.0	1.0	3.5	0.5	-	0.5	9.0	4.0
Apatite	1.0	3.5	2.0	3.0	3.0	6.0	1.5	3.0	2.5	2.0	8.5
Epidote	-	4.5	7.0	11.0	4.5	9.5	7.0	8.0	6.5	7.5	9.0
Garnet	-	8.5	10.5	9.5	13.5	14.5	14.5	16.5	21.0	14.0	11.0
Hematite	-	-	-	-	-	-	-	-	1.0	0.5	1.0
Hornblende	0.5	43.0	41.0	42.5	28.0	41.0	37.5	33.0	25.0	41.5	39.0
Ilmenite	1.0	0.5	2.5	1.0	3.5	0.5	0.5	0.5	3.5	2.0	0.5
Kyanite	-	3.0	4.5	2.0	2.0	2.5	1.5	1.5	3.5	6.0	8.5
Magnetite	3.5	11.5	11.5	8.5	30.5	13.5	27.5	19.0	22.0	4.5	4.5
Pyrite	-	-	-	-	-	-	-	-	-	0.5	-
Pyroxene	-	1.0	3.5	3.0	-	1.0	-	2.0	3.5	-	0.5
Rutile	0.5	3.0	1.5	0.5	2.5	2.5	0.5	0.5	0.5	0.5	1.5
Shell Fragments	92.5	7.5	5.0	5.0	1.0	1.5	1.0	4.5	0.5	3.0	2.5
Sillimanite	-	3.0	1.0	2.0	2.5	-	3.0	2.0	0.5	2.5	1.5
Sphene	-	1.0	1.0	0.5	0.5	0.5	1.5	-	0.5	0.5	1.5
Staurolite	-	0.5	-	-	0.5	-	0.5	1.0	1.5	2.0	1.5
Tourmaline	-	-	1.0	1.0	1.0	-	1.5	1.0	3.5	1.5	1.0
Zircon	-	5.0	1.5	3.0	4.5	1.5	1.5	5.0	2.5	2.5	2.5
Others	1.0	2.5	3.0	2.5	1.5	2.0	-	2.5	1.5	-	1.5

Appendix II (Cont'd)

Station No.	726-22	726-24	726-26	726-28	728-31	728-32	729-27	730-27	730-29	730 29.5	731-29
Wt. % Heavies	3.0	4.0	5.0	14.0	4.7	0.1	10.0	-	1.0	5.0	4.0
Andalusite	1.0	6.5	3.0	4.0	3.0	1.0	6.0	4.0	3.0	10.0	12.0
Apatite	1.0	1.5	5.0	9.5	5.5	1.0	4.0	2.0	5.5	3.5	6.5
Epidote	0.5	11.5	7.0	15.0	5.5	14.0	10.0	5.5	4.5	7.5	12.0
Garnet	3.5	10.0	11.5	7.5	6.0	15.0	16.0	20.0	17.5	11.5	8.5
Hematite	-	-	-	-	0.5	-	-	-	-	-	-
Hornblende	8.5	38.0	34.5	24.0	55.0	17.0	35.5	34.0	19.5	44.5	37.0
Ilmenite	0.5	3.5	3.0	3.5	1.5	2.0	3.0	2.5	2.0	1.5	1.5
Kyanite	2.5	11.0	1.5	4.5	1.0	1.0	5.0	1.0	3.0	4.5	3.5
Magnetite	2.0	4.5	15.5	10.5	11.5	29.5	7.5	12.5	7.0	7.5	6.5
Pyrite	0.5	-	0.5	1.5	-	-	-	1.0	1.5	0.5	0.5
Pyroxene	-	1.0	1.0	1.0	0.5	1.0	1.0	-	-	-	0.5
Rutile	-	0.5	1.0	2.0	2.0	-	2.0	1.0	0.5	0.5	3.0
Shell Fragments	78.0	2.5	4.5	1.0	2.5	11.0	1.5	1.0	27.0	-	-
Sillimanite	-	2.0	2.5	-	2.0	0.5	1.0	2.0	1.5	1.5	1.5
Sphene	0.5	0.5	2.0	6.5	1.0	1.0	0.5	-	4.5	0.5	0.5
Staurolite	-	1.0	-	2.5	-	3.0	3.0	1.0	1.0	0.5	0.5
Tourmaline	1.5	0.5	1.5	1.5	-	0.5	0.5	1.5	1.0	1.5	1.0
Zircon	-	5.0	4.0	3.0	1.0	1.5	2.0	5.0	0.5	3.5	4.0
Others	-	0.5	2.0	2.5	1.5	1.0	1.5	6.0	1.5	1.0	1.0

Appendix II (Cont'd)

Station No.	731 29.5	732-27	732-32	733-33	733 39.5	734-20	734-22	734-26	734-28	734 30.5	734-32
Wt. % Heavies	10.0	1.0	4.0	0.2	2.0	4.0	14.0	5.0	2.0	4.0	5.0
Andalusite	5.0	1.5	2.5	-	-	4.0	4.5	4.5	5.0	2.5	2.0
Apatite	2.5	1.0	1.5	0.5	-	6.5	3.5	3.5	4.0	2.0	6.0
Epidote	14.5	8.0	11.5	5.0	5.0	9.5	9.5	15.5	10.5	2.5	10.5
Garnet	11.0	13.0	14.5	15.0	27.0	5.5	12.5	14.5	5.0	19.5	17.5
Hematite	1.0	-	-	0.5	-	1.0	0.5	1.0	-	1.5	1.0
Hornblende	29.5	21.5	24.0	22.5	8.0	42.5	37.0	21.0	40.5	25.0	19.5
Ilmenite	3.5	1.5	2.0	3.0	2.5	0.5	3.0	7.0	2.5	2.5	4.0
Kyanite	4.0	3.0	3.5	1.0	1.5	7.0	4.0	3.5	5.0	6.0	4.0
Magnetite	11.0	27.0	28.5	23.5	33.0	6.0	13.0	16.5	11.5	22.5	19.5
Pyrite	1.5	-	-	1.0	-	-	0.5	2.0	0.5	1.0	-
Pyroxene	-	0.5	0.5	2.5	-	-	0.5	-	0.5	-	0.5
Rutile	0.5	4.0	2.0	1.0	1.0	1.0	1.5	1.0	0.5	1.5	-
Shell Fragments	-	13.0	4.0	12.0	17.5	-	3.0	-	0.5	2.0	0.5
Sillimanite	2.5	0.5	2.0	0.5	-	3.0	2.0	2.0	2.5	1.5	1.5
Sphene	0.5	0.5	1.5	1.5	1.5	1.5	-	-	0.5	0.5	2.0
Staurolite	1.5	2.0	0.5	2.0	1.0	6.0	3.0	1.0	3.0	1.0	2.5
Tourmaline	0.5	1.0	0.5	2.0	0.5	1.0	0.5	1.0	1.5	-	-
Zircon	4.0	1.0	0.5	5.0	1.5	3.5	2.0	6.0	1.5	2.0	4.0
Others	7.0	1.0	0.5	1.5	-	1.0	-	-	5.0	6.5	5.0

Appendix II (Cont'd)

Station No.	734-49	740 24.5	742-34	742-40	746-23	746-30	746-32	746-33	746-34	746-40	746 43.5
Wt. % Heavies	2.5	1.5	4.3	10.2	3.8	4.1	2.8	6.7	9.1	2.5	5.0
Andalusite	2.5	2.0	2.0	-	2.5	0.5	1.0	4.5	3.0	0.5	-
Apatite	1.5	1.5	7.0	1.0	4.0	1.5	3.0	1.5	2.5	0.5	3.5
Epidote	12.5	8.5	13.5	8.5	5.5	10.5	5.5	8.0	10.0	6.5	8.0
Garnet	9.0	15.0	5.5	22.0	7.5	12.0	11.0	6.5	12.0	11.5	11.0
Hematite	-	-	-	-	0.5	0.5	-	-	-	-	-
Hornblende	44.5	18.0	35.5	14.0	47.0	43.0	35.0	51.5	37.5	41.5	15.0
Ilmenite	1.5	2.5	1.5	1.0	0.5	1.5	4.0	4.0	0.5	2.5	2.0
Kyanite	4.0	3.0	2.5	3.5	3.0	1.5	1.5	2.0	3.0	4.0	4.5
Magnetite	9.5	39.5	18.0	41.0	18.0	6.5	21.0	9.0	13.5	20.5	12.5
Pyrite	-	-	-	-	-	-	-	-	-	-	-
Pyroxene	0.5	-	2.0	1.0	1.5	4.0	3.5	4.0	2.5	0.5	0.5
Rutile	1.5	-	1.5	2.0	0.5	2.5	1.0	1.5	2.5	2.5	-
Shell Fragments	7.0	3.0	1.5	2.5	-	1.0	3.5	2.0	3.0	1.0	33.0
Sillimanite	1.0	2.0	3.0	0.5	2.0	2.5	1.0	1.5	-	1.5	1.5
Sphene	-	1.0	4.0	-	1.5	0.5	1.0	1.0	2.0	1.0	0.5
Staurolite	2.0	1.5	-	1.5	1.0	2.5	1.0	-	0.5	2.5	-
Tourmaline	1.5	-	-	1.5	-	3.5	2.0	-	3.0	2.5	1.5
Zircon	0.5	1.0	-	-	2.5	3.0	3.5	0.5	2.0	-	5.0
Others	1.0	1.5	2.5	-	2.5	3.0	2.0	2.5	2.5	1.0	1.5

Appendix II (Cont'd)

Station No.	746-44	746-46B	750-30	750-32	750-34	750-36	750-40	750-42	750-43	750-44	750-48
Wt. % Heavies	2.8	2.1	3.9	2.3	1.7	1.0	2.7	1.0	5.9	5.3	2.3
Andalusite	1.5	2.0	0.5	0.5	1.0	3.0	2.5	0.5	1.0	1.5	2.0
Apatite	2.0	1.5	3.5	1.0	1.0	4.0	1.5	1.5	2.0	1.0	2.0
Epidote	2.0	5.5	9.5	11.0	6.5	8.5	11.5	5.0	7.5	9.5	8.0
Garnet	31.0	12.0	14.5	25.5	18.5	11.0	25.5	30.0	10.0	14.0	27.0
Hematite	0.5	-	-	-	-	-	-	-	-	-	-
Hornblende	26.5	32.5	33.0	19.5	26.0	38.5	10.0	18.0	38.5	29.5	16.0
Ilmenite	1.0	3.0	4.0	1.5	5.0	3.0	-	5.0	1.0	1.5	2.5
Kyanite	2.5	6.0	1.0	2.0	2.5	3.0	5.0	1.0	3.0	1.0	1.5
Magnetite	22.0	27.5	18.0	30.0	17.5	22.0	23.0	18.5	26.5	32.0	25.5
Pyrite	-	-	0.5	-	0.5	-	-	0.5	-	-	-
Pyroxene	-	1.0	3.0	0.5	4.0	0.5	1.0	1.5	1.0	0.5	-
Rutile	1.5	2.0	1.0	4.0	0.5	1.0	2.0	2.0	1.5	1.0	2.0
Shell Fragments	4.0	3.0	-	1.5	5.0	0.5	15.5	4.5	0.5	2.5	6.0
Sillimanite	2.0	0.5	2.0	-	-	-	0.5	1.5	1.5	1.5	2.5
Sphene	-	0.5	0.5	-	1.0	2.0	0.5	1.0	-	1.0	-
Staurolite	2.0	1.5	1.5	1.5	2.5	0.5	1.0	3.5	0.5	1.5	2.0
Tourmaline	-	-	1.0	0.5	3.5	0.5	0.5	-	1.5	1.5	-
Zircon	-	0.5	4.0	1.0	3.0	1.5	-	4.5	3.5	-	0.5
Others	1.5	1.0	2.5	-	2.0	0.5	-	1.5	0.5	0.5	2.5

Appendix II(Cont'd)

Station No.	750-50	751-37	752-36	754-34	754-36	754-38	754-40	754-42	754-45	754-46	754-50
Wt. % Heavies	1.3	1.9	1.0	7.6	1.5	2.2	2.4	4.4	2.9	14.2	2.8
Andalusite	-	2.0	0.5	1.0	0.5	2.5	2.0	3.0	0.5	-	5.0
Apatite	0.5	0.5	0.5	2.0	1.5	2.5	7.0	3.5	0.5	0.5	0.5
Epidote	5.0	10.5	10.5	8.0	7.5	9.0	5.0	6.0	7.5	6.0	6.0
Garnet	17.0	23.5	14.0	12.5	7.5	5.0	15.5	10.5	12.5	17.5	10.0
Hematite	1.5	0.5	-	-	-	-	-	-	-	-	0.5
Hornblende	16.5	19.5	12.5	28.0	45.5	41.5	21.0	32.5	28.0	22.5	34.0
Ilmenite	7.5	2.5	2.0	5.0	3.0	4.0	2.0	2.5	1.5	3.0	4.0
Kyanite	1.0	5.0	2.5	1.0	0.5	4.5	2.5	3.0	2.0	1.0	3.0
Magnetite	30.5	19.0	30.5	25.0	25.0	17.5	30.5	25.5	38.5	31.0	14.0
Pyrite	0.5	-	-	-	-	-	-	-	-	-	-
Pyroxene	1.0	1.0	-	2.0	2.5	-	1.5	1.0	2.5	2.5	2.5
Rutile	3.0	4.5	3.5	1.0	1.0	3.5	2.5	2.0	1.0	1.0	1.0
Shell Fragments	0.5	3.0	18.0	-	-	2.0	0.5	4.0	-	2.0	9.5
Sillimanite	2.0	1.0	1.0	1.0	1.0	3.0	2.0	2.5	-	0.5	2.0
Sphene	1.5	0.5	-	1.0	0.5	1.5	1.0	1.0	2.0	-	2.0
Staurolite	1.5	5.0	0.5	1.5	1.0	1.0	0.5	0.5	0.5	2.0	2.0
Tourmaline	3.0	1.5	1.0	2.0	0.5	-	0.5	0.5	1.5	1.0	-
Zircon	4.5	0.5	0.5	5.0	1.5	2.0	2.5	0.5	0.5	7.0	1.0
Others	3.0	-	2.5	5.0	1.0	0.5	3.5	1.5	1.0	2.5	3.0

Appendix II (Cont'd)

Station No.	754-52	755 43.5								
Wt. % Heavies	6.8	2.4								
Andalusite	2.5	-								
Apatite	1.5	0.5								
Epidote	9.5	4.0								
Garnet	12.0	24.0								
Hematite	-	1.0								
Hornblende	37.5	6.0								
Ilmenite	2.0	2.5								
Kyanite	3.0	2.0								
Magnetite	24.5	20.5								
Pyrite	-	-								
Pyroxene	1.0	-								
Rutile	0.5	1.5								
Shell Fragments	1.0	27.0								
Sillimanite	-	-								
Sphene	1.0	-								
Staurolite	1.0	3.5								
Tourmaline	-	2.5								
Zircon	2.0	2.5								
Others	1.0	2.5								

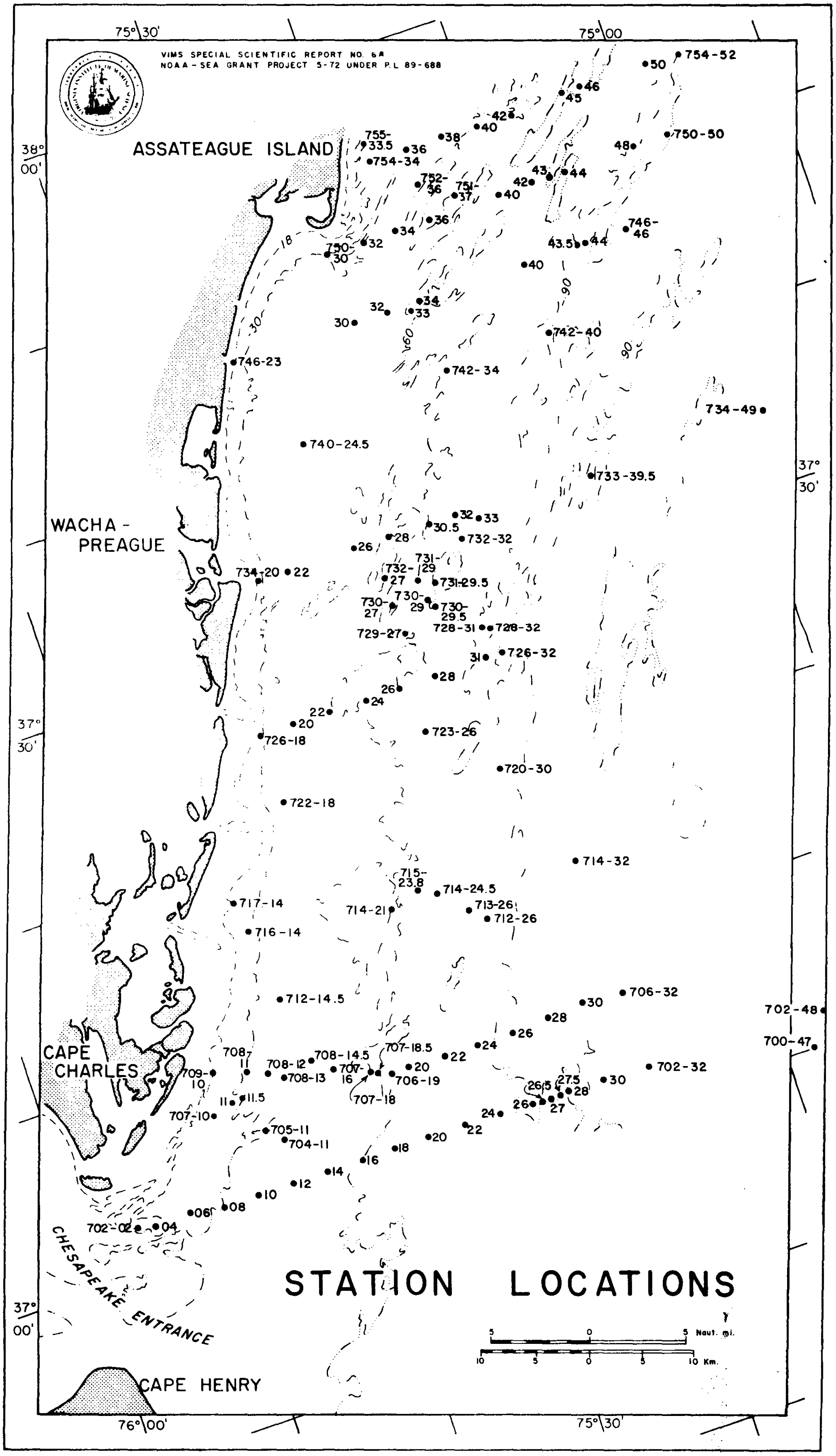

Figure 1. Location of sampling stations

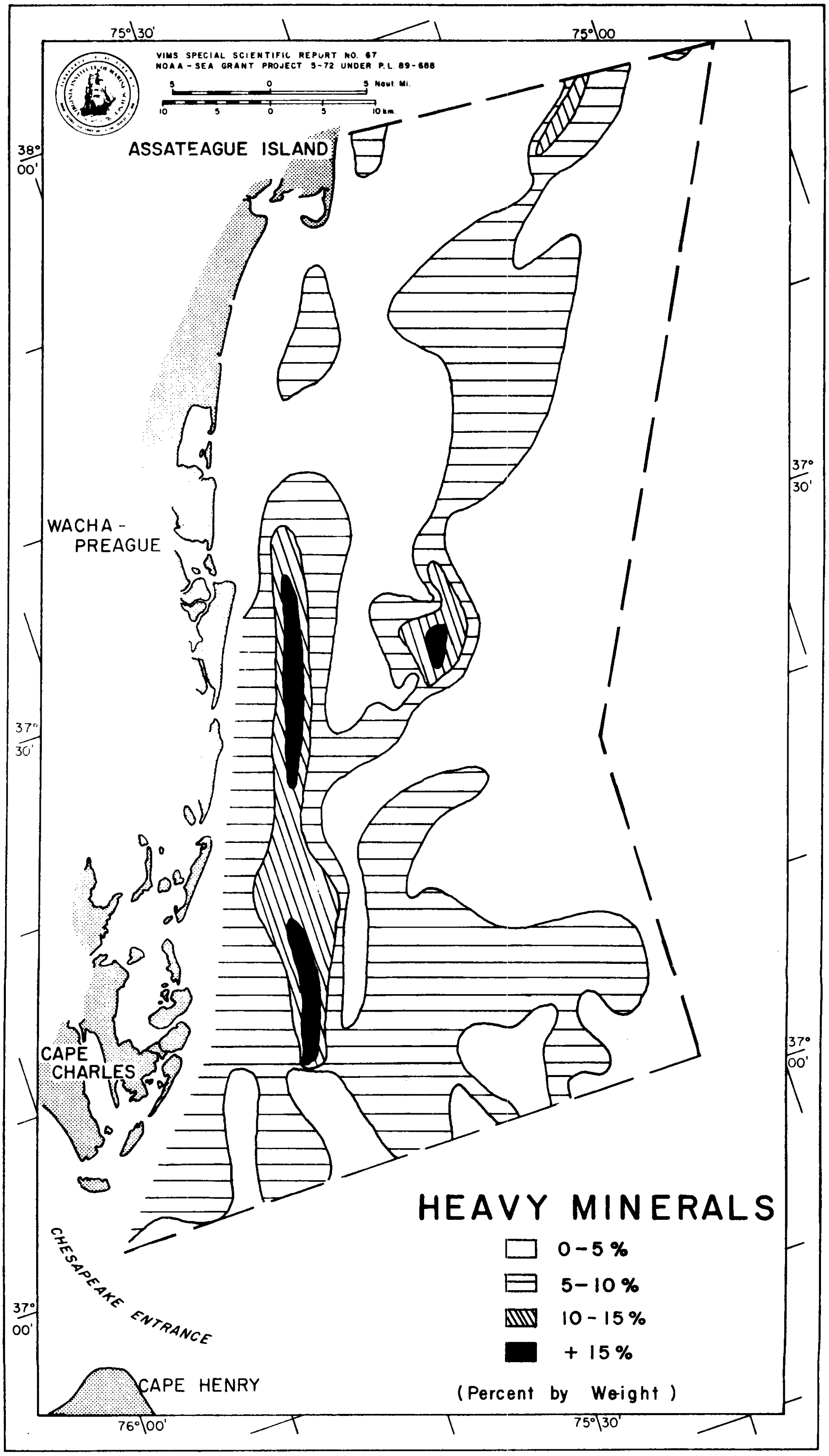

Figure 2. Distribution of heavy minerals by weight percent

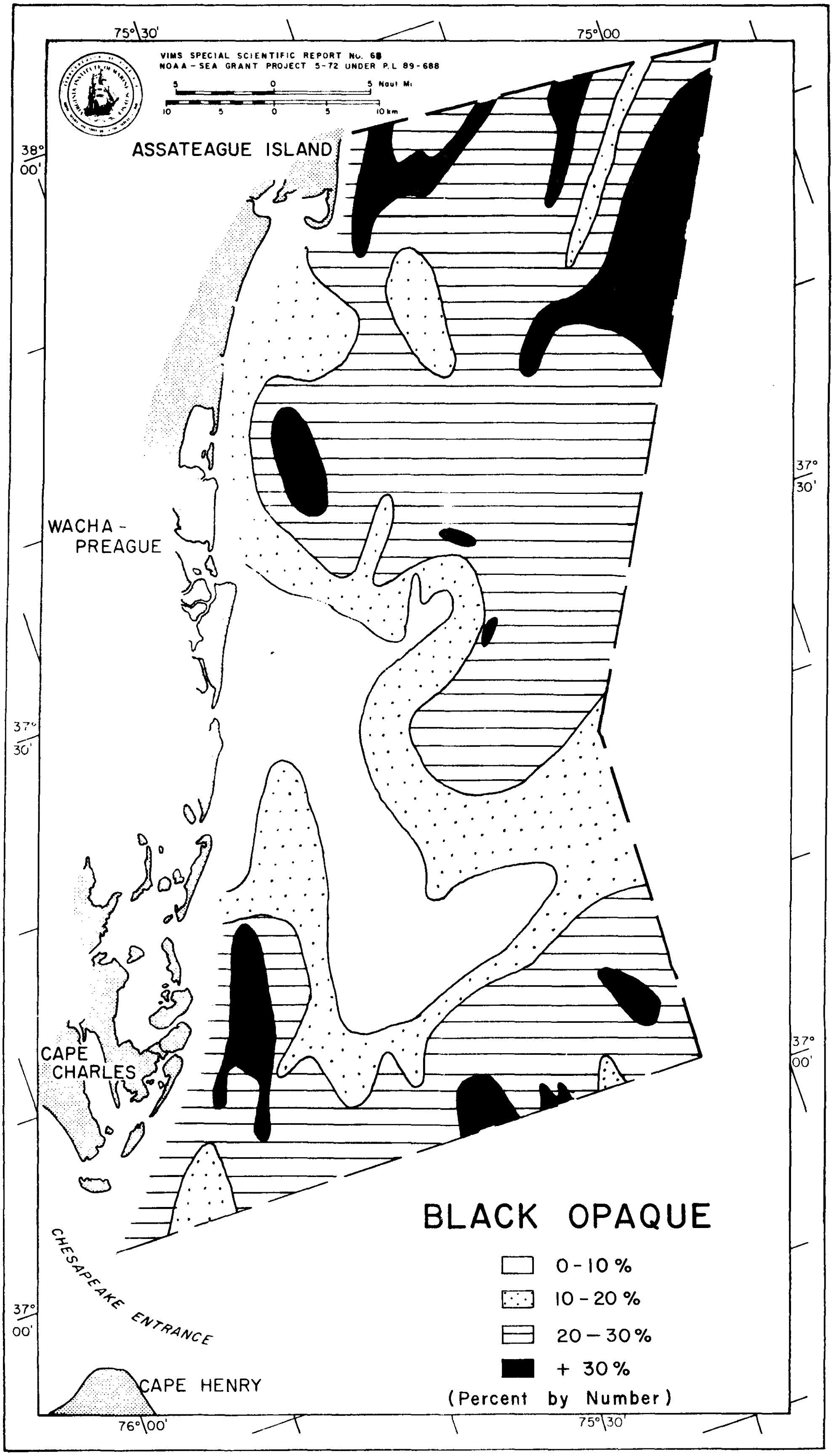

Figure 3. Distribution of black opaque minerals by grain percent

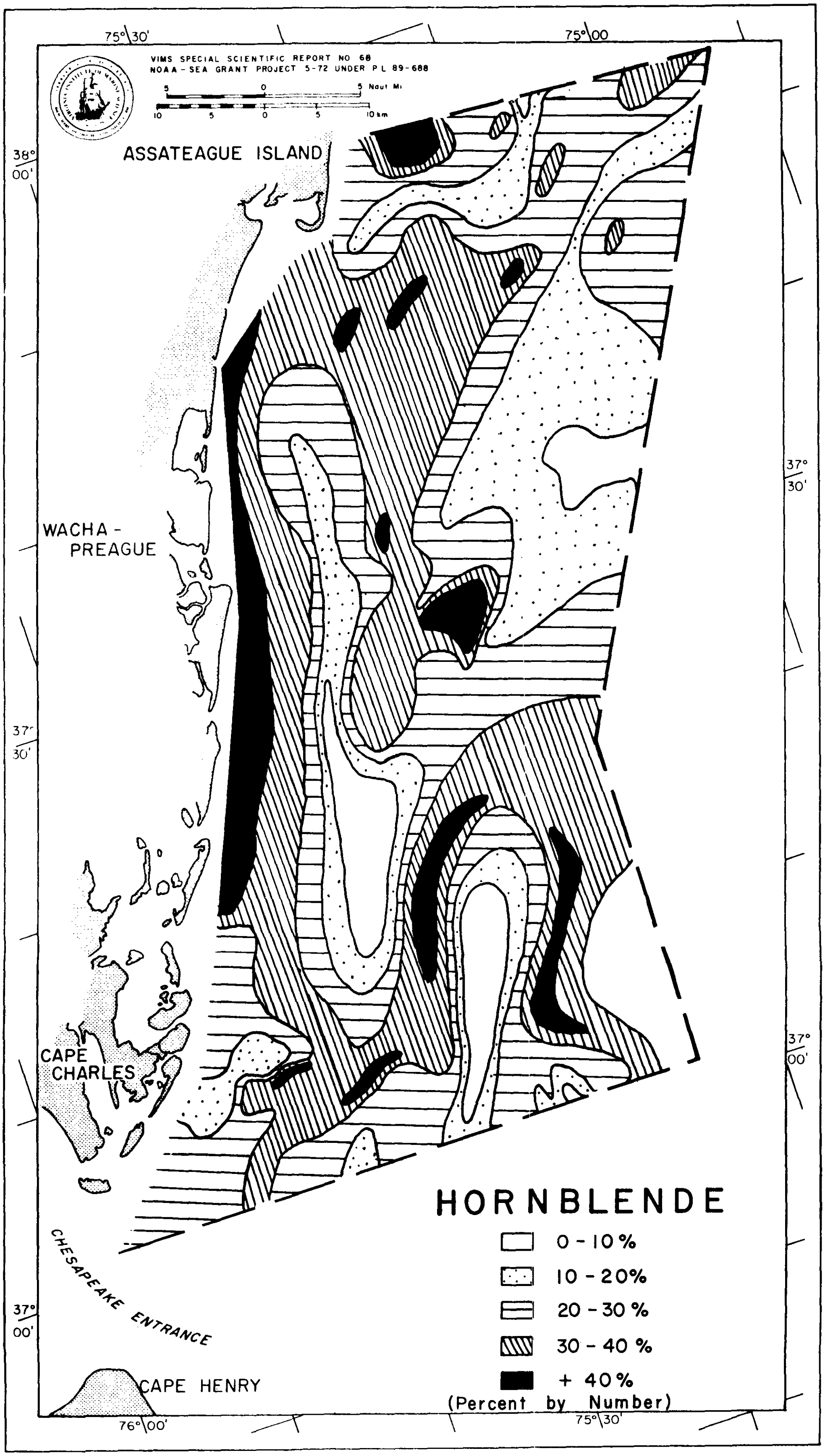

Figure 4. Distribution of hornblende by grain percent

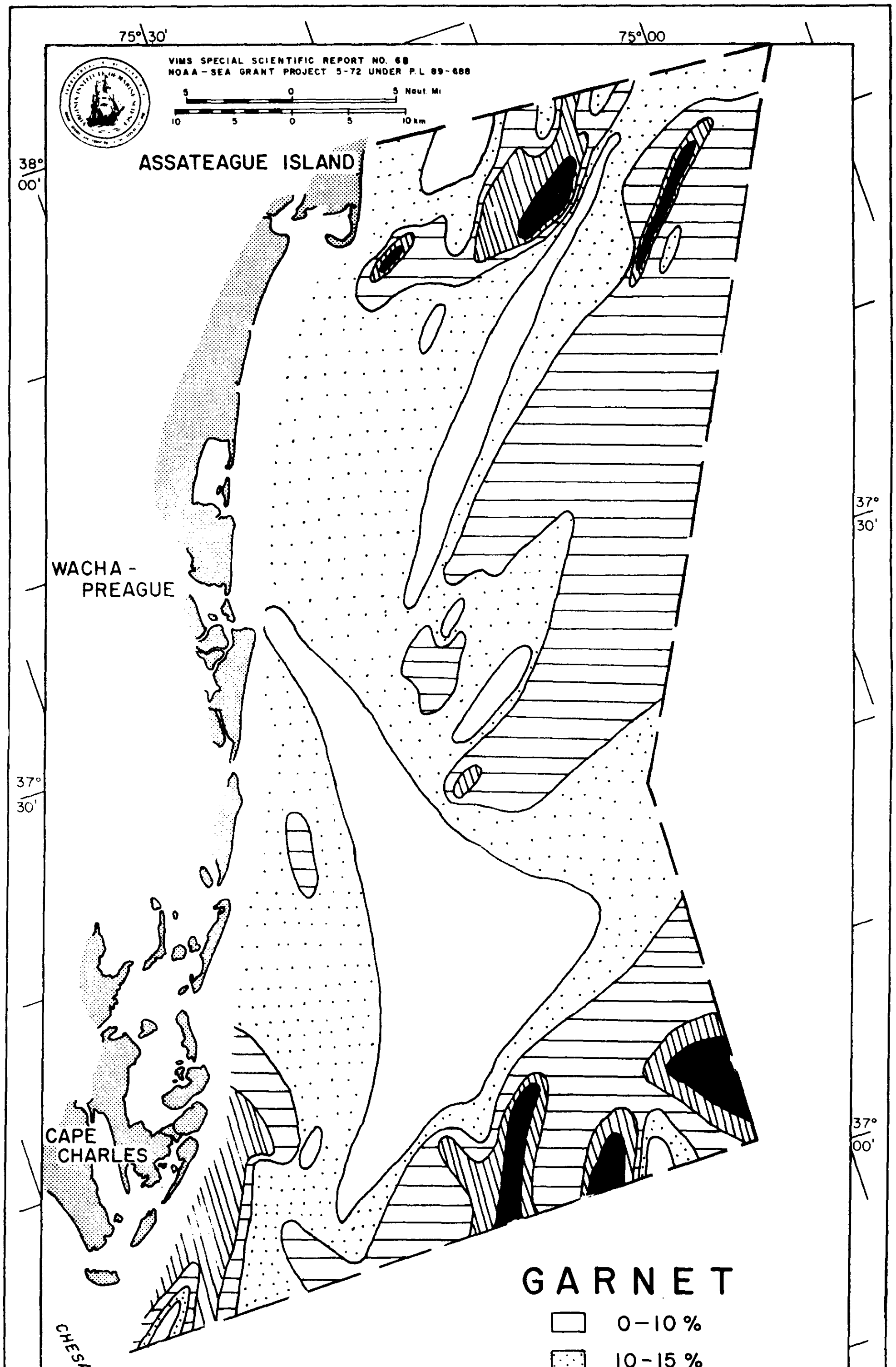

Figure 5. Distribution of garnet by grain percent

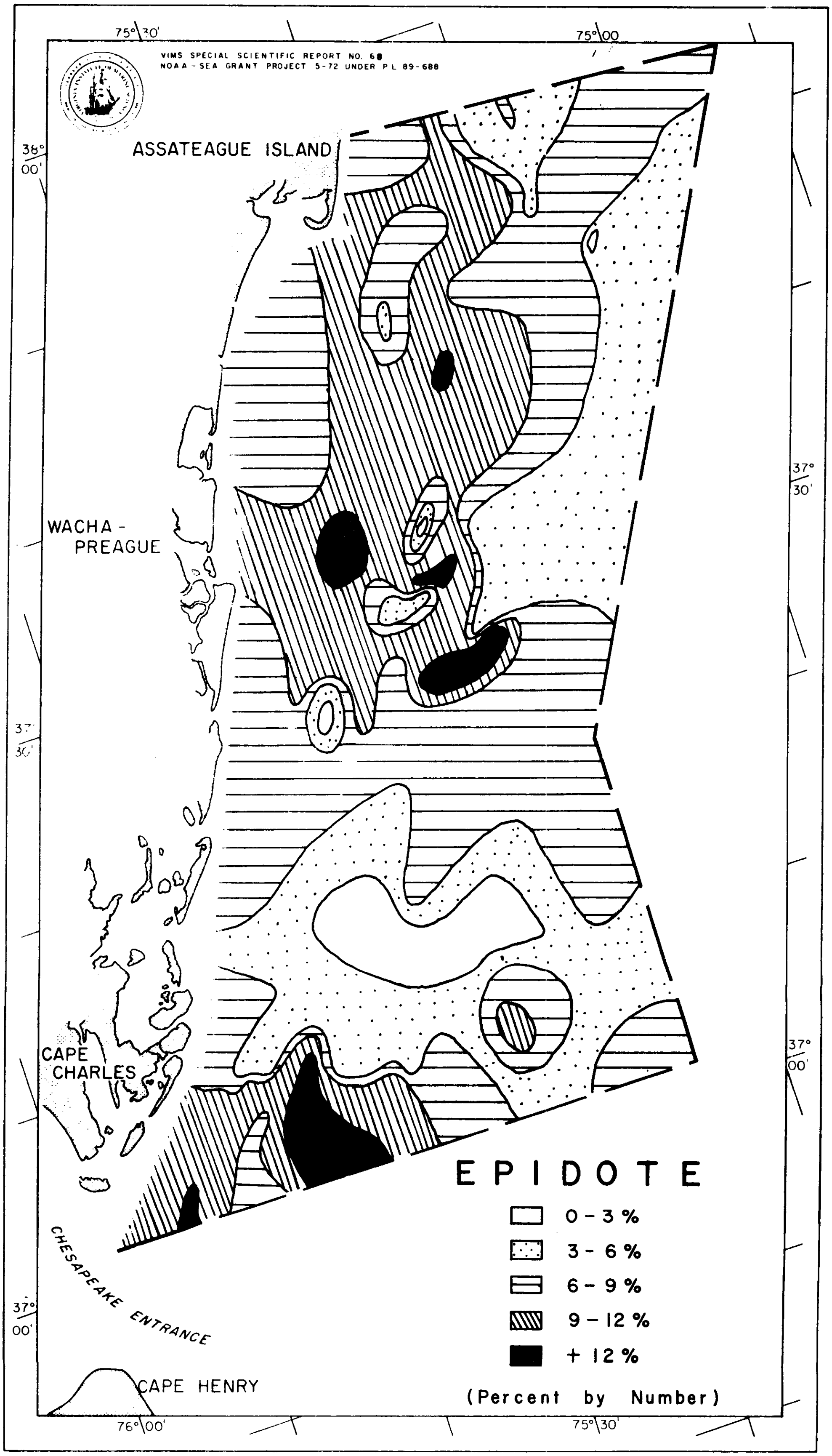

Figure 6. Distribution of epidote by grain percent

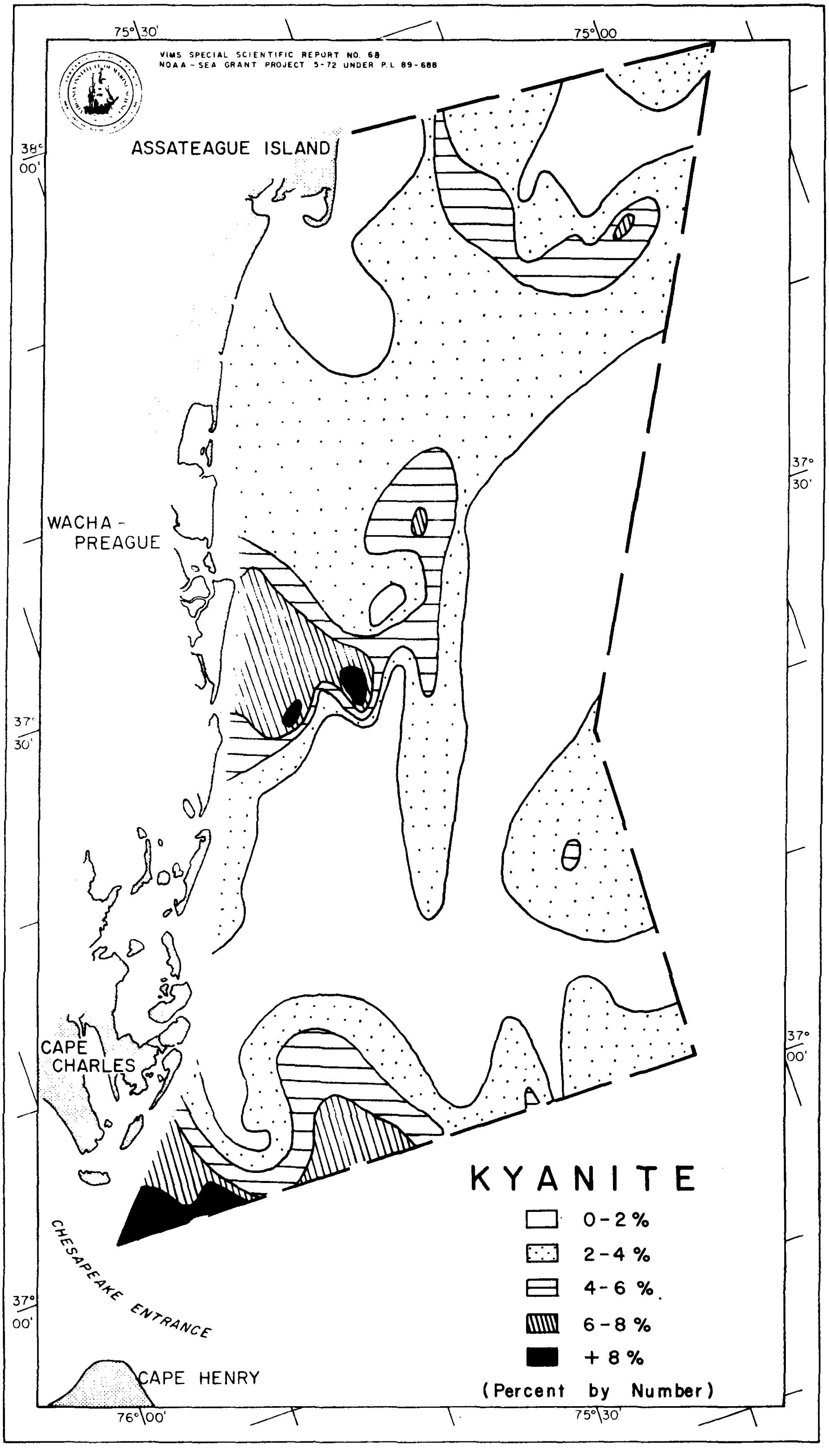

Figure 7. Distribution of kyanite by grain percent

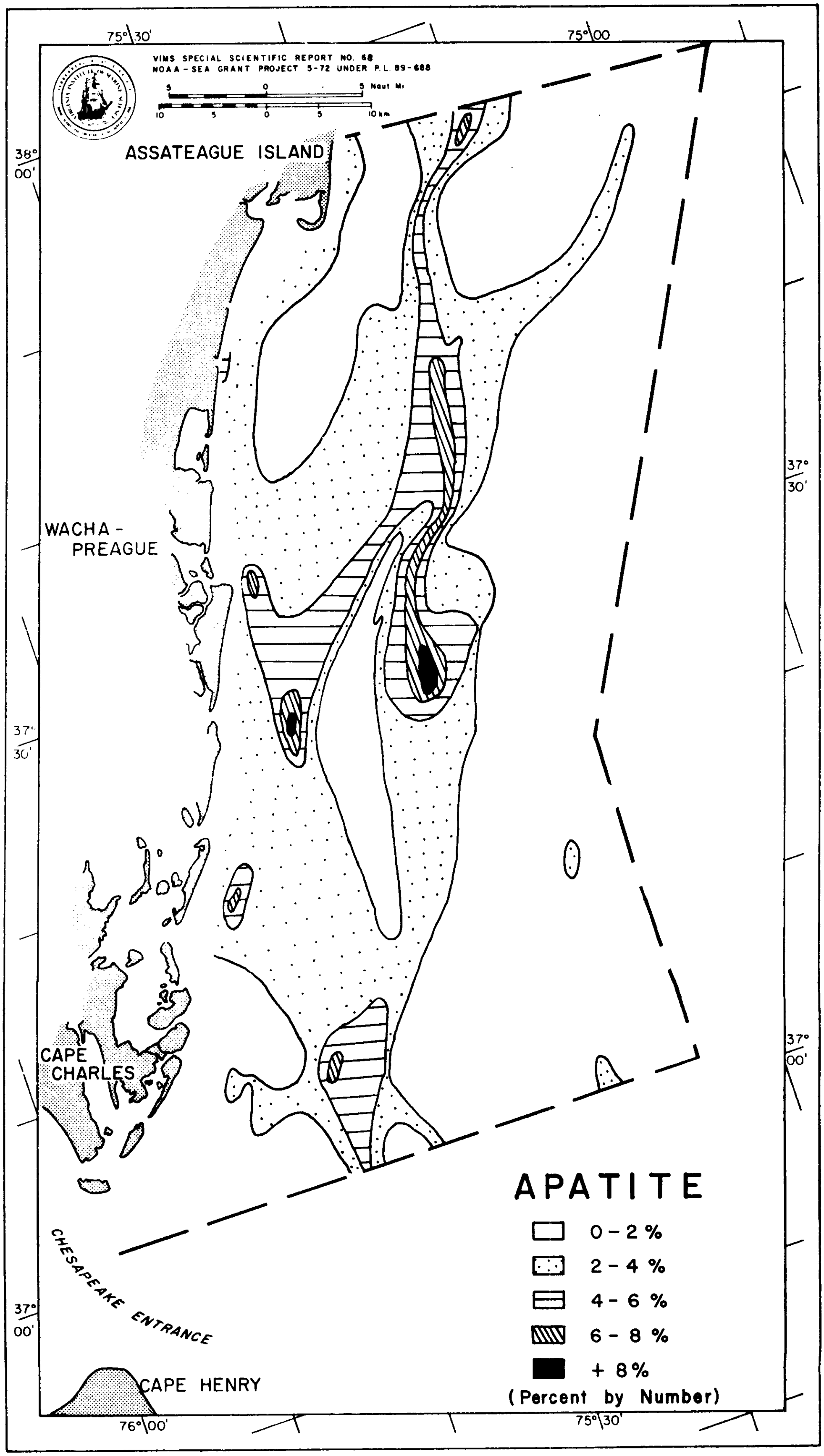

Figure 8. Distribution of apatite by grain percent

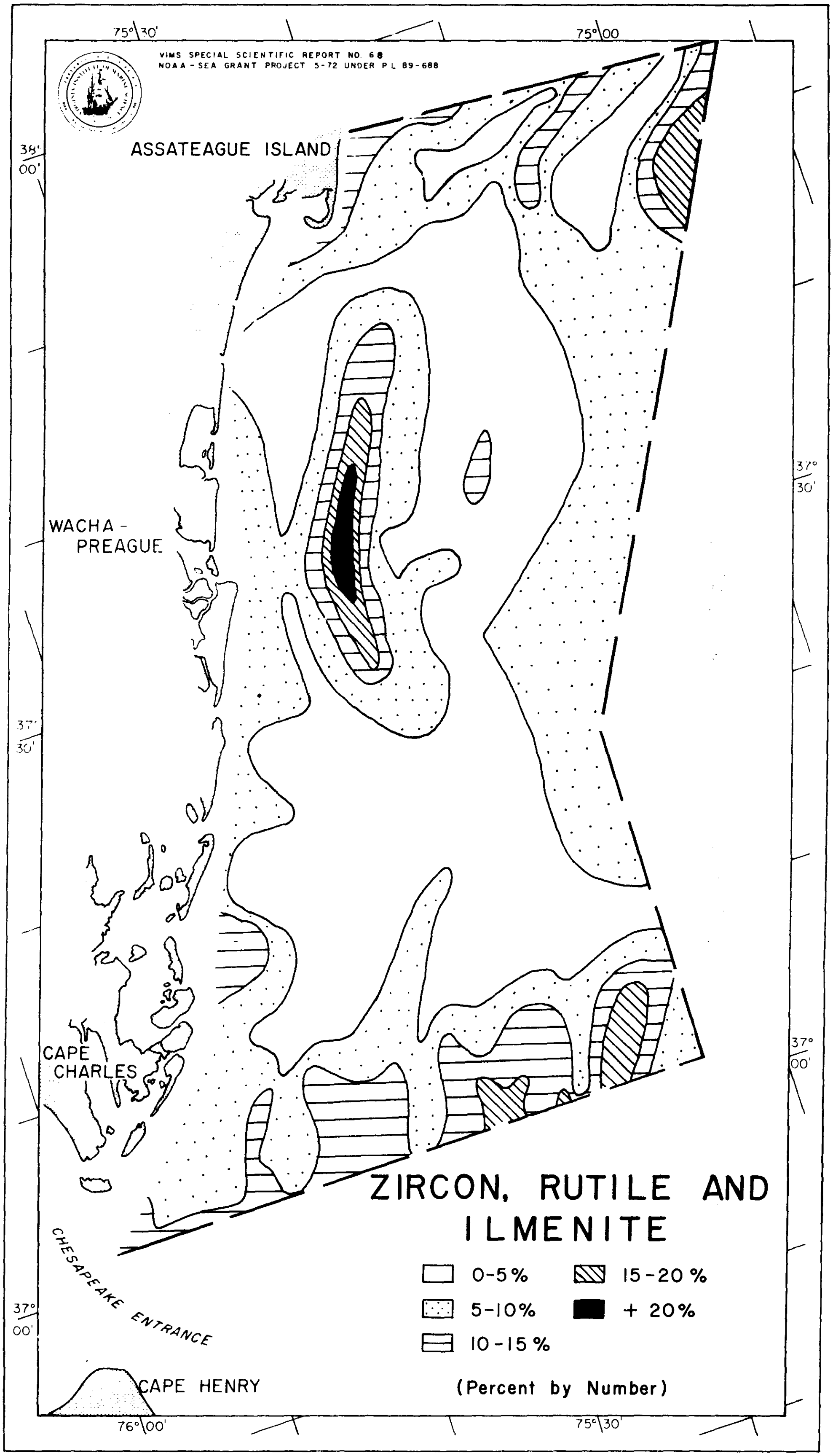

Figure 9. Distribution of combined zircon, rutile, and ilmenite by grain percent

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