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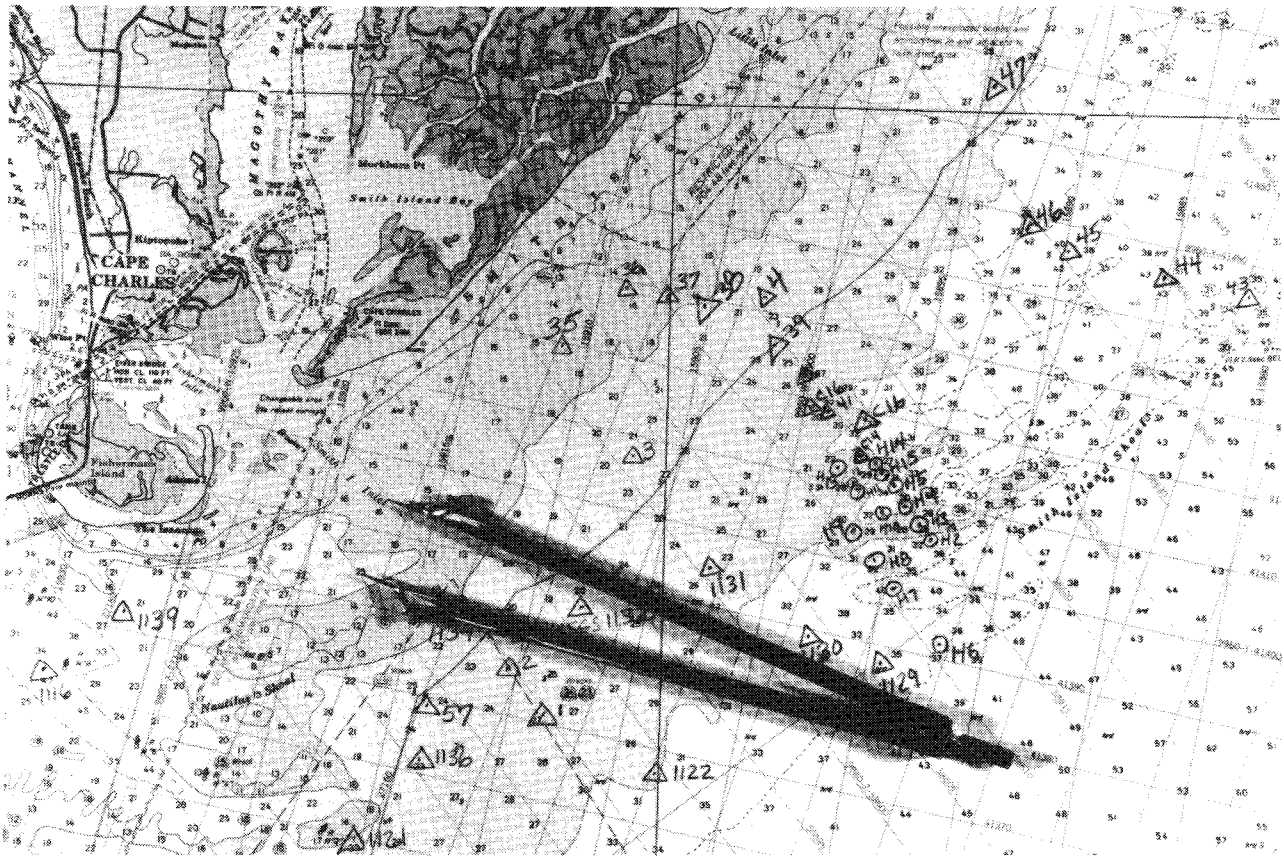
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HEAVY-MINERAL STUDIES — VIRGINIA INNER CONTINENTAL SHELF

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HEAVY-MINERAL VARIABILITY AND PROVENANCE OF THE VIRGINIA INNER SHELF AND LOWER CHESAPEAKE BAY

L.J. Calliari[1], C.T. Fischler[2], and C.R. Berquist, Jr.[3]

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ABSTRACT

The mineral composition of the 3- to 4-phi (0.125 to 0.063 mm) size fraction of 49 surficial grab samples, located north and south of the entrance to Chesapeake Bay and of 38 surficial samples, located in the bay mouth, was determined during this study. Although up to 17 minerals were identified, principal components analysis indicated that seven minerals accounted for 96 percent of the composition variance in the bay samples. By using Q-mode factor analysis, three mineral composition end-members (factors) were selected from the sample data and provided an adequate description of the spatial variation in heavy-mineral composition. The end-members suggest possible mineral sources.

One end-member (amphibole, pyroxene, and epidote), shows that the interior of the bay is a possible source for the amphibole and pyroxene in the samples. A second end-member, comprised of zircon, garnet, and amphibole, suggests two different sources for the sediment, (one source is in the lower bay and the other is south of the bay mouth). The sample composition gradient of a third end-member, comprised of garnet, amphibole, and epidote, suggests sediment transport into the bay resulting from southerly littoral drift along the Delmarva Peninsula. This sediment flux from the north does not appear to bypass the bay mouth and move south, at least not in the sampled area extending up to 5 km offshore.

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INTRODUCTION

FACTOR ANALYSIS

When dealing with a large number of samples and many columns of observed measurements, such as heavy-mineral data, it is commonly difficult to determine meaningful trends related to geologic processes by merely inspecting the data. Q-mode factor analysis, a mathematical procedure, can be used in an attempt to simplify such multi-variable data. Because this study relies on Q-mode factor analysis, definition of terms and a brief explanation of the method is given here; however, references and a more complete discussion is given by Berquist (1986).

Successful use of Q-mode factor analysis can result in a reduction of the number of variables in a large array of data to a few new variables, called factors. The factors, just like samples, have a defined composition in terms of the original variables; the compositions of all samples are then redefined in terms of a few factors instead of the many, original variables. For the analysis of mineral-composition data in this study (the minerals are the variables), we required that the composition of each of the factors (new variables) should approximate the composition of actual samples. For example, if three actual samples are mathematically chosen from the data, the result is called a 3-factor solution and the composition of each of the three chosen samples becomes the composition of a respective factor. The original compositions of all the samples are then redefined, and instead of being comprised of garnet, staurolite, zircon, etc., the samples may be comprised of, say, 80 percent factor I, 10 percent factor II, and 10 percent factor III. During the computation, the composition of each factor may be adjusted and then may only approximate the composition of its corresponding actual sample. The "approximated" compositions are called "end-members".

At the completion of the method when applied to heavy-mineral data, an important relationship exists between the factor composition and original variables. The two or three minerals commonly making up the bulk of the composition of each factor define a mineral suite, or mineral assemblage. In other words, the use of Q-mode factor analysis defines mineral suites (factors) and redefines the composition of all samples in terms of these mineral suites.

Successful use of factor analysis on mineral-composition data is followed by more common approaches of explanation and interpretation. Much the same as making a contour map of zircon concentration over a study area, we can make a contour map of factor concentrations. A mineral suite defining a particular factor may be the mineral assemblage that represents a geologic province. The factor composition gradient in the study area should point to the local (as opposed to ultimate) origin (area of highest concentration) of that mineral assemblage. Also, the down-gradient direction should reflect the direction of transport, or dilution, of the mineral suite away from its source. Thus, sediment transport pathways are defined by the gradient patterns. An analogy is the case where a small amount of dye is introduced into a larger amount of water; concentration of the dye will be highest at its source of entry and decrease away from its source. In summary, two reasons, or applications, for using factor analysis on heavy minerals are, one, a geologic province may be identified and, two, a local source and sediment transport directions may be suggested.

HEAVY MINERALS AND SEDIMENT TRANSPORT

Heavy minerals can be used as natural tracers to define provenance or to assist with studies of sediment transport. The relationship of bottom sediment movement between Chesapeake Bay and the inner continental shelf has been discussed by Firek (1975), Firek and others (1977), Berquist (1986), Colman and others (1988), and Hobbs and others (1986). In these studies provenance and transport direction of sediment were identified, but more data were needed from the inner shelf. The recognition of sedimentary provinces in the lower Chesapeake Bay and inner continental shelf is complicated by the existence of multiple sediment sources. Little knowledge about the sediment transport processes make it difficult to separate the effects of the natural estuarine processes from anthropogenic influences in the sediment source areas.

Previous studies (Firek, 1975; Firek and others, 1977; Berquist, 1986) show that the spatial distribution of selected heavy-mineral suites helps to identify the sedimentary provenance of the complex mineral assemblages. Firek and others (1977), using the mineral distribution patterns in conjunction with analysis of variance, were able to identify characteristic mineral suites for arbitrary geographic areas within the lower bay. Firek and others (1977) also subjected seven major heavy minerals to an R-mode factor analysis, using a 2-factor solution, and proposed that sediment maturity and sediment provenance may have contributed to the observed mineral suites. Based on the relationships of the minerals in each factor and on the way the minerals of the predefined areas compared with one another, Firek and others (1977) found evidence of a bayward influx of littoral and inner shelf sediments.

Berquist (1986) combined Firek's (1975) data with new data from near the bay-mouth area. Q-mode factor analysis defined three suites or end-members. Concentration gradients of one of the factors (a mineral assemblage) were not easily explained in terms of provenance. Of the other two factors, one showed sediment transport into the bay, whereas the concentration gradient of the other factor suggested a source within the bay. These findings are in agreement with Firek and others (1977). Firek's (1975) and Berquist's (1986) heavy-mineral trends were based on data from the northern inner shelf and the bay mouth.

The primary objective of the present study is to project

the sediment transport pathways defined by Berquist (1986) and Firek (1975) using the heavy-mineral variability in the Chesapeake Bay mouth into the inner continental shelf of Virginia. A second purpose is to provide more information on particular mineral assemblages along the inner shelf, especially south of the bay. This study includes part of the data previously analysed by Firek (1975) and Berquist (1986) as well as 49 new grab samples from the Virginia inner shelf (Figure 1). The study relies upon heavy-mineral composition gradients obtained through Q-mode factor analysis. Figure 1 defines the study area and shows the location of the samples used.

METHODS

The 49 grab samples used in this study were obtained while conducting a project funded by the Virginia Subaqueous Mineral and Materials Study Commission (Berquist and Hobbs, 1988). Approximately 0.75 grams of the archived heavy mineral samples were sieved to remove the 3- to 4-phi (0.125 to 0.063mm) size fraction. A portion of this fraction was mounted on a glass slide with Caedax. The heavy minerals were point-counted using a petrographic microscope. Seventeen minerals, including opaques, were identified. Based on their apparent variability in the samples only seven transparent minerals were selected for this study. Point counts continued until at least 200 transparent grains were counted on each slide. This resulted in a total count of 300 to 600 grains per slide. This wide range is due to the variable concentrations of the opaques in the samples. To check reproducibility between individual observations, minerals on two slides were identified and counted by two of us, and the results compared. The results showed replication to within 3 percent in each mineral species.

The complete data set included the 49 grab samples and 38 additional samples analyzed with similar methodology from Firek (1975) and Berquist (1986). The final data matrix consisted of seven minerals (zircon, sphene, amphibole, epidote, staurolite, pyroxene, and garnet) from 87 samples (Table 1). These seven minerals (Table 1) were chosen because principal components analysis performed previously by Berquist (1986) showed them to account for 96 percent of the mineral variability among samples, in the lower Chesapeake Bay area. In order that the composition of all samples added up to 100 percent, the composition of samples characterized by more than the seven minerals were normalized.

These data were analyzed by Q-mode factor analysis. The analysis and conclusions are based on the assumption that high concentrations of heavy minerals are found at or near the source (or end-member) and that these concentrations decrease away from the source by dilution with other materials. It is the concentration gradients that make the use of factor analysis particularly suitable. For each factor, the concentrations of the factor in the samples were plotted on a map and

values were contoured. The final results are shown in Figures 2, 3, and 4 and in Table 2.

RESULTS AND DISCUSSION

We attempted 2-, 3-, and 4-factor solutions, but the 3-factor solution was chosen as the most appropriate for the problem at hand. The 2-factor solution showed high communality values for each factor used to describe the samples, but large negative end-member compositions made this solution unrealistic. The 4-factor solution showed high communalities and no negative values of end-member compositions, but two end-members were redundant as they had nearly the same composition. The 4-factor solution was rejected.

The best practical description was achieved with the 3-factor solution because it accounted for 98.3 percent of the variance, had positive composition loadings, high communalities for each sample, and provided good reproduction of the raw-data matrix. Most importantly, the locations of the end-members (Figure 1) represented by the 3-factor solution provide a reasonable geologic explanation. The first end-member (composed entirely of factor I material) is located inside the bay midway between the mouth of the James River and Cape Henry. The second end-member (composed entirely of factor II) is located on the inner shelf south of the bay's mouth. The third end-member (composed entirely of factor III) is located in the vicinity of Fishermans Island. The compositions of the end-members are listed in Table 3. Figures 2, 3, and 4 are contoured plots of the factor abundance (listed in Table 2) in each sample from the 3-factor solution.

Factor I is comprised, in order of decreasing abundance, primarily of amphibole, pyroxene, and some epidote (Table 3), and is an immature mineral assemblage. The plot (Figure 2) of factor I shows a trend of decreasing concentration offshore suggesting sediment transport out of the bay and to the south. This interpretation differs from what we should expect from the circulation studies done in the inner shelf adjacent to the bay mouth (Boicourt, 1981; Harrison and others, 1967) and modern shelf and bay sedimentation (Swift and others, 1971; Hobbs and others, 1986; Colman and others, 1988). However, relevant studies regarding sediment transport and bottom types in this area were conducted by Ludwick (1970, 1974) and others, who estimated bottom shear stress and found net sediment transport near the bed can be ebb-dominated around Cape Henry. His studies support our interpretation of offshore transport in this area. Furthermore, Ludwick's (1978) study of coastal currents from the entrance of Chesapeake Bay to south of Virginia Beach found that tidal currents are rotary, with major elliptical axis nearly parallel to the shoreline. These tidal currents produce a net southerly current at depths of 8 to 15 meters. Ludwick postulates that wave motion superimposed on this net southerly tidal current produces a southerly flowing stream of sand about 5 km wide off Virginia Beach (Inman and Dolan, 1989).
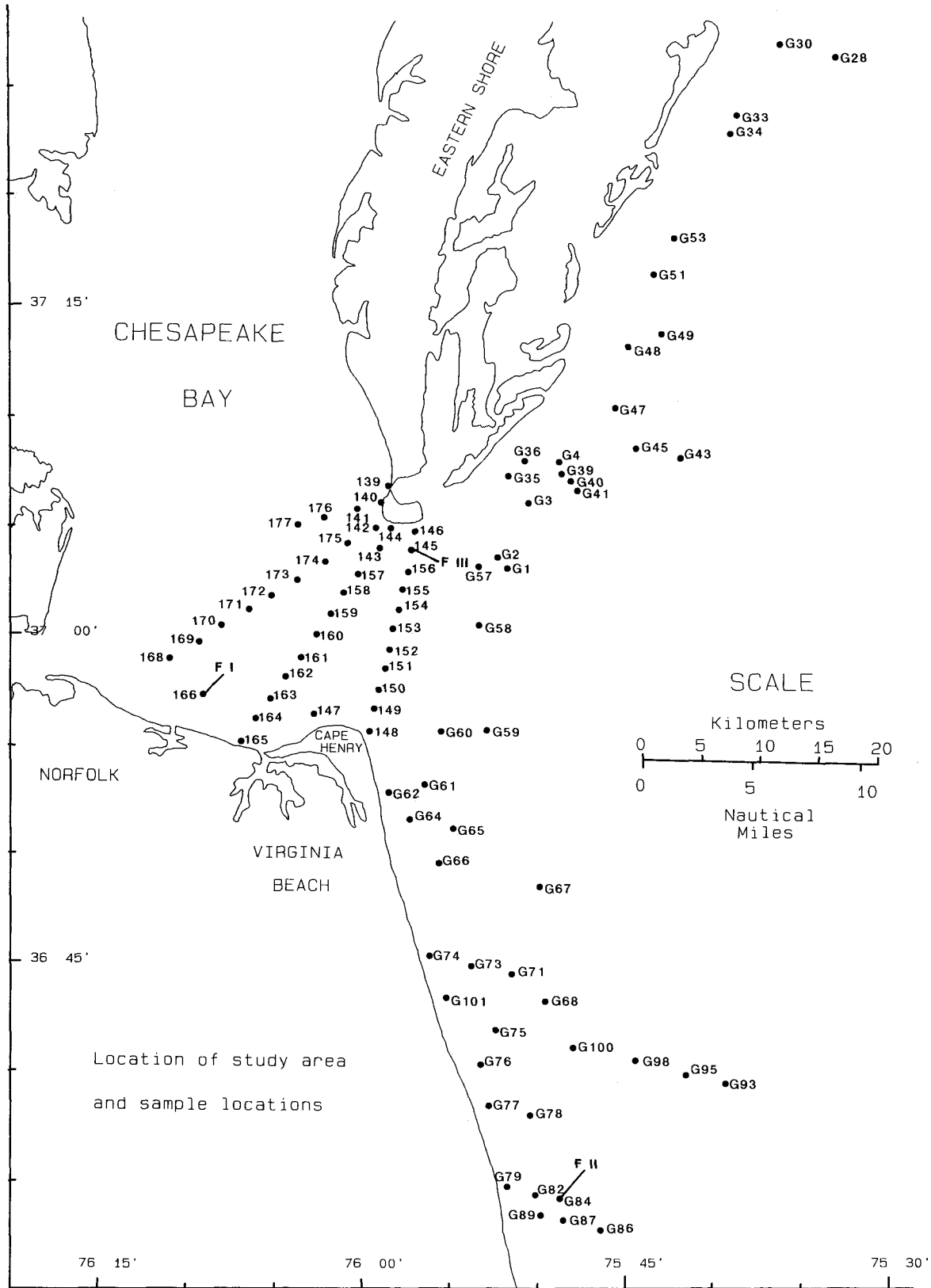
Figure 1. Location of study area, sample sites, and factors (F I, F II, F III).
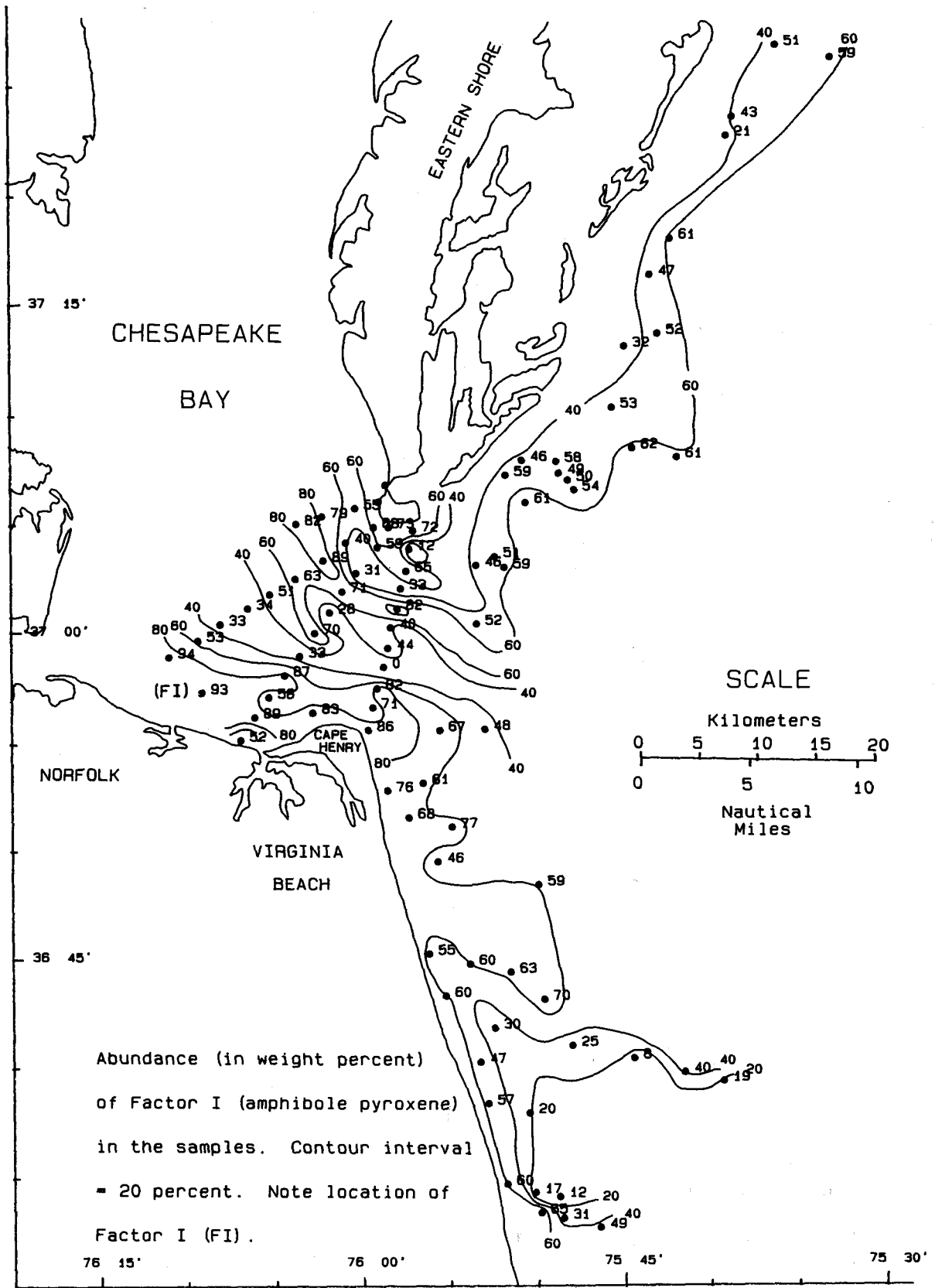
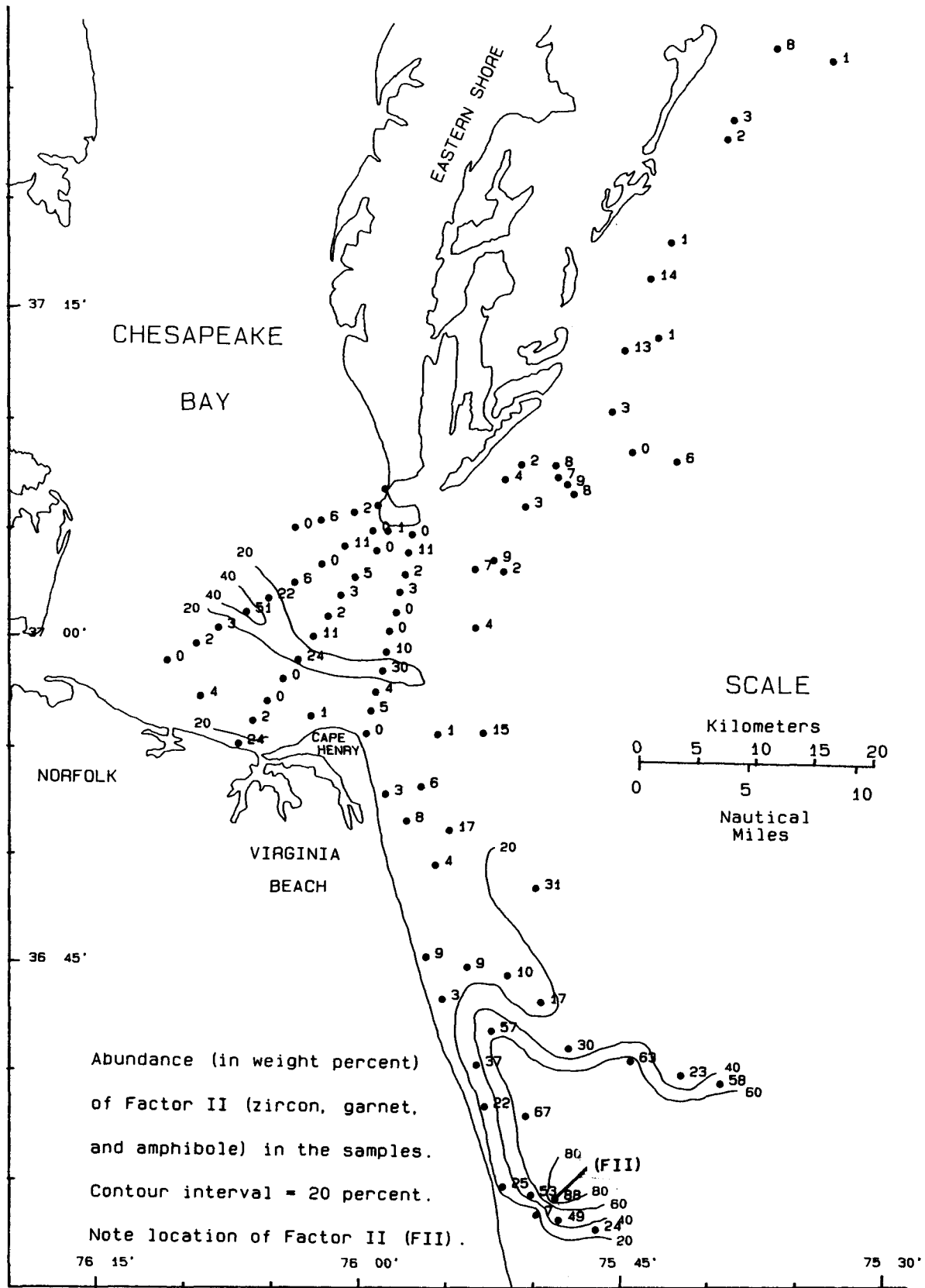Figure 2. Abundance of Factor I (amphibole, pyroxene) in samples.

Figure 3. Abundance of Factor II (zircon, garnet and amphibole) in samples.
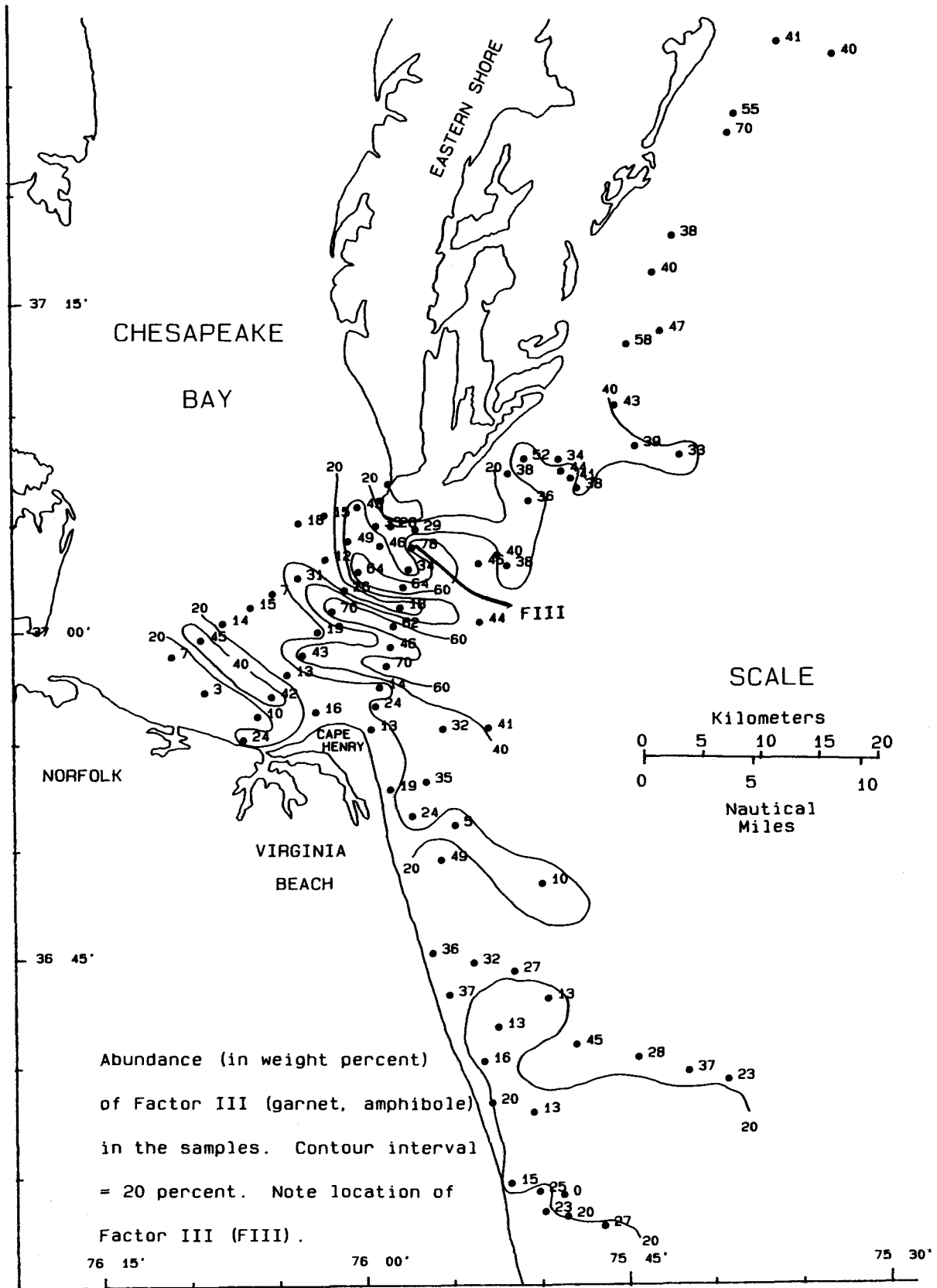
Figure 4. Abundance of Factor III (garnet, amphibole) in samples.

Table 1. Raw-data matrix percentages.

SAMPLE	ZIRCON	SPHENE	AMPHIBOLE	EPIDOTE	STAUROLITE	PYROXENE	GARNET
139	0.00	2.90	60.14	7.25	0.00	13.77	15.94
140	4.14	4.14	47.93	5.92	4.73	12.43	20.71
141	3.27	1.96	47.06	4.58	0.65	14.38	28.10
142	0.60	1.80	56.29	5.99	3.59	10.78	20.96
143	0.00	2.65	48.34	3.97	0.00	17.22	27.81
144	1.72	3.45	55.75	5.17	2.87	13.79	17.24
145	6.94	7.55	24.24	4.48	8.22	5.71	43.57
146	1.16	1.16	56.98	4.65	2.91	13.95	19.19
147	1.39	1.39	61.11	6.25	2.08	15.97	11.81
148	0.56	0.56	56.50	4.52	4.52	22.60	10.73
149	3.52	4.93	58.45	5.63	2.82	7.75	16.90
150	2.40	3.59	55.09	2.40	5.99	19.16	11.38
151	14.86	16.57	17.71	5.14	4.00	1.14	40.57
152	6.67	2.78	36.67	2.22	4.44	17.22	30.00
153	1.40	4.90	42.66	4.90	3.50	6.29	36.36
154	0.58	3.47	53.76	4.05	3.47	21.97	12.72
155	4.03	6.71	36.24	3.36	5.37	7.38	36.91
156	2.35	1.76	51.76	4.71	2.35	14.71	22.35
157	5.00	6.88	35.62	6.25	2.50	6.25	37.50
158	2.21	4.42	52.49	4.97	4.42	14.36	17.13
159	3.57	5.36	36.31	6.55	2.98	4.17	41.07
160	5.26	4.68	48.54	7.02	5.26	14.62	14.62
161	11.80	4.35	32.30	12.42	4.35	6.21	28.57
162	0.58	2.31	59.54	8.67	0.58	18.50	9.83
163	1.35	0.68	52.03	6.76	5.41	7.43	26.35
164	1.16	3.47	47.40	4.62	4.05	30.64	8.67
165	11.26	11.26	41.06	7.95	4.64	5.96	17.88
166	1.69	2.81	56.18	5.62	4.49	23.60	5.62
168	0.00	3.64	55.15	5.45	3.64	25.45	6.67
169	2.60	2.60	49.35	9.09	2.60	5.84	27.92
170	1.73	4.05	50.87	5.78	2.31	24.28	10.98
171	18.07	9.04	24.70	9.04	17.47	5.42	16.27
172	7.82	8.38	35.20	7.82	6.15	25.14	9.50
173	2.70	3.38	47.97	13.51	4.05	9.46	18.92
174	0.56	1.13	62.71	2.26	2.26	20.90	10.17
175	5.77	5.13	35.90	9.62	7.05	7.69	28.85
176	3.77	1.89	54.09	3.77	1.89	21.38	13.21
177	0.67	1.33	61.33	7.33	2.67	14.00	12.67
G30	6.66	0.61	48.48	3.03	0.61	10.91	29.70
G34	4.12	1.03	31.96	9.28	0.00	7.22	46.39
G41	4.55	1.51	42.05	12.50	0.00	15.15	24.24
G45	0.47	0.00	42.72	14.55	0.00	19.72	22.54
G49	2.69	1.61	43.01	6.99	0.00	16.67	29.03
G58	3.77	2.15	41.93	9.14	0.00	15.59	27.42
G59	9.50	1.60	37.40	7.40	0.50	14.70	28.90
G65	8.20	1.09	54.64	10.93	2.19	14.21	8.74
G71	4.95	1.10	44.51	12.64	0.55	17.57	18.68
G84	41.94	1.61	17.20	10.22	3.22	4.84	20.97
G100	13.61	1.18	26.63	17.16	4.14	7.10	30.18
G1	2.87	1.64	47.13	7.38	0.00	16.39	24.59
G2	6.30	1.00	40.80	6.80	0.00	18.00	27.20

Table 1. (continued).

SAMPLE	ZIRCON	SPHENE	AMPHIBOLE	EPIDOTE	STAUROLITE	PYROXENE	GARNET
G3	2.30	0.90	45.60	11.20	0.00	17.20	22.80
G4	4.90	1.00	43.80	9.40	0.00	17.70	23.20
G35	3.44	2.59	49.57	7.76	0.43	11.64	24.57
G36	3.00	2.63	42.10	8.27	0.00	12.42	31.58
G39	5.00	0.50	43.30	10.90	0.50	11.40	28.40
G40	5.70	0.50	42.40	10.90	1.00	12.90	26.70
G57	5.90	1.00	43.30	6.90	0.00	11.80	31.00
G60	1.69	0.42	50.21	8.01	0.00	18.57	21.10
G61	2.60	2.16	45.89	11.25	0.43	15.59	22.08
G62	3.49	0.50	60.70	8.95	0.99	11.44	13.93
G64	5.00	2.00	52.00	8.50	0.50	14.50	17.50
G66	3.85	1.92	38.46	7.69	0.96	16.83	30.29
G67	17.10	0.37	48.33	3.72	0.74	13.38	16.36
G73	4.90	2.86	43.26	9.39	0.41	17.96	21.22
G74	6.50	0.44	48.92	6.06	0.86	11.25	25.97
G75	29.71	0.85	30.12	5.44	2.09	8.79	23.00
G76	17.30	2.00	34.20	11.40	0.00	16.30	18.80
G78	33.47	0.42	23.73	7.20	4.24	6.36	24.58
G28	2.20	0.90	52.60	9.20	0.90	8.80	25.40
G33	3.20	0.90	42.30	11.70	0.40	8.10	33.30
G43	3.50	0.40	43.50	13.00	0.90	17.80	20.90
G47	3.40	1.40	45.70	8.60	0.50	13.00	27.40
G48	8.60	0.00	34.40	8.10	0.50	9.60	37.80
G51	9.04	1.13	46.89	7.34	1.13	5.66	28.81
G53	1.50	0.00	49.50	12.60	0.50	12.10	23.80
G68	8.50	1.00	58.50	15.00	0.00	4.50	12.50
G77	11.34	2.57	50.00	12.37	3.10	3.10	17.52
G79	13.10	1.40	50.50	10.20	1.00	7.80	16.00
G82	30.60	1.60	25.90	6.70	1.60	3.60	30.00
G86	12.30	1.90	41.50	9.40	2.40	10.40	22.20
G87	25.83	1.10	34.07	8.24	2.20	3.84	24.72
G89	4.28	2.14	51.70	8.11	2.56	11.97	19.24
G93	31.60	0.00	27.70	3.03	3.03	4.74	29.90
G95	12.74	1.12	41.20	7.49	4.12	4.87	28.46
G98	31.60	1.00	18.10	9.80	1.00	6.70	31.60
G101	1.80	0.00	46.10	16.00	0.50	13.20	22.30

Table 2. Location and sample composition in terms of factors for the 3-factor solution; negative values were converted to zero before contouring. Factor composition sums may not equal 100 because of rounding.

SAMPLE	LATITUDE	LONGITUDE	FACTOR I	FACTOR II	FACTOR III
139	37.06.8	75.58.5	78	-2	25
140	37.06.0	75.58.8	62	7	32
141	37.05.7	76.00.2	55	2	43
142	37.04.9	75.59.2	68	-1	33
143	37.04.0	75.58.9	59	-4	46
144	37.05.0	75.58.2	73	1	26
145	37.03.9	75.57.1	12	11	78
146	37.04.7	75.56.9	72	0	29
147	36.56.4	76.02.6	83	1	16
148	36.55.6	75.59.5	86	0	13
149	36.56.6	75.59.3	71	5	24
150	36.57.4	75.59.0	82	4	14
151	36.58.5	75.58.6	0	30	70
152	36.59.4	75.58.4	44	10	46
153	37.00.3	75.58.2	40	-2	62
154	37.01.2	75.57.8	82	0	18
155	37.02.0	75.57.6	33	3	64
156	37.02.9	75.57.3	65	2	34
157	37.02.8	76.00.1	31	5	64
158	37.01.9	76.00.9	71	3	26
159	37.01.0	76.01.8	28	2	70
160	37.00.0	76.02.6	70	11	19
161	36.59.0	76.03.4	33	24	43
162	36.58.1	76.04.2	87	0	13
163	36.57.1	76.05.1	58	0	42
164	36.56.2	76.06.0	89	2	10
165	36.55.2	76.06.8	52	24	24
166	36.57.2	76.09.0	93	4	3
168	36.59.0	76.10.8	94	0	7
169	36.59.7	76.09.2	53	2	45
170	37.00.4	76.07.9	83	3	14
171	37.01.2	76.06.4	34	51	15
172	37.01.8	76.05.1	71	22	7
173	37.02.5	76.03.7	63	6	31
174	37.03.4	76.02.1	89	0	12
175	37.04.2	76.00.7	40	11	49
176	37.05.3	76.02.2	79	6	15
177	37.05.0	76.03.6	82	0	18
G30	37.26.64	75.36.13	51	8	41
G34	37.22.64	75.38.84	21	2	77
G41	37.06.56	75.47.70	54	8	38
G45	37.08.46	75.44.32	62	0	39
G49	37.13.68	75.42.81	52	1	47
G58	37.00.49	75.53.23	52	4	44
G59	36.55.63	75.52.89	43	16	41
G65	36.51.15	75.54.85	77	17	5
G71	36.44.41	75.51.51	63	10	27
G84	36.34.10	75.48.76	12	88	0
G100	36.41.05	75.47.94	25	30	45
G1	37.03.03	75.51.69	59	2	38

Table 2. (continued).

SAMPLE	LATITUDE	LONGITUDE	FACTOR I	FACTOR II	FACTOR III
G2	37.03.55	75.52.19	51	9	40
G3	37.05.99	75.50.49	61	3	36
G4	37.07.85	75.48.65	58	8	34
G35	37.07.22	75.51.55	59	4	38
G36	37.07.90	75.50.64	46	2	52
G39	37.07.30	75.48.49	49	7	44
G40	37.06.97	75.48.04	50	9	41
G57	37.03.10	75.53.31	46	7	46
G60	36.55.60	75.55.39	67	1	32
G61	36.53.16	75.56.46	61	3	35
G62	36.52.81	75.58.36	76	6	18
G64	36.51.56	75.57.18	68	8	24
G66	36.49.52	75.55.56	46	4	49
G67	36.48.51	75.49.83	59	31	10
G73	36.44.82	75.53.83	60	8	32
G74	36.45.26	75.56.16	55	9	36
G75	36.41.88	75.52.33	30	57	13
G76	36.40.31	75.53.22	47	37	16
G78	36.37.99	75.50.39	20	67	13
G28	37.26.07	75.33.01	59	1	40
G33	37.23.45	75.38.55	43	3	55
G43	37.07.97	75.41.73	61	6	33
G47	37.10.31	75.45.44	53	3	43
G48	37.13.09	75.44.71	30	13	58
G51	37.16.37	75.43.30	47	14	40
G53	37.17.95	75.42.15	61	1	38
G68	36.43.16	75.49.55	70	17	13
G77	36.38.42	75.52.75	57	22	20
G79	36.34.72	75.51.73	60	25	15
G82	36.34.36	75.50.05	17	58	25
G86	36.32.70	75.46.39	49	24	27
G87	36.33.17	75.48.56	31	49	20
G89	36.33.42	75.49.84	65	7	28
G93	36.39.38	75.39.29	19	58	23
G95	36.39.82	75.41.54	40	23	37
G98	36.40.41	75.44.47	08	63	28
G101	36.43.32	75.55.21	60	3	37

Table 3. Composition of end-members (factors) from the 3-factor solution

FACTOR I sample 166	FACTOR II sample G84	FACTOR III sample 145
64% amphibole	47% zircon	57% garnet
22% pyroxene	23% garnet	24% amphibole
8% epidote	11% amphibole	8% epidote
3% garnet	9% epidote	5% sphene
2% staurolite	6% staurolite	4% zircon
1% sphene	3% sphene	2% staurolite
-.1% zircon	1% pyroxene	1% pyroxene

Factor II is comprised primarily of zircon, garnet, and amphibole and is a more stable mineral assemblage. It is important to visualize the extreme differences in gradients along the inner shelf as well as the middle bay (Figure 3). The highest composition loading values are found south of the bay's mouth with a small area of slightly lower values located in the lower bay. Factor II probably represents reworked deposits of Pleistocene age.

Results of other studies compiled by Berquist (1986) showed that zircon is abundant in ancient coastal plain sediments. Swift and others (1977) have shown through seismic data and vibratory coring that older sediments are exposed on the inner shelf commonly in the troughs of the sand ridges. Recent seismic data provided by Hobbs (this volume) and side-scan sonar results obtained by Green (1986) shows that south of the bay mouth older sediments crop out in the troughs of sand ridges and at other places.

Some of our samples with high concentration of factor II are located in the vicinity of older (Pleistocene?) sediments. The high concentrations of zircon found in Firek's and Berquist's data in samples from the lower bay can be explained by the reworking of the older sediments and erosion of the nearby shoreline. Colman and others (1988) showed that, south and west of the Chesapeake channel, a thin layer of modern sediment covers an irregular Tertiary surface. We believe the two areas of high concentration are related only in that they involve reworking of the older sediments. Gradients do not indicate sediment transport between the two areas.

Factor III is comprised primarily of garnet, amphibole, and some epidote and is also an unstable mineral assemblage. Factor III concentration gradients show trends similar to those shown by previous studies (Figure 4). Firek and others (1977) reasoned that erosion of the east side of Delmarva Peninsula (a source of garnet) was a source of sediment to the bay mouth province. Berquist's (1986) factor III was comprised of the same components (garnet, amphibole, and epidote) as our factor III. Goodwin and Thomas (1973) studied the 0- to-4 phi (1.00 to 0.0625mm) fraction and found high concentrations of garnet, hornblende, and epidote on the shelf between Assateague Island and the Chesapeake Bay mouth. Studies done by Swift and others (1971) also support the idea of the shelf

as a source of garnet. Our plot of factor III (Figure 4) suggests an influx of sediment into the bay from the inner shelf off the Eastern Shore, the concentrations decreasing towards the bay.

CONCLUSIONS

The results of this study in the northern section of the bay mouth are consistent with those of Berquist (1986) and Firek (1975). However, the influx of sediment into the bay from the inner shelf is not evident in the southern part of the bay mouth especially around Cape Henry. Three end-members define three sediment sources around the Chesapeake Bay mouth and nearby inner continental shelf. Factor I represents a source from inside the bay where the percent composition decreases towards the bay mouth. Factor II shows the influence of two older sediment sources (possibly Pleistocene), one inside the bay and the other south of the bay mouth on the inner shelf. The gradient patterns do not suggest sediment transport between the inside and outside of the bay. Factor III represents a source located to the north, along the Eastern Shore, and is in agreement with other studies in the northern part of the bay mouth.

The gross sediment transport patterns based on the mineral compositions shown in our work are not entirely consistent with the general model of sediment transport for estuaries. If our defined transport pathways reflect active movement of sand-sized materials, then the generalized models of sediment transport based solely on current studies are insufficient to explain our observations. This suggests a need for more detailed studies in sediment transport that consider spatial variability of bottom types (roughness and sediment composition) and flow regimes. Wright and others (1987) showed that the lower bay and inner shelf are characterized by appreciable spatial variability in both bottom types and benthic flow regimes, which are key factors in controlling the shear stress on the bottom and consequently sediment transport processes.

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