

**DISTRIBUTION ANALYSIS OF HEAVY MINERALS
ON THE INNER CONTINENTAL SHELF OF VIRGINIA**

A Thesis

Presented to

The Faculty of the School of Marine Science
The College of William and Mary in Virginia

In Partial Fulfillment

Of the Requirements for the Degree of
Master of Arts

by

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1989

APPROVAL SHEET

This thesis is submitted in partial fulfillment of
the requirements for the degree of

Master of Arts



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Approved, December 1989



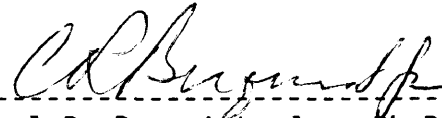
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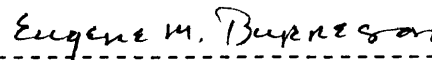
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DEDICATION

This thesis is dedicated to my family's best friend Mr. Mustafa Kardesler. His friendship and support made me cross the Atlantic ocean.

TABLE OF CONTENTS

	<u>page</u>
ACKNOWLEDGEMENTS	v
LIST OF TABLES	vi
LIST OF FIGURES	vii
ABSTRACT	viii
1. INTRODUCTION	2
1.1. General Statement of the Research Interest	2
1.2. Objectives	8
2. PREVIOUS INVESTIGATIONS	9
3. PHYSICAL SETTING OF THE STUDY AREA	19
4. METHODOLOGY AND DATA ANALYSIS	21
4.1. Laboratory Techniques	21
4.2. Factor Analysis	29
4.2.1. Q-mode Factor Analysis	30
4.2.2. Computer Programs	38
5. RESULTS AND DISCUSSION	42
6. SUMMARY AND CONCLUSIONS	56
7. REFERENCES	59
8. APPENDIX A : An ID key for isotropic minerals	67
9. APPENDIX B : An ID key for colorless anisotropic minerals	68
10. APPENDIX C : An ID key for colored nonpleochroic anisotropic minerals	69
11. APPENDIX D : An ID key for pleochroic minerals	70
12. APPENDIX E : Locations and compositions of samples	71
13. APPENDIX F : The oblique composition loadings matrix [D]	77
14. VITA	83

ACKNOWLEDGEMENTS

This study was carried out as a part of the research project of the Department of Geological and Benthic Oceanography, Virginia Institute of Marine Science, College of William and Mary. Primarily, I would like to thank Dr. Carl R. Berquist, Jr., a co-principal investigator of the project, and the most helpful person; also my committee chairman, Assistant Prof. Carl H. Hobbs, III, for allowing me to work on this project and for guidance throughout my research. They were always there, friendly and enthusiastic about my study.

My sincere appreciations are extended to Prof. John D. Boon, III, for his assistance in the understanding and use of factor analysis, and constructive criticisms. I thank my other committee members, Prof. Maynard M. Nichols and Assoc. Prof. Eugene M. Burreson for their reviews of my manuscripts, ideas and helpful discussions. Special thanks are also extended to Prof. L. Donelson Wright as the department head, for his encouragement and leadership.

Many thanks to my dear friends Mr. Lauro J. Calliari, Mrs. Cindy T. Fischler and Mrs. Sara M. Dydak, with whom I enjoyed working. The laboratory analysis would not have been completed in a relatively short period of time without their help and company.

I thank my loving family very much for their support and encouragement on the each step of my study. Even though they are 13,000 km away, I wouldn't have been able to get it done without them.

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1.	Some physical, optical and chemical properties of identified heavy minerals	26
2.	Approximate relative chemical stability and general derivations of some common heavy minerals	41
3.	Communalities and factor loadings of extreme normalized samples	46
4.	Compositions of end-members obtained from the 3-factor solution	49

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
1. Location of the study area on the Atlantic coast of southern Delmarva Peninsula	4
2. Index map of the southern Delmarva Peninsula	6
3. Inferred paleochannels across Delmarva Peninsula and the continental shelf by lithologic and spatial relations ...	12
4. Off-shore distribution of surficial heavy minerals by weight percent	14
5. The three paleochannel systems across Delmarva Peninsula	17
6. Locations of 116 grab and 13 vibracore samples	24
7. Typical heavy mineral grains as seen under the microscope ...	27
8. An example for the summary of rotational solutions of Q-mode factor analysis	36
9. Compositions of the factors obtained from Q-mode factor analysis of 129 surficial, off-shore heavy mineral samples ..	47
10. Contour map of sample composition loadings on Factor 1	50
11. Contour map of sample composition loadings on Factor 2	52
12. Contour map of sample composition loadings on Factor 3	54

ABSTRACT

Based on analysis of the 3-4 phi size (very fine sand) fraction of 129 surficial heavy mineral samples, three different local source areas of heavy minerals were identified using Q-mode factor analysis along the inner continental shelf of Virginia. This area has a high potential for heavy-mineral resources, and it is located within 15 km off-shore of the Atlantic side of the southern Delmarva Peninsula.

The heavy-mineral analyses were concerned only with the movable, non-cohesive, upper layer of benthic sediment (0-20 cm). Q-Mode factor analysis was performed on the heavy-mineral data matrix which consisted of 129 samples (observations) and 7 minerals (variables). A 3-factor solution accounted for 98.0 percent of the variance in the entire set of data and provided a geologically suitable model.

The first factor (consisting of amphibole, pyroxene, and epidote) indicated Chesapeake Bay as a possible source for amphibole and pyroxene, because concentrations of these minerals decreased from inside the bay-mouth to off-shore. The second factor (consisting of zircon, garnet, and amphibole) showed that the southern part of the bay mouth and approximately 4 km south east off Wachapreague inlet are potential sources for zircon and garnet due to higher concentrations of these heavy minerals. The third factor (consisting of garnet, amphibole, and zircon) indicated a bayward influx of sediments from the adjacent shelf, and also the eastern shore of Delmarva Peninsula as a source for garnet, amphibole and zircon. This factor may be an indicator for the southerly long-shore drift of the sediments by current and wave action.

Although 2,4 and 5-factor solutions also were applied to explain the regional variability and local source areas of heavy-minerals, a 3-factor solution was selected, because better mathematical results were obtained from this solution to explain geologically meaningful distribution patterns. The 4-factor solution of the same data set caused redundancy of the end-member samples of the 3-factor solution.

**DISTRIBUTION ANALYSIS OF HEAVY MINERALS
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1. INTRODUCTION

1.1. General Statement of the Research Interest

The sources of modern sediments of the sea bed and indications of net transport within the dispersal system can be distinguished by the distribution of heavy minerals (Barrie, 1980). Heavy minerals are volumetrically minor components of terrigenous rocks. They are studied as a guide to source rock lithologies, dispersal patterns, erosional weathering, and tectonic history of the source area. Heavy minerals are characterized as having a specific gravity greater than 2.85 (specific gravity : weight of the mineral in air / weight of an equal volume of water at 4 degrees Celcius) (Lindholm, 1987). Some of them (e.g., zircon, rutile, and tourmaline) are most stable and durable species and are able to survive several cycles of sedimentary processes (Hubert, 1971). In fluvial sedimentary sequences, their associations can provide significant clues to paleogeography. Different size and density of heavy minerals may cause segregation during transport and deposition. For example, hornblende is a major component in near-shore sediments but a minor one in outer delta sediments. This is caused by selective sorting because hornblende is considerably coarser than the other minerals (e.g. epidote and pyroxene) in near shore sediments (Lindholm, 1987).

Previous sedimentological and geophysical survey results indicate that the Atlantic shelf of the southern Delmarva peninsula (Figures 1 and 2) has a high potential for heavy minerals (Berquist and Hobbs, 1985). Therefore in this research, the main goal was to answer

the following questions: where do the various heavy minerals come from, and how are they dispersed through the area of interest? Answers to these questions may be found following the rationale: As heavy minerals arrive into a basin from various sources, they are mixed into new proportions. If this is an ancient system and we are relying on core samples, and our objective is to find the source of these heavy minerals, we would not know how many sources (end-members) there are. An advanced mathematical method, Q-mode factor analysis has the potential of finding these end-members which represent compositional extremes of these heavy mineral samples. In this method, each sample of a set of data is analyzed in terms of the proportions of all end-members that contribute to its composition (Berquist, 1986). The results of Q-mode factor analysis procedure indicates how much of each end-member (factor) is present in each sample. Once a suitable number of factors has been determined, composition gradients for each end-member can be established by contouring the percentage of the factor in each sample (Hobbs and others, 1986). The resulting distribution patterns suggest sediment transport directions.

Since worldwide land reserves of heavy minerals will be almost totally consumed in about 20 years (Grosz and others, 1986) because of the increased need for economically important elements (such as titanium), establishment of these distribution patterns and provenances may provide important information especially for mining interests.

Figure 1 Location of the study area on the Atlantic coast of southern Delmarva Peninsula.

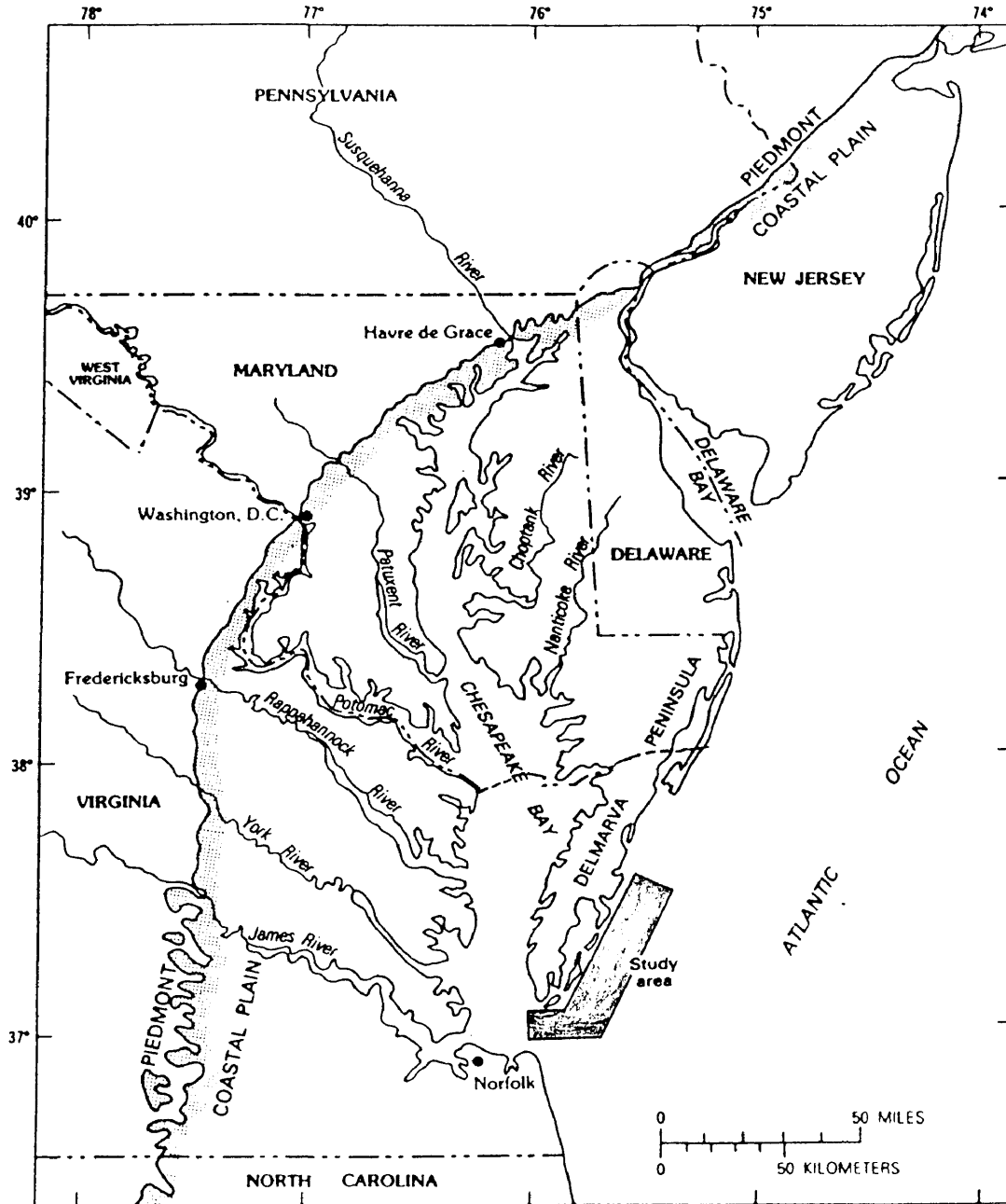
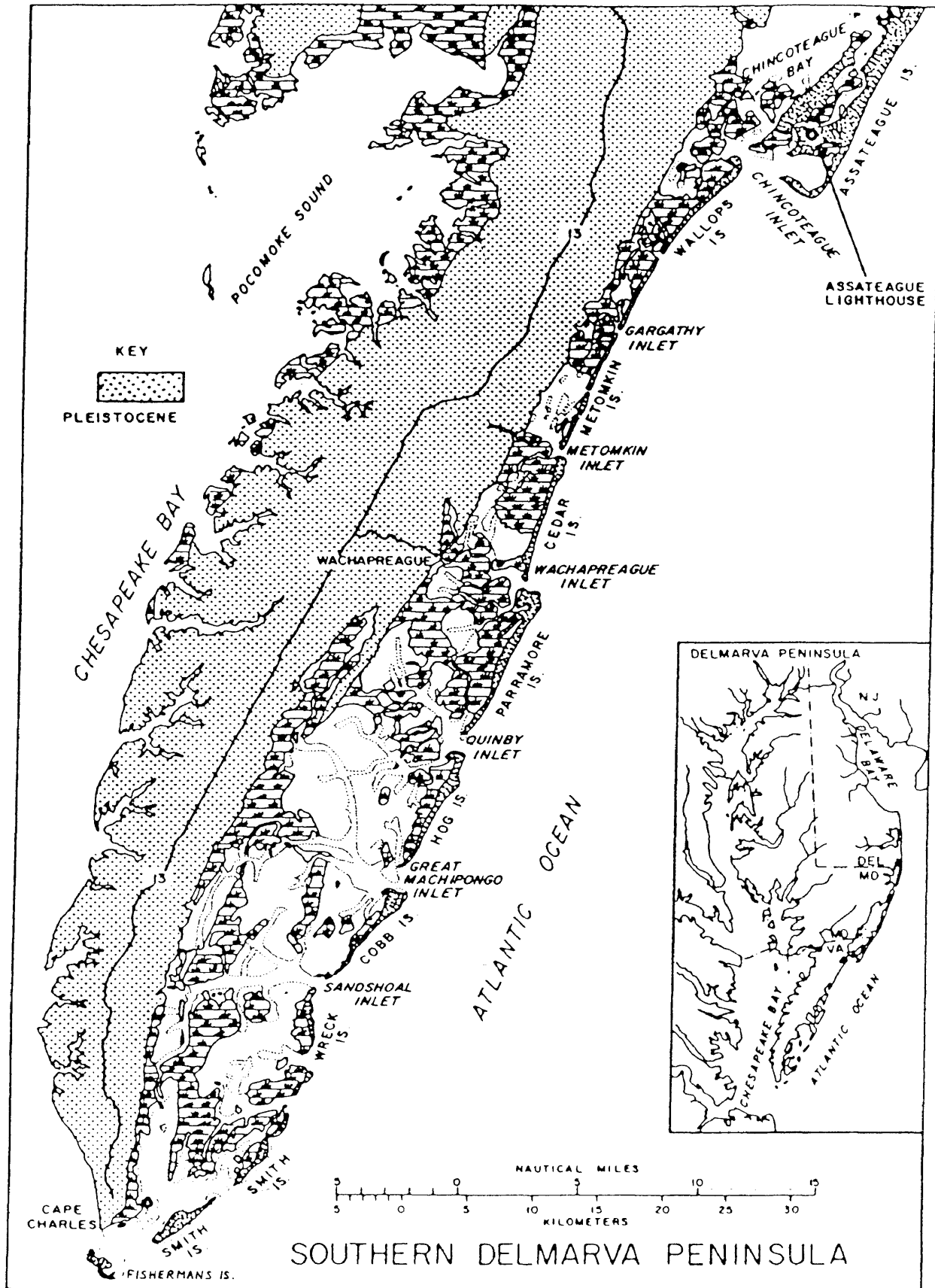


Figure 2 Index map of the southern Delmarva Peninsula. Inset map shows Delmarva Peninsula between Delaware and Chesapeake Bay estuaries (from Harrison, 1972).



1.2. Objectives

Potentially economic concentrations of placer heavy minerals have been reported in the inner continental shelf deposits of southern Delmarva Peninsula by Grosz and Escowitz (1983) and Berquist and Hobbs (1985). Therefore the objectives of this study are; (1) to determine the regional variations of heavy minerals in post-Wisconsinan sands of the inner shelf of the southern Delmarva Peninsula (Figure 2), (2) to establish the locations and influences of the multiple local sources (if there are any) of heavy minerals, and (3) to review sediment transport pathways by examining distribution patterns of heavy minerals along the area of interest.

The establishment of heavy mineral distribution patterns can provide significant information about the sediment sources and dispersal paths.

2. PREVIOUS INVESTIGATIONS

There are several studies about the inner continental shelf sediments of Virginia, but not many about the heavy minerals and their distribution patterns.

Swift and others (1971) studied the heavy minerals in an area within 8 km off-shore between Cape Hatteras and Cape Henry. Their results indicated three well-defined heavy mineral provinces, which were an amphibole-garnet-kyanite suite on the beach, an amphibole-epidote-kyanite suite in the nearshore zone, and another amphibole-garnet-kyanite suite offshore.

Harrison (1972) described the textures, biota and depositional structures of the tidal flat complexes of the Atlantic coast of Maryland and Virginia. According to his conclusions, major storms cut new inlets through the barrier islands, push the eroded sandy sediment into the bays and build new channel-levee systems, therefore causing sediment reworking and new transport pathways (Harrison, 1972; Rice and Leatherman, 1983). He also studied stratigraphic records as well as gravels associated with recent sediments and gave a chart presenting inferred paleochannels across Delmarva Peninsula and the continental shelf (Figure 3). His study provides important implications regarding late-Pleistocene sediment transport pathways and topography.

Kraft (1971) studied the post-Wisconsinan sediments (less than 10,000 years B.P.) in coastal Delaware. He showed that the sediments are infilling a drowned Pleistocene topography and a large portion of the post-Wisconsinan sediments are being eroded by the modern transgression of the Atlantic Ocean.

One of the most comprehensive investigations about the character and distribution of surficial sediments of the Atlantic continental shelf and slope between northern Maine and southern Florida has been made by Milliman and others (1972). Based on more than 6,000 bottom samples, they defined the texture, composition, types, and sources of the surficial sediments and provided information about the broad distribution of heavy minerals.

In their study of the late Quaternary stratigraphy of the Inner Virginia Continental Shelf, Shideler and others (1972) presented the Quaternary structure and stratigraphy of the inner continental shelf from southeast of Cape Henry, Virginia to the North Carolina border. They proposed that the storm related currents are sufficiently effective to mobilize surficial sea-floor sediment. Their data were based on continuous seismic reflection survey records and radiocarbon ages of vibracore samples.

Nichols (1972) and Thompson and Nichols (1973) provided information about the lithology and composition of bottom sediments of the inner continental shelf of Virginia, and they reported that these sediments have an average mean grain size of fine sand, and they are well sorted. High concentrations of heavy minerals were reported by Goodwin and Thomas (1973) around this region (Figure 4). Their aim was to investigate the compositions of shelf sands. They hypothesized two major high concentration areas for heavy minerals: (1) Chesapeake Bay and its tributaries and (2) the sediments swept down along the coast from the Delaware Bay estuary.

The regional variations of heavy minerals in bottom sediments of the lower Chesapeake Bay estuary and the bay mouth sediment transport

processes have been examined by Firek and others, (1977) and Berquist (1986). Firek and others (1977) showed the possible provenances of heavy minerals by their distribution patterns within the complex mineral assemblage and defined the sediment transport pathways based on compositional variations of heavy minerals. Using their data and 38 additional heavy-mineral samples from adjacent shelf deposits, Calliari and others (in press) extended the interpretation of heavy mineral distributions in surficial sediments. According to the results of their Q-mode factor analysis of heavy-mineral data, there are three different high-concentration areas and distribution patterns of benthic sediments. The first one shows a source inside the bay, the second indicates two sources, one inside the bay and the other south of the bay's mouth, and the third shows a source from the north, along the eastern shore of southern Delmarva Peninsula.

The Quaternary stratigraphic evolution of the southern Delmarva coastal zone was investigated in detail by Shideler and others (1984). Their study was based on high-resolution seismic reflection surveys and shallow core samples. They reported that the southern Delmarva Peninsula consists mainly of unconsolidated, clastic, marly deposits gently dipping and thickening eastward.

Grosz and others (1986) reported that a high potential for titanium-rich minerals exists around the central and southern Atlantic shelf regions. In their study, data were obtained from grab samples and approximately 1,300 vibracores as well as 17,000 km of high-resolution seismic reflection profiles.

Figure 3 Inferred paleochannels across Delmarva Peninsula and the continental shelf by lithologic and spatial relations. Figure shows that the Potomac River (dots) extended from the mouth of the present river to Washington Canyon, during the Illinoian glacial age (the second glacial stage of the Pleistocene epoch in North America). During the Wisconsinan ice age (the last glacial stage of the Pleistocene epoch), the Susquehanna River (dashes) probably connected to Norfolk Canyon (from Harrison, 1972, p. 98).

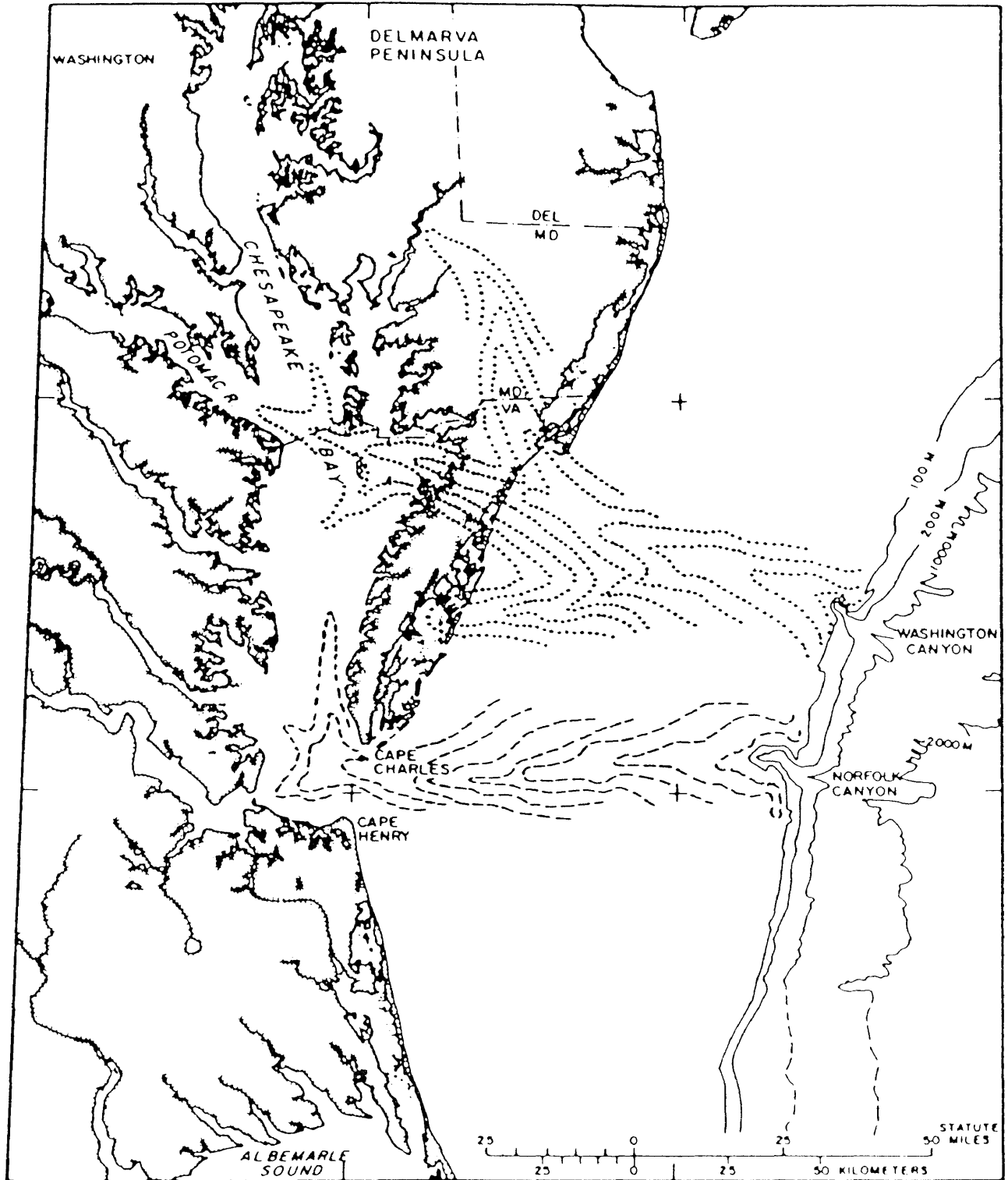
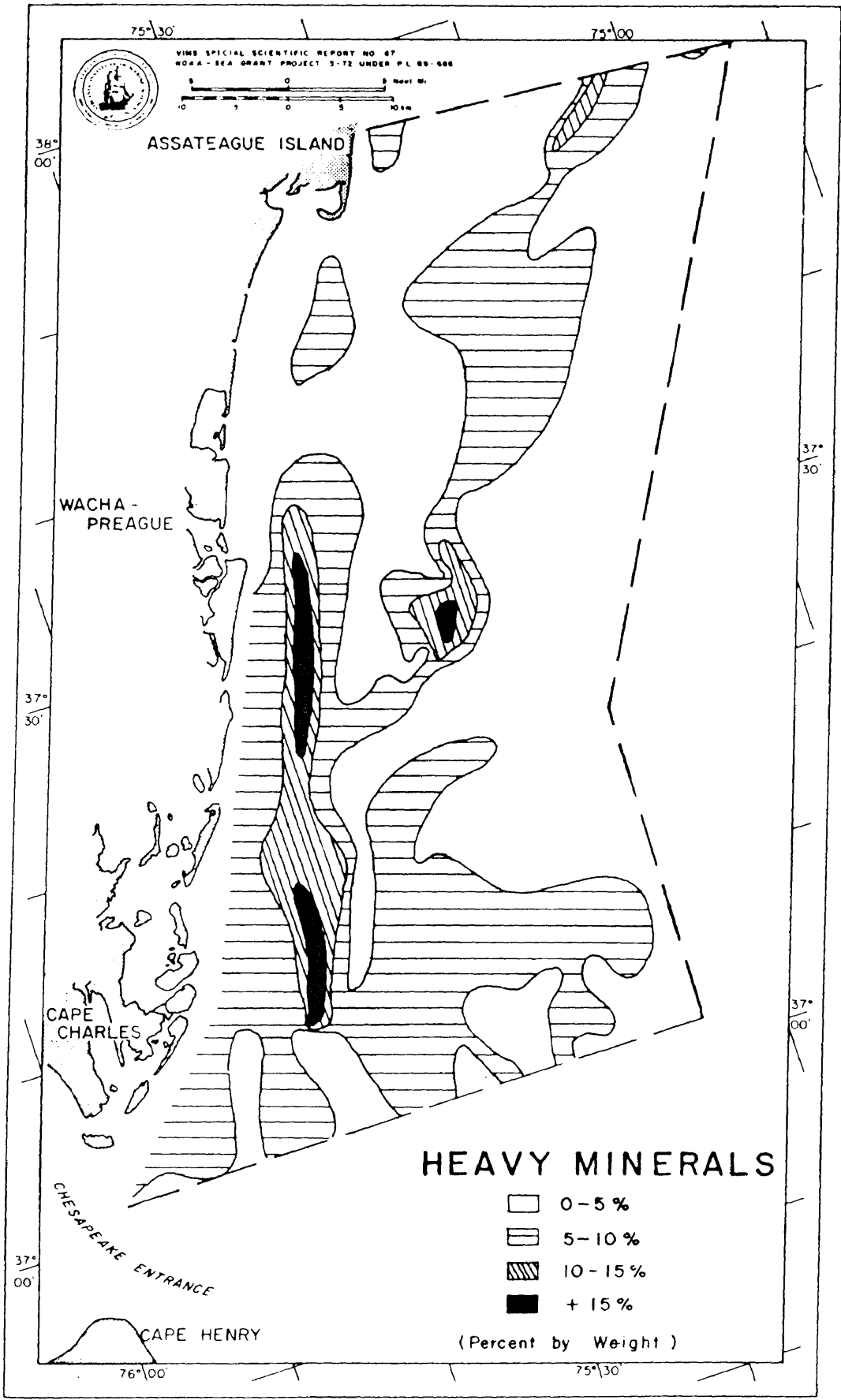
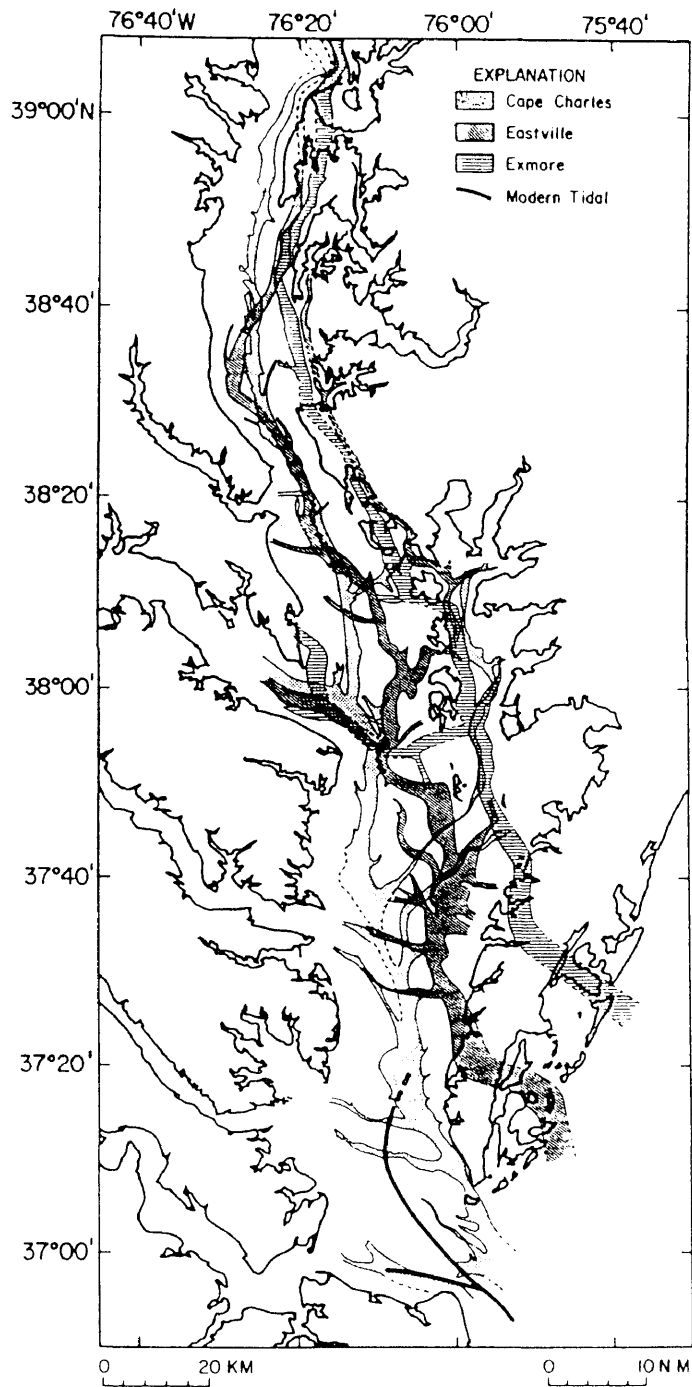


Figure 4 Off-shore distribution of surficial heavy minerals along the southern Delmarva Peninsula by weight percent (from Goodwin and Thomas, 1973, p. 27).



One of the most detailed studies on the structure, composition and origin of the Chesapeake bay-mouth shoal deposits has been made by Colman and others (1988). Based on several previous investigations (Colman and Hobbs, 1987) and new shallow seismic reflection records, they concluded that the bay-mouth shoal complex and related sediments are composed of uniform, gray, fine sand and that sand was brought to the bay-mouth by southerly longshore drift along the Delmarva Peninsula. These deposits are being transported into the bay by bayward estuarine circulation (Hobbs and others, 1986; Ludwick, 1974; Boon and Frisch, 1983). Recently, Berquist and Hobbs (1988-b) presented a detailed report containing sample locations and heavy mineral concentration techniques that I used in my research. Their study includes the analysis of 390 core and surface grab samples as well as interpretations of shallow seismic profiles and side-scan sonar records. Their conclusions indicate that sediments along the inner continental shelf of the southern Delmarva Peninsula and Chesapeake Bay-mouth, have high concentrations of ilmenite and zircon and lesser amounts of monazite and rutile. Colman and others (in press) studied ancient channels of the Susquehanna River beneath the Chesapeake Bay and the Delmarva Peninsula. They proposed three paleo-channel systems which were formed during the glacial low sea level stands and they are about 2 - 4 km wide and 30 - 50 m deep (Figure 5). These channels trend southeast, crossing beneath the Delmarva Peninsula and were formed at progressively younger ages toward the south. This work provides a new, alternate interpretation to the paleochannel system proposed by Harrison (1972) (Figure 3).

Figure 5 The three paleochannel systems across Delmarva Peninsula proposed by Colman and others (in press). The youngest (Cape Charles) is about 18 ka, the intermediate one (Eastville) is about 150 ka, and the oldest (Exmore) is in the range of 200 to 400 ka (ka : kilo annum).



3. PHYSICAL SETTING OF THE STUDY AREA

The study area is located along the Middle Atlantic Bight, in the vicinity of the Eastern Shore of Virginia, between latitudes 37 deg. 00 min. N and 37 deg. 49 min. N, longitudes 75 deg. 30 min. W and 76 deg. 10 min. W. It is about 50 km long and extends up to 15 km off-shore from Delmarva Peninsula (Figures 1 and 2). Along the Atlantic coast of the southern Delmarva Peninsula tides are semi-diurnal and the mean tide range is about one meter (Harrison, 1972).

Surficial sediments consist basically (1) grey-colored, rounded, well-sorted fine sand and (2) poorly-sorted, rich in shell, medium to coarse sand (Nichols, 1972). The coastal plain strata dip gently eastward and unconformably overlay Precambrian to Triassic aged crystalline rocks (Shideler and others, 1984).

The stratigraphic records indicate that after the Wisconsin glaciation (80,000 - 10,000 yrs. B.P.), sea level started rising and formed a transgressive sedimentary sequence across the Atlantic continental shelf of the U.S. (Kennett, 1982; Finkelstein, 1986). About 8,000 years ago, sea level rise continued at a rate of about 30 cm per century. From about 3,000 yrs. B.P., it rose at about 15 cm per century (Kraft, 1971). Rice and Leatherman (1983) analyzed historical shoreline records for twelve barrier islands along the Eastern Shore of Virginia. As they indicated, mean retreat (erosion rate) of Smith Island ranges between 4 and 15 m per year.

The stratigraphic records off-shore Assateague Island were examined by Field (1980) who found that the bottom sediments are highly bioturbated, reworked and that they presumably are derived from the

eroding barrier islands. This island chain is a transgressive system formed during the Holocene rise in sea level (Rice and Leatherman, 1983). Shideler and others (1984) suggested that the barrier islands along the eastern shore of Virginia have a minimum age of 3,800 yr and they probably began developing at least 5,500 yr ago. The circulation of shelf water off Virginia's coast causes a significant bottom drift of shelf sediments. Although there are areal and seasonal variations, in general, this bottom drift tends to move southwesterly and causes large amounts of surficial sediments to move. The effect of the bottom drift increases with distance from shore and gets greater when the water column is not thermally stratified (Harrison and others, 1967). This southerly longshore drift system along the Atlantic shore of the Delmarva Peninsula drives substantial amounts of sandy sediment (averaging 15 m in thickness in the lower most portion of the bay) into the Chesapeake Bay through its mouth (Hobbs and others, 1986; Colman and Hobbs, 1987; Colman and others, 1988) and into the adjacent lagoonal complex of the barrier island system of southern Delmarva Peninsula by overwash processes (Shideler and others, 1984).

Mixon (1985) reported on the geology of the mainland adjacent to the study area. He found the unconsolidated, Quaternary sand, gravel, silt, clay and peat deposits (2-60 m thick) unconformably overlay an approximately 100 m thick, more consolidated, upper Tertiary glauconitic sand (potassium and iron rich) and clay-silt deposits in the surface and subsurface sediments of the southern Delmarva Peninsula.

4. METHODOLOGY AND DATA ANALYSIS

4.1. Laboratory Techniques

In this study, the heavy-mineral analyses are concerned only with the mobile, non-cohesive, upper layer of benthic sediment (about 0-20 cm). Sixty-four samples originally were selected for analysis (Figure 6). They were a combination of 13 core and 51 grab samples. As will be discussed later, this set of 64 sample was augmented by additional samples to yield a final suits of 129 samples. Only the top portion (0-20 cm) of the core samples were analyzed. All samples were collected during 1986-87 cruises by the Virginia Institute of Marine Science (Berquist and Hobbs, 1988-a).

These samples were part of the project funded by the Subaqueous Minerals and Materials Study Commission, Commonwealth of Virginia. In the present study, data gathering started with the selection of previously collected, concentrated, and archived heavy-mineral samples. Detailed information about sample preparation, concentration, heavy liquid and magnetic separation of these selected heavy mineral samples can be found in Berquist and Hobbs (1988-b).

As an average, 0.75 grams of each archived heavy-mineral sample was sieved to obtain the 3-4 phi (0.125-0.063 mm) size fraction. The reason for choosing the 3-4 phi (very fine sand) size fraction was to eliminate variations in concentrations due to selective sorting of minerals. The more equant minerals (e.g., epidote) and heavier minerals (e.g., opaques, zircon, garnet) have a higher probability of being selected for permanent deposition during the sedimentary processes

(Flores and Shideler, 1977) and also tend to be sheltered behind the larger grains (Peterson and others, 1988).

Very small amounts of recovered heavy-mineral samples (about 0.2 g) were mounted on glass slides by using Caedax medium as a glue (R.I.= 1.56). Each glass slide was heated on the hot plate in order to melt the Caedax medium to cover the slide. After pouring the sample on the slide, a cover glass was put on the sample for extra protection and stability. The slides were point-counted under the petrographic microscope to estimate the abundances of 17 transparent minerals as well as opaques. More than 200 transparent grains (average 210) were identified along the random line traverses on each slide. Some typical grains are shown in Figure 6 and some physical, optical and chemical properties of the identified heavy minerals are given in Tables 1 and 2.

The optical analysis under the petrographic microscope started with the determinations of major optical characteristics of the unknown transparent grains, whether an unknown grain was **isotropic** (the mineral is isotropic if it remains dark at all positions of the stage of the petrographic microscope when nicols are closed) or **anisotropic** (the mineral is anisotropic if it is alternately light and dark during one revolution of the stage when nicols are closed). If the grain was anisotropic, then the second step was to determine whether it is **colorless** or **colored** and **pleochroic** (pleochroism is the ability of an anisotropic crystal to differentially absorb various wavelengths of transmitted light in various crystallographic directions and thus to show different colors in different directions (Bates and Jackson, 1984)) or **nonpleochroic**. One of the most helpful properties to identify an anisotropic mineral is its extinction angle. The extinction is the

darkness obtained from an anisotropic mineral at two positions during a complete rotation of mineral under the petrographic microscope and crossed nichols. This characteristic for the identified heavy minerals is given on Table 1. Finally, an unknown grain could be found by comparing its characteristics with those listed under the detailed identification keys (Lindholm, 1987) (Appendices A, B, C, and D).

Figure 6 Locations of 116 grab and 13 vibracore samples
(C : core sample).

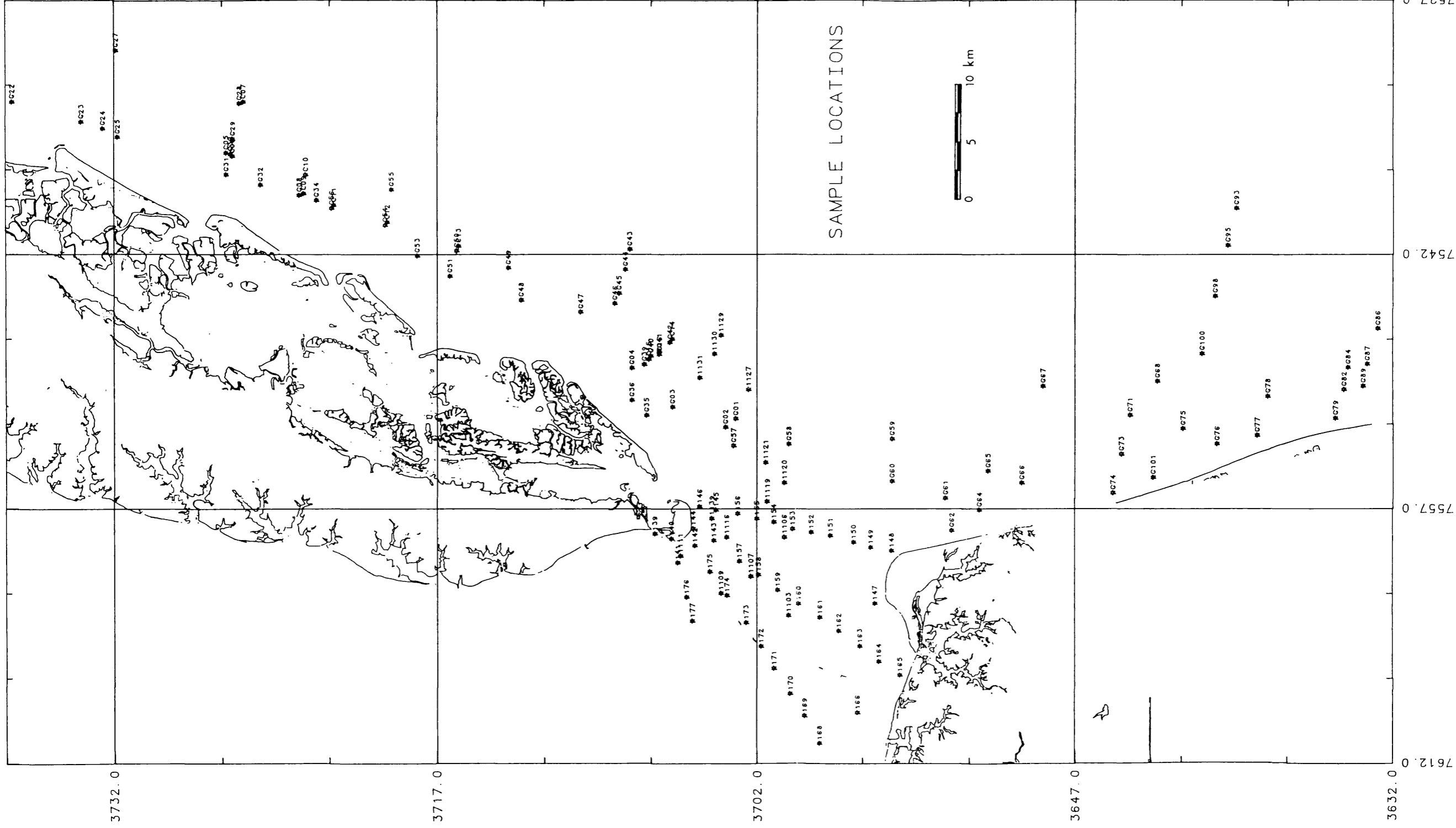


TABLE - 1

Some physical, optical and chemical properties of identified heavy-minerals (Tickell, 1965).

MINERAL	HARDNESS	SPEC. GRAVITY	EXT. ANGLE	CHEMICAL COMP.
ZIRCON	7.5	3.9-4.8	Parallel	ZrSiO ₄
SPHENE	5.0-5.5	3.45	N. A.	CaTiSiO ₅
HORNBLLENDE	5.0-6.0	3.0-3.4	15 - 25	Complex Silicate
EPIDOTE	6.0-7.0	3.3-3.5	N. A.	Complex Silicate
STAUROLITE	7.0-7.5	3.73	Parallel	Complex Silicate
HYPERSTENE	5.0-6.0	3.3-3.5	Parallel	(Mg,Fe)SiO ₃
GARNET	7.0	3.8	N. A.	Complex Silicate
APATITE	5.0	3.2	Parallel	Comp. Ca ₄ (PO ₄) ₃
KYANITE	4.0-7.0	3.67	30	Al ₂ SiO ₅
TOURMALINE	7.0-7.5	3.0-3.25	Parallel	Comp. Borosilicate
RUTILE	6.0-6.5	4.18-4.25	Parallel	TiO ₂
MONAZITE	5.0	4.8-5.5	N. A.	(Ce,La,Di,Th)PO ₄
PYRITE	6.0-6.5	5.0	N. A.	FeS ₂
MAGNETITE	5.5-6.5	5.2	N. A.	Fe ₂ O ₄

Figure 7 Typical heavy mineral grains as seen under the petrographic microscope (from Lindholm, 1987, p. 217).



Key

- A apatite
- Am amphibole
- An andalusite
- B brookite
- E epidote
- G garnet
- K kyanite
- M monazite
- P pyroxene
- R rutile
- Si sillimanite
- St staurolite
- Sp sphene
- Spi spinel
- T tourmaline
- Z zircon
- Zo zoisite

4.2. Factor Analysis

Factor analysis is an advanced mathematical procedure used to simplify and to explain the relationships among large quantities of multivariate data. The goal of this procedure is to define a lesser number of new but more meaningful variables which are composed of linear combinations of the original variables (Rummel, 1967). An early geological application of factor analysis involved the classification of carbonate sediments (Imbrie and Purdy, 1962).

Factor analysis has two major classes which are called R-mode and Q-mode techniques. Imbrie and Van Andel (1964) used Q-mode factor analysis techniques to identify provenances of heavy minerals. In R-mode analysis, the main concern is to find relationships among variables and then compare relationships among variables on the basis of the samples. But in Q-mode factor analysis, the main concern is to inspect relationships among samples on the basis of the variables (percent mineral composition in the present case). Selection of one or the other procedure primarily depends on the aim of the research. In this research, Q-mode factor analysis was chosen because Q-mode analysis finds the most compositionally extreme samples (end-members) in the data set which may represent potential source areas of heavy minerals (as it is explained in the following chapter). The Q-mode factor solution considers the remaining samples as proportional compositions of these end-members (Appendix D).

Although applications of Q-mode factor analysis to geological data are described in Imbrie and Van Andel (1964), Joreskog and others,

(1976), Miesch (1976), and Davis (1986), a brief explanation of Q-mode factor analysis will be presented here.

4.2.1. Q-mode Factor Analysis

In this method, the first step is to put the raw data into a row-normalized matrix format. The original data matrix is defined as $[X]$. It is an "n" by "m" matrix where "n" represents the number of samples (rows) and "m" represents number of variables (columns). In practice the number of samples (n) is usually much greater than the number of variables (m). In the raw data matrix $[X]$, an individual element would be called x_{ij} which is j'th mineral in i'th sample. Therefore a given sample would be represented by a single row in the raw data matrix as " $x_{i1}, x_{i2}, x_{i3}, \dots, x_{im}$ ".

In order to eliminate the effects of size differences among samples, this raw data matrix $[X]$ has to be row-normalized. In matrix notation, row-normalization can be done as follows ;

$$[W] = [D]^{-1/2}[X]$$

where $[W]$ is the row-normalized data matrix, also on the order of n by m, and $[D]$ is an n by n diagonal matrix which contains the sums of the squares of each row along the diagonal and zeros the rest of the matrix (Davis, 1986, p. 563). A diagonal matrix is a square symmetrical matrix

and the off-diagonal elements of which are all zero. In row-normalization, each member in a row of the data matrix is divided by the square root of the sums of squares for that row. Thus, this operation provides that every row vector of [W] is a vector of unit length (Joreskog et al., 1976, p. 90).

After normalization of the data, Q-mode factor analysis begins with the calculation of the compositional similarity between all pairs of samples. The cosine of the angle θ between any two sample vectors is defined as the coefficient of proportional similarity (Imbrie and Van Andel, 1964). So, the coefficients of proportional similarity (cos θ similarity matrix) can be found by the equation

$$[\cos \theta] = [W] [W]' = [Q]$$

where [W]' is the transpose of the row-normalized data matrix [W]. The transpose of a matrix is the original matrix with all the rows and columns interchanged. The above multiplication gives "major product matrix [Q]" (Davis, 1986, p. 519). Values in this [cos θ] matrix give the similarity in proportional composition between all pairs of samples. Any individual element in this matrix can be given by the equation

$$\cos \theta_{ij} = \frac{\sum_{r=1}^m x_{ir} x_{jr}}{\sqrt{\sum_{r=1}^m x_{ir}^2} \sqrt{\sum_{r=1}^m x_{jr}^2}}$$

where "i" and "j" are the row vectors of the data matrix, and $r = 1, 2, \dots, m$ (Davis, 1986, p. 563).

The coefficients in $[\cos \theta]$ have the range of 0 to 1. If the coefficient is zero for two samples, it means they have nothing in common (vectors at 90 degrees). If it is one, they have equal proportions (colinear vectors) (Imbrie and Van Andel, 1964).

After rearranging the matrices, The Eckard-Young theorem shows that the any real matrix $[W]$ can be expressed as the product of three other matrices

$$[W] = [V] [\Lambda] [U]'$$

where $[V]$ is an n by r matrix, whose columns are orthonormal and $[U]'$ is the transpose of an m by r matrix, $[U]$. The columns of matrix $[U]$ are also orthonormal. $[V]$ and $[U]$ contain orthogonal eigenvectors, and $[\Lambda]$ is a r by r square matrix, its diagonal contains the square roots of the associated eigenvalues of $[R]$ and $[Q]$ described below. The major product moment of the row-normalized data matrix is given

$$[Q] = [W] [W]'$$

whereas

$$[R] = [W]'$$

is the minor product moment.

The columns of $[V]$ contain the eigenvectors of $[Q]$, and those of $[U]$ contain the eigenvectors of $[R]$. $[Q]$ and $[R]$ have the same eigenvalues. The number of non-zero eigenvalues in the matrix determines the rank of both $[U]$ and $[V]$. It also determines the maximum number of end-members (factors).

The projections of vectors onto a factor axis are called "loadings" and they range between -1 and +1, because each factor axis has a unit length of one (due to normalization). The Q-mode (principal) factor loadings matrix can be found as

$$[A^Q] = [V] [\Lambda]$$

(Appendix - F). But from the Eckard-Young theorem,

$$[V] [\Lambda] = [W] [U] \quad \text{so that}$$

$$[A^Q] = [W] [U] .$$

$[F^Q]$ is the unrotated Q-mode factor scores matrix and equal to $[U]$, the matrix of eigenvectors from $[R]$. It follows that

$$[A^Q] = [W] [F^Q] \quad \text{and} \quad [W] = [A^Q] [F^Q]^{-1}$$

$[F^Q]$ can be used to locate new objects in the factor space, which are not part of the original data matrix.

As can be found in the factor loadings matrix $[A^Q]$ (which is an n by r matrix), the sum of the squares of elements in any row represents the total information in that sample, explained by the " r " orthogonal factors (r : rank of a matrix). This row sums of squares called the sample communality. If the sample is completely represented by its projection on the r 'th factor axis, the communality for that sample is equal to 1.0.

The unrotated Q-mode factor solution has the effects of all different samples. Rotation of factor axes to a sample or a group of samples may remove the effects of unnecessary (less meaningful) axes and enables us to assign the patterns independent of them (Rummel, 1967). By rotating the axes, we try to place the factors so that each of them contains only a few highly loaded samples (close to +1 or -1), then the factors become combinations of interdependent samples only (Joreskog and others, 1976).

In order to do the necessary rotation, several techniques are available, one of which is called Kaiser's Varimax rotation (Davis, 1986, p. 555). In this method, each factor axis moves to a new position with respect to the variables, so that projections from each variable (sample) onto the factor (end-member) axis become close to the extremes (which are +1 and -1) or to the origin. Positive or negative signs do not have any effect on the solution (Figure 8).

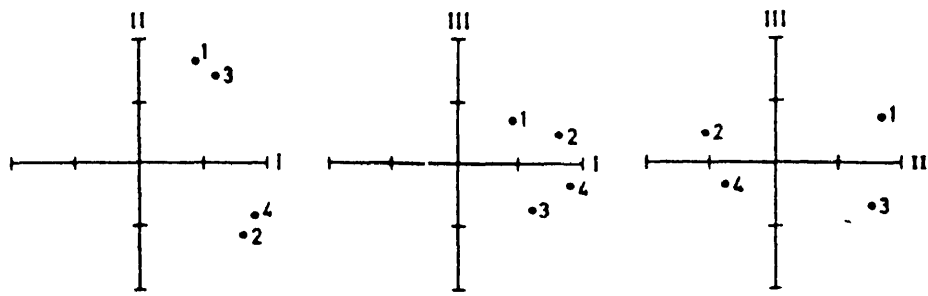
While rotating these orthogonal vector axes to new positions, we still keep their orthogonality but put them in different locations so they can provide better loadings of variables. This system of factors is rotated around the origin until the system is maximally aligned with the separate groups of samples (Figure 8). Thus, the aim of factor rotation is to isolate basic groups of samples that are compositionally similar and separate them from other groups of samples that are also similar among themselves but dissimilar compared to other groups. If all the groups of samples are dissimilar, then each orthogonal factor will be aligned with a distinct group of samples.

Although the Varimax rotation provides a good way for the interpretation of data, in the oblique projection method, a better

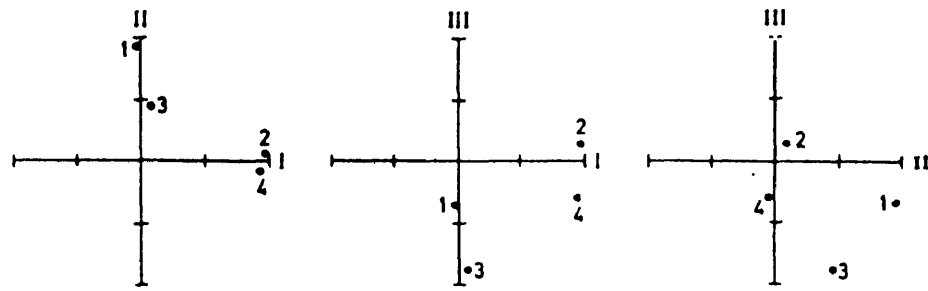
position of reference axes can be obtained by forcing the factors individually, to be collinear with the actual variable vectors (samples) in the factor space (Joreskog and others, 1976, p. 139) (Figure 8). This method allows us to select the most divergent sample vectors as end-members and defines the other vectors (samples) in relation to them.

The composition loadings of the samples on each factor axis can be obtained from the oblique composition loadings matrix [D]. The calculation of this matrix is the last step of Q-mode factor analysis (Appendix F). Each column in matrix [D] is plotted on a map, then the composition gradients can be established by contouring the percentage of the end-member in each sample (Figures 10, 11, 12 and 13).

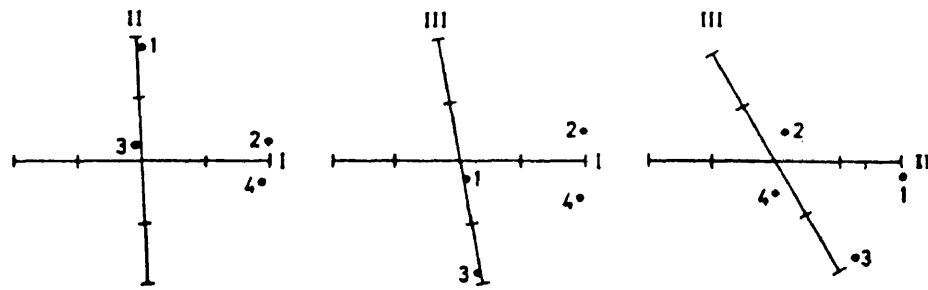
- Figure 8** An example for the summary of rotational solutions of Q-mode factor analysis (Joreskog and others, 1976)
- A. Orthogonal, unrotated principal components axes.
 - B. Orthogonal Varimax axes.
 - C. Oblique axes.
 - D. An example to oblique rotation of two-factor orthogonal Varimax axes.



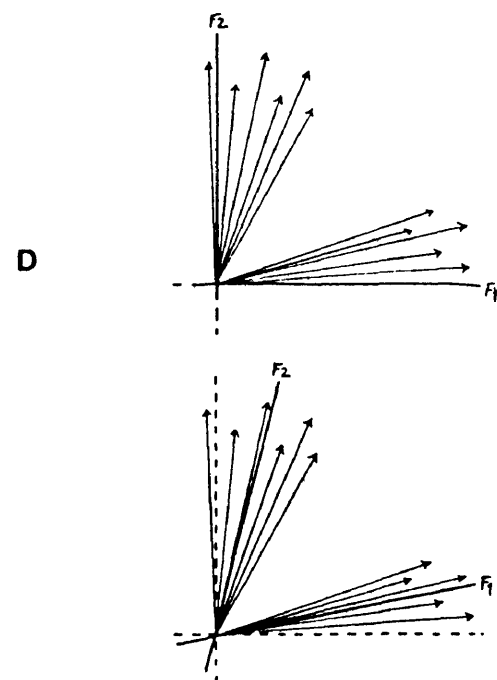
A



B



C



D

4.2.2. Computer Programs

In this research, three advanced computer programs were used to analyse compositional data :

1- Program CABFAC was developed by Klovan and Imbrie (1971). It computes a Cosine-Theta matrix from the raw data matrix and converts a normalized eigenvector to a factor by multiplying every element of the eigenvector by the square root of the related eigenvalue. CABFAC calculates and lists the eigenvalues and their cumulative variance, but the user has to specify number of common factors in the factor model. In general, this program does the following:

- a) Transforms the original data matrix to row-normalized form.
- b) Computes a Cosine-Theta matrix.
- c) Computes normalized principal factor scores matrix.
- d) Computes rotated Varimax factor scores matrix.
- e) Computes Varimax loadings matrix (with communalities).
- f) Computes composition loadings and composition scores matrices (Klovan and Miesch, 1976).

2- Program QMODEL was written by Klovan and Miesch (1976) to extend the capability of the CABFAC program. QMODEL takes the output from CABFAC and providing a composition loadings matrix, factor scores matrix, estimated row data matrix (by multiplying the previous two matrices), and goodness of fit statistics (Klovan and Miesch, 1976).

3- EXQMODEL program (extended Q-model) was revised from the QMODEL program by Full and others (1981), to eliminate negative compositions because better solutions for geological mixing problems require positive compositions of samples and factors (Berquist, 1986, p. 39). Extended Q-model program defines the compositionally most extreme samples which are considered end-members (Full and others, 1981).

In this study, I used the above Q-mode factor analysis programs. Consequently, I chose the oblique solution (yielding real samples as the extreme end-members) by using option-3 on program QMODEL and EXQMODEL, to determine heavy mineral composition gradients for each end-member (factor) in my data. In the above programs, by choosing the option-3, I identified and used the samples of extreme normalized composition as reference axes. Thus, the factor axes of my Q-mode factor solution were not orthogonal but oblique.

The first data set to be analyzed consisted of 8 abundant minerals (zircon, epidote, amphibole, pyroxene, garnet, tourmaline, apatite, and kyanite) counted in 64 samples. These original data were used in 2, 3, 4 and 5-factor solution models. The 3-factor solution provided better mathematical results compared to the 2-factor solution. Using additional factors caused redundancy of the end-member samples of the 3-factor solution. Although mathematical results were satisfactory, the end-member sample locations of 3-factor solution were close to each other and the distribution patterns were geologically meaningless. This was most probably due to homogeneous character of the study area and the lack of variability in the data.

Therefore, I decided to supplement my data with the comparable data of Calliari and others (in press). Their study area was adjacent to mine and they followed the same procedures in order to find the distribution patterns of heavy minerals.

The data in their report had been collected from inside the bay, the northern and southern parts of the bay entrance, and the inner shelf. Their data were also obtained from surficial samples. Thus, the final raw-data matrix, with 64 original and 65 supplemental heavy-mineral samples, had 129 samples (Figure 6 and Appendix E). In order to make comparison with previous studies such as Berquist (1986), Calliari and others (in press) and to follow similar data analyses procedures, I reduced the number of variables in my last data set from 8 to 7 (zircon, sphene, amphibole, epidote, staurolite, pyroxene, garnet). In his research, Berquist (1986) used these 7 minerals because they had accounted for 96 percent of the total composition variance among his samples, and they were chosen by Principal Component Analysis (Firek and others, 1977; Berquist, 1986; Davis, 1986, p. 527).

The abundances of individual minerals in each sample were calculated as the grain percentage. For example, in sample C6 the sum of transparent heavy minerals was 238 and the total number of zircon grains was 29. Since the 238 grains represent 100 percent of the total transparent grains in sample C6, the percentage of zircon in the sample was simply calculated as 12.18 percent. Finally, based on the abundances of the 7 transparent heavy minerals and 129 samples (116 grab, 13 core) the raw data matrix was ready to apply Q-mode factor analysis. Appendix E gives the raw data matrix obtained from laboratory studies.

TABLE - 2

Approximate relative chemical stability and general derivations (ultimate source) of some common heavy minerals (Hubert, 1971 and Tickell, 1965).

STABILITY	MINERAL	DERIVATION (Parent Rock)
Ultrastable	Rutile	Igneous and metamorphic rocks.
Ultrastable	Zircon	Igneous and metamorphic rocks.
Ultrastable	Tourmaline	Acidic plutonics and metamorphics.
Stable	Leucosene	Decomposition product of ilmenite.
Stable	Muscovite	Igneous and metamorphic rocks.
Stable	Chlorite	Metamorphic rocks.
Stable	Hematite	Igneous and metamorphic rocks.
Semistable	Apatite	Acidic igneous rocks.
Semistable	Monazite	Acidic igneous rocks. Granites.
Semistable	Staurolite	Metamorphic rocks.
Semistable	Sillimanite	Metamorphic rocks.
Semistable	Kyanite	Metamorphics, schists and gneisses
Semistable	Epidote	Metamorphics, altered limestones.
Unstable	Biotite	Igneous and metamorphic rocks.
Unstable	Garnet	Metamorphic rocks.
Unstable	Magnetite	Igneous and metamorphic rocks.
Unstable	Ilmenite	Igneous rocks.
Unstable	Hornblende	Igneous and metamorphic rocks.
Unstable	Augite	Basic igneous rocks.
Unstable	Olivine	Ultra-basic rocks.

5. RESULTS AND DISCUSSION

The appropriate number of factors for the Q-mode analysis of the data set (Appendix E) is determined by examining (1) the amount of cumulative variance in the entire data set (from CABFAC program), (2) the estimate of raw data matrix (from QMODEL program) and (3) the diagonal elements of the extreme normalized sample loadings matrix (Table 3; from EXQMODEL program) on the computer program outputs after each factor (2, 3, 4 and 5) solution. The diagonal elements of this matrix represent the loading value of each end-member samples on the associated factor axes. As explained earlier, if these values are close to 1.00, meaning a very good explanation of the sample composition is given by the factors retained.

For the compositional heavy mineral data of 129 samples and 7 variables (minerals), the 3-factor solution (1) accounted for 98.0 percent of the total compositional variation of samples. The 3-factor solution (2) provided the most geologically suitable model because there was no redundancy in either composition or location of the end-member samples, in addition to (3) high communalities (average communality was 0.97), as well as (4) high diagonal values on the extreme normalized sample loadings matrix and the (5) high coefficients of determination. These coefficients obtained from goodness of fit statistics (from EXQMODEL program) were considerably higher compared to the other factor solutions. The coefficients of determination explain how well the factor model approximation fits the original data. Higher coefficient values represent better goodness of fit statistics, thus a better mathematical solution. Therefore the 3-factor solution was selected in

order to give the most reasonable explanation of the distribution patterns of the heavy minerals, consistent with the data.

The 2-factor solution was rejected because only 96.3 percent of the compositional information was explained and sample projections (factor loadings) were interdependent (when loadings on one factor increased, loadings on the other factor decreased). This mathematical dependency would interfere with geological explanations of the composition gradients.

Although the 4-factor solution accounted for 99.2 percent of the total compositional variation of the samples, provided higher communalities and relatively similar distribution patterns of heavy minerals, it duplicated two end-member suites of minerals and their locations of the 3-factor solution.

Figure 9 shows the composition scores of factors obtained from the 3-factor solution, and Table 4 gives the numerical values of these compositions. Contoured plots of composition loadings on each factor of the 3-factor solution are given in Figures 10, 11, and 12.

Factor 1 (Figure 10) is composed of amphibole (62 percent), pyroxene (20 percent) and epidote (13 percent). As it shows easterly (off-shore) decreasing concentrations of heavy minerals southwest of Fishermans Island, this could be an indication for the off-shore transport of bay-originated amphibole, pyroxene, and epidote. High concentrations of amphibole and pyroxene northeast of Smith Island are most probably related with the troughs of the sand shoals as Goodwin and Thomas (1973) and Rowland (1988) mentioned. However these shoals may also be potential sources of some heavy minerals such as ilmenite, magnetite, epidote, staurolite, garnet and zircon as Grosz and Escowitz

(1983), Berquist and Hobbs (1985, 1988-a, and 1988-b) and Rowland (1988) have suggested.

Higher off-shore concentrations of mature minerals like zircon might represent a high concentration area for relatively older inner continental shelf sediments, moving under the influence of south-westerly bottom currents (Harrison and others, 1967). This concept agrees with the results of Swift and others (1977) who concluded that older sediments (possibly more mature Pleistocene deposits) are exposed on the inner shelf, commonly in the troughs of the sand ridges, located within 12 km of the Eastern Shore of Virginia (Rowland, 1988).

Factor 2 is composed of zircon (43 percent), garnet (21 percent), and amphibole (19 percent). The concentrations of these minerals decrease seaward (Figure 11). This indicates that the erosion of the Eastern Shore and its tributaries as well as channel-levee systems between barrier islands (especially by the winter storms) may be local sources for zircon and garnet as can be seen off Parramore Island (Morton and Donaldson, 1973; Rice and Leatherman, 1983). Factor 2 also shows higher concentrations in the western part of the central bay mouth area, which suggests Chesapeake Bay as a localized source, contributing zircon, garnet, and amphibole to the shelf.

Factor 3 is very rich in garnet (51 percent), it also includes amphibole (32 percent), and zircon (10 percent). This end-member is located at about 3 km southeast of Fisherman's island. It shows that high concentrations of garnet and amphibole around bay mouth area are decreasing westerly (bayward). This might reflect a bayward influx of adjacent littoral and shelf sediments by coastal erosion as Firek and others (1977) and Berquist (1986) suggested. Factor 3 indicates an high

concentration area (about 5 km north east of Quinby inlet) for the southerly moving minerals along the eastern shore of Virginia (Figure 12). More mature minerals like zircon and garnet might be derived from Delaware Bay estuary, the northern part of Delmarva peninsula and/or the sand-shoal deposits around Quinby Inlet.

During the Pleistocene epoch, continental glaciers advanced and retreated several times. Each time the glaciers advanced, sea level was dropped and the Susquehanna river extended southeast over the former continental shelf (Figure 3). The Exmore paleochannel (about 200 to 400 thousand years old) crosses beneath the Delmarva Peninsula somewhere around the Quinby Inlet and filled with late Pleistocene age estuarine sediments (Colman and Hobbs, 1987; Colman and others, 1988; Colman and others, in press) (Figure 4). The heavy minerals associated with these paleochannels during the Sangamon and Wisconsinan glacial stages of the Pleistocene epoch have been buried by the infilling Wisconsinan sediments. Therefore they might have no relation with the younger (post-Wisconsinan) surficial, inner shelf sediments. This concept indicates that the relict source areas for these surficial heavy minerals may not be the buried paleochannels of the ancient Susquehanna River but the shoreface connected and/or isolated linear sand shoals as Goodwin and Thomas (1973) and Rowland (1988) reported.

As shown on Figure 12, composition gradients of Factor 3 are "spotty" but show a possible tendency to decrease in a southerly direction. Consequently, southward transport of innershelf sediments along the eastern shore of Delmarva peninsula may be suggested. The patterns are slightly different around the bay mouth. Higher concentrations of garnet and amphibole off Fisherman's Island decrease

bayward. Therefore, isopleths of the 3-factor solution show a tendency of sediment movement into the bay around Fisherman's island. This pattern matches with the conclusions in the studies of Firek and others (1977), Boon and Frisch (1983), Berquist (1986) and Colman and others (1988).

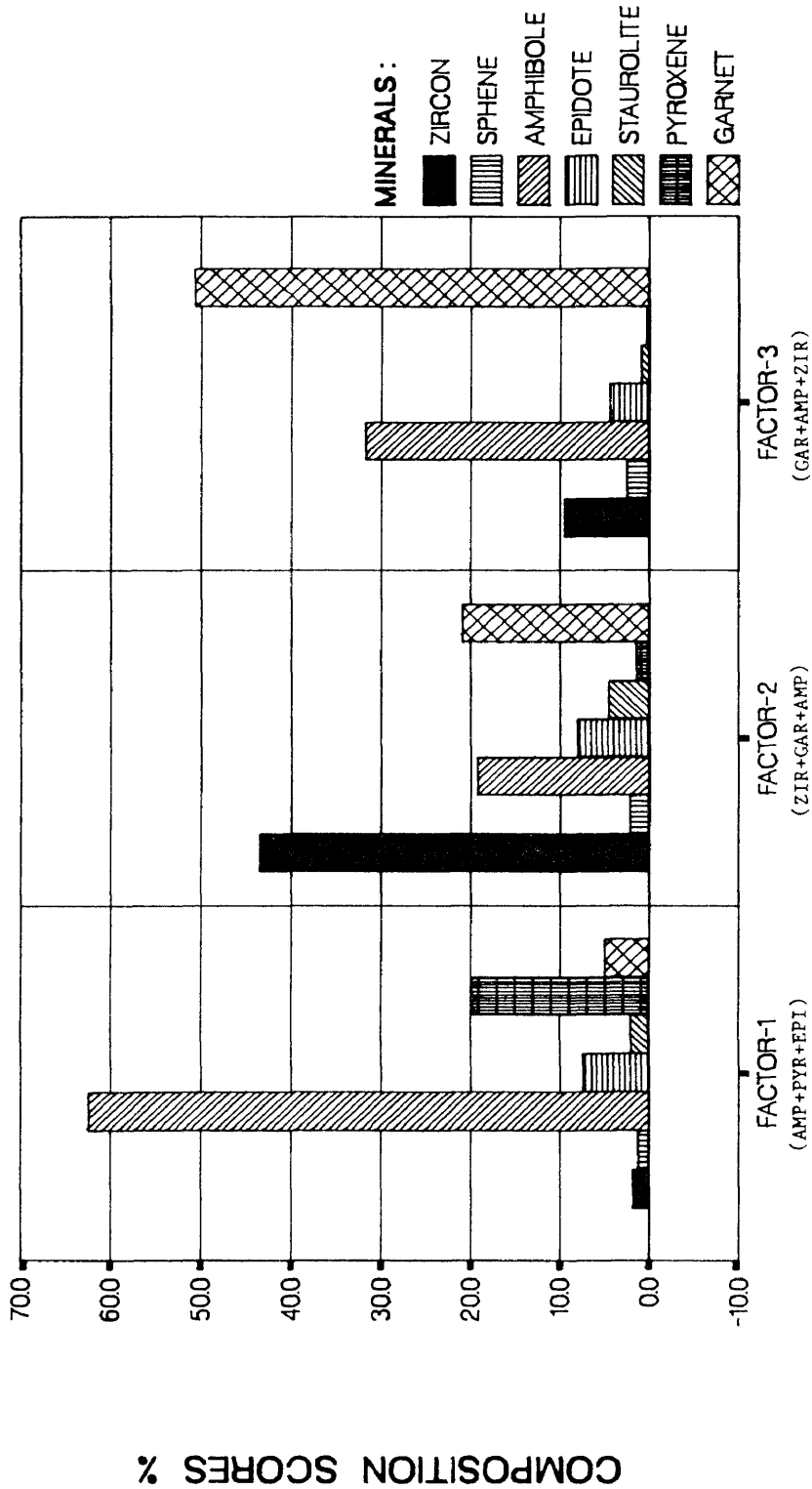
TABLE - 3

Communalities and loadings of extreme normalized samples of 3-factor solution. They are selected as population end-members.

END-MEMBER	COMMUNALITY	1	2	3
166	1.0000	0.9640	0.2031	0.1713
G84	0.9994	-0.0089	0.9866	0.1609
145	0.9986	0.1914	0.3507	0.9160

Figure 9 Compositions of the factors obtained from Q-mode factor analysis of 129 surficial off-shore heavy mineral samples.

COMPOSITION SCORES OF FACTORS (3-FACTOR SOLUTION)



FACTORS
(END-MEMBERS)

TABLE - 4

Compositions of end-members obtained from the 3-factor solution.

FACTOR-1 (sample - 166) (AMP+PYR+EPI)	FACTOR-2 (sample - G84) (ZIR+GAR+AMP)	FACTOR-3 (sample - 145) (GAR+AMP+ZIR)
62.4 % amphib.	43.5 % zircon	50.6 % garnet
19.9 % pyroxe.	20.9 % garnet	31.7 % amphib.
7.4 % epidot.	19.2 % amphib.	9.4 % zircon
4.9 % garnet	8.1 % epidot.	4.4 % epidot.
2.1 % zircon	4.5 % stauro.	2.5 % pyroxe.
1.8 % stauro.	2.1 % pyroxe.	0.8 % sphene
1.1 % sphene	1.4 % sphene	0.3 % stauro.

Figure 10 Contour map of sample composition loadings on Factor 1 (final solution). Factor 1 is sample 166 (Figure 7) and located at the south western part of the interest area.

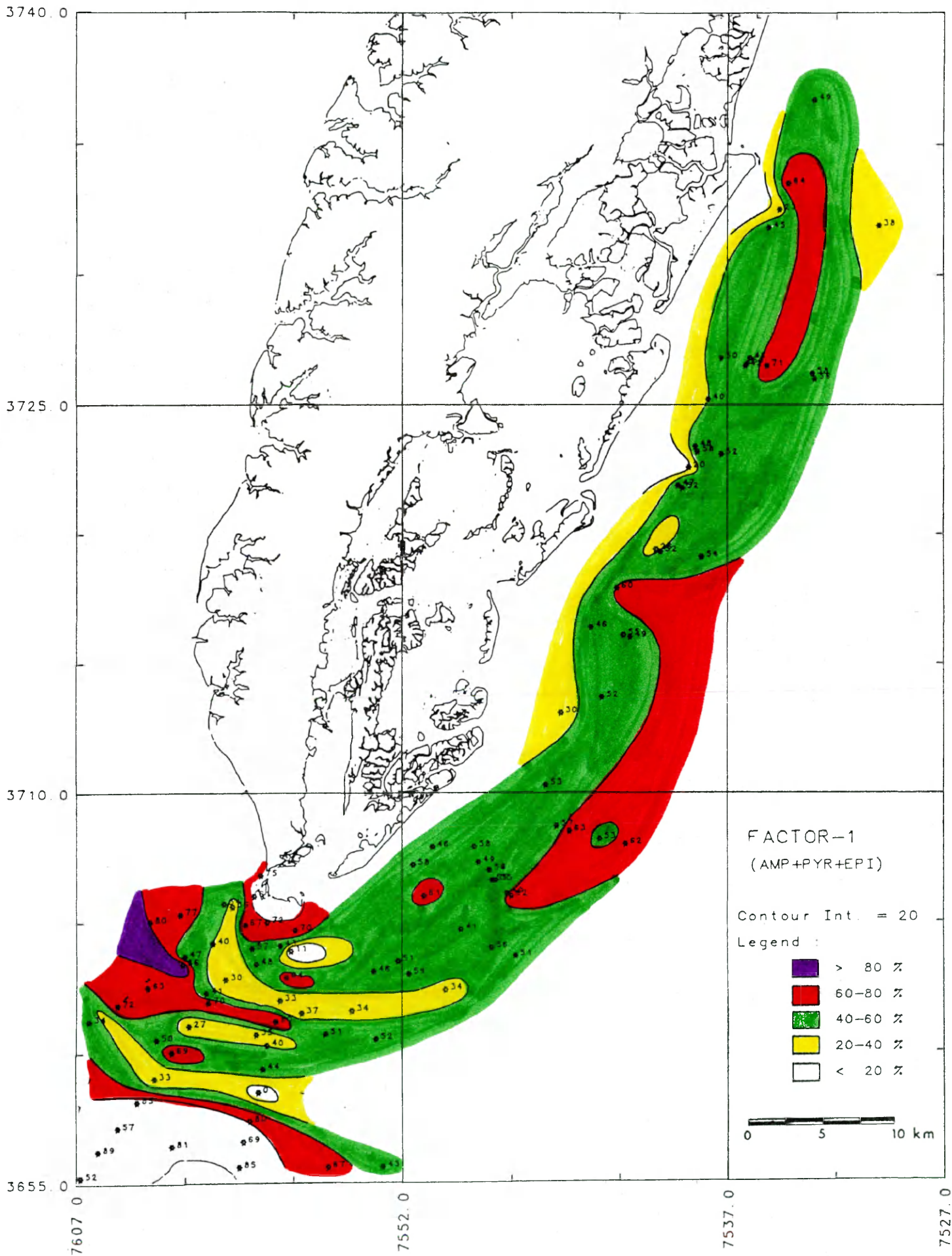


Figure 11 Contour map of sample composition loadings on Factor 2 (final solution). Factor 2 is sample G84 (Figure 7) and located at the southernmost part of the interest area.

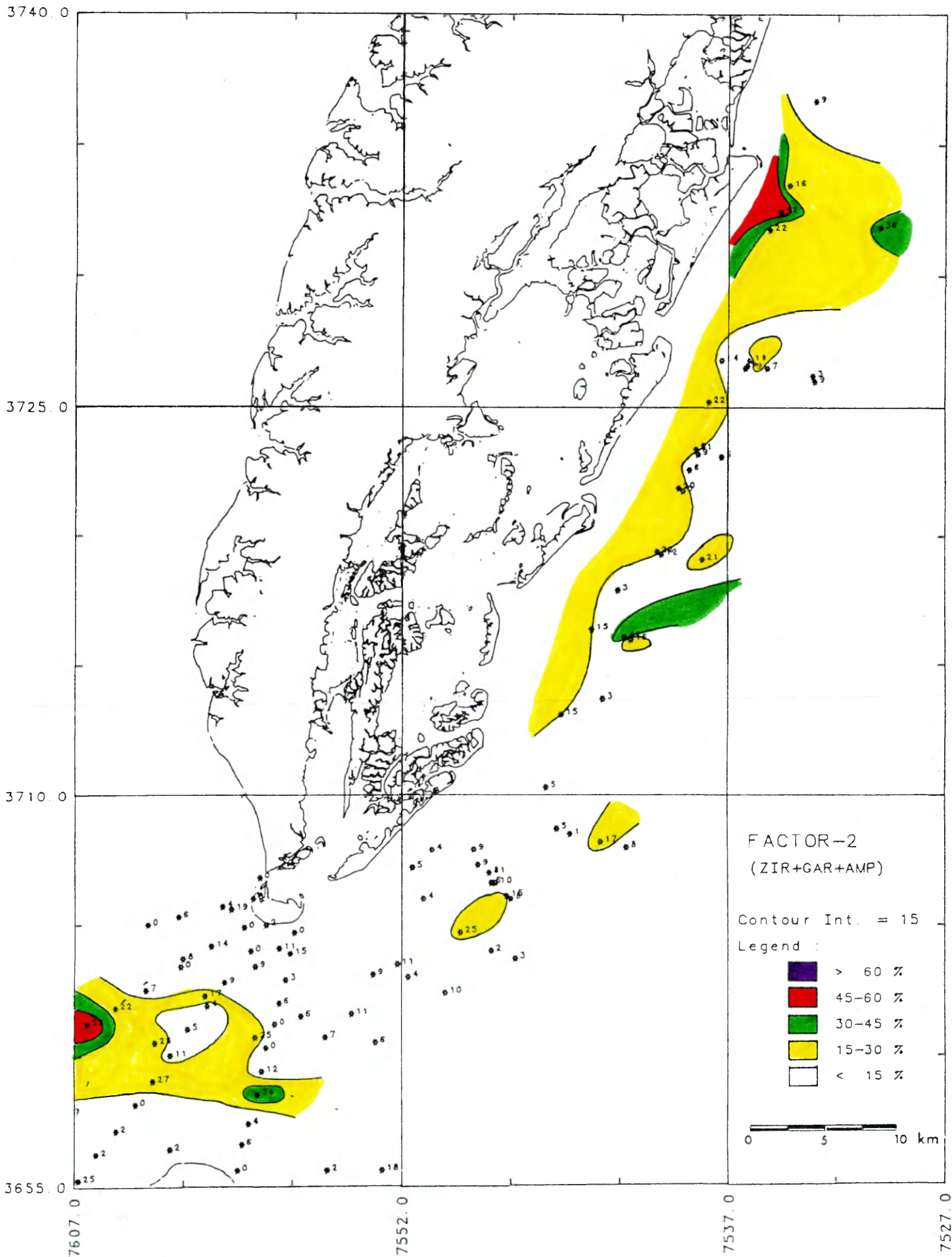


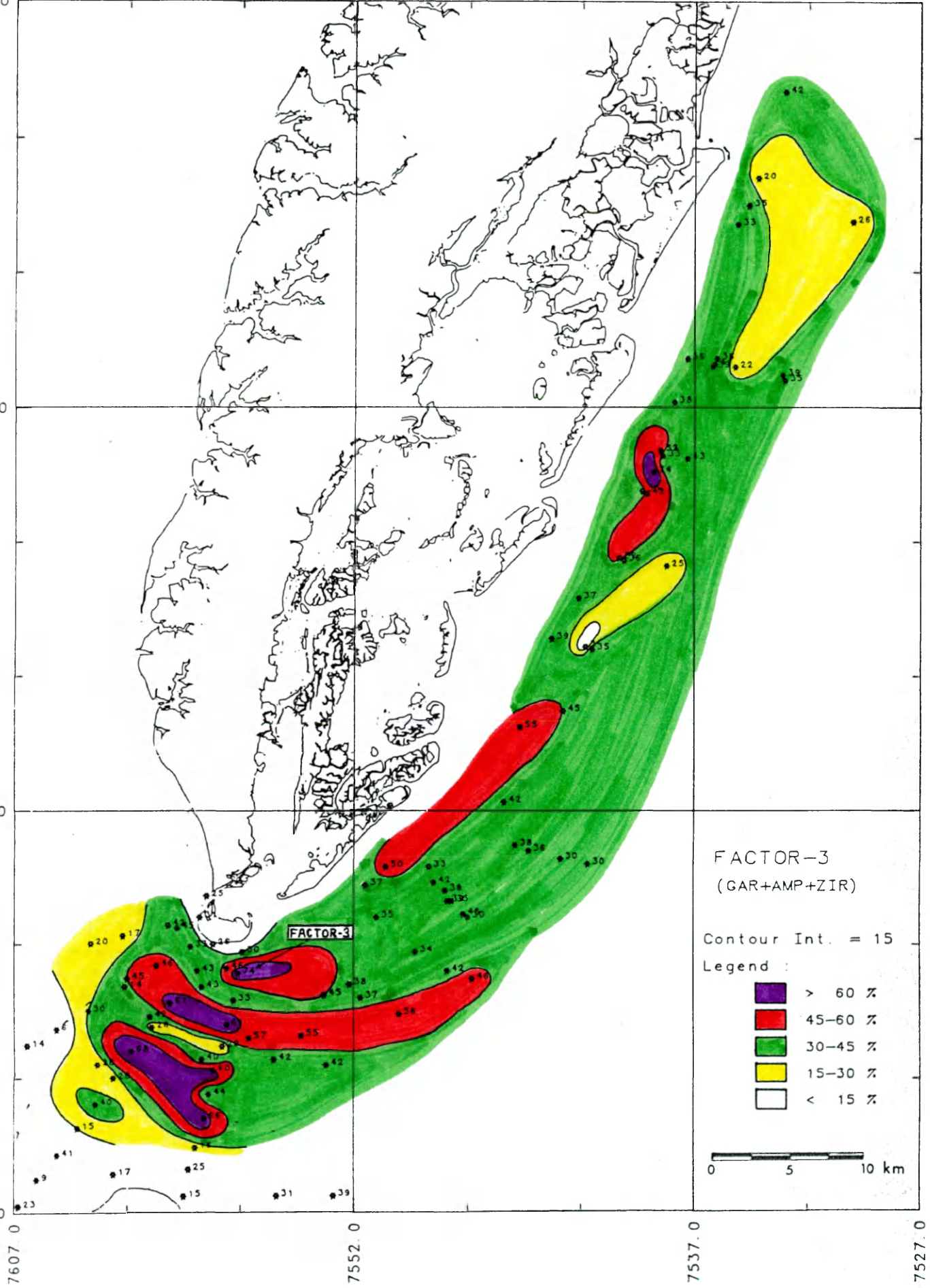
Figure 12 Contour map of sample composition loadings on Factor 3 (final solution).

3740.0

3725.0

3710.0

3655.0



FACTOR-3
(GAR+AMP+ZIR)

Contour Int. = 15

Legend :

- > 60 %
- 45-60 %
- 30-45 %
- 15-30 %
- < 15 %

0 5 10 km

7607.0

7552.0

7537.0

7527.0

6. SUMMARY AND CONCLUSIONS

In this study, the Q-mode factor analysis is used as a tool to establish the distribution patterns of the selected associations of transparent heavy minerals and, in turn to suggest directions of sediment transport.

The mathematical results and geological interpretations of the factor maps of 129 surficial samples of heavy minerals taken from the inner continental shelf off the southern Delmarva peninsula indicate three different mineral associations. Each mineral suit consists of seven transparent heavy minerals and is defined by the composition of an end-member in terms of the percentages of its seven minerals. These three end-members represented the compositional extremes of the data set. Thus, the remaining 126 samples were considered as mixtures of these extreme samples. Mineral composition isopleths were defined by contouring the composition loadings of samples on each factor.

Factor 1 shows easterly (off-shore) decreasing concentrations of heavy minerals from about 7 km southwest of Fisherman Island and suggests off-shore movement of the bay-originated amphibole, pyroxene, and epidote mineral associations. Factor 2 provides a relatively homogeneous distribution pattern, but suggests Chesapeake Bay, and an area approximately 4 km southeast of Wachapreague inlet, as potential sources for zircon, garnet and amphibole. Factor 3 suggests a landward sediment transport from the shelf adjacent to the baymouth and from approximately 5 km southeast of Hog Island.

In conclusion, heavy minerals on the inner continental shelf of southern Delmarva peninsula exhibit regional variations under the

effects of modern hydrodynamic processes and circulation patterns of continental shelf waters. Their concentration isopleths tend to parallel the present day coastline. These regional variation patterns are produced by sediment dispersal from (1) the northern Delmarva Peninsula due to southerly longshore transport of sediments, (2) barrier islands of Delmarva Peninsula, especially from the sandy beaches and inlets along the coastline by the effects of severe winter storms, (3) relict, reworked, possibly Pleistocene age more mature inner continental shelf sediments, associated with linear off-shore sand shoals, and (4) Chesapeake Bay sediments deposited during the post-Wisconsinan time interval. The main energy required to move these sediments is derived from tides, waves, and wind. Differences in wave parameters, such as direction, height and period, may cause variations in the rates of accretion, erosion and transportation of these sediments, and hence the different concentrations of heavy minerals. Unfortunately, the year-round circulation patterns and magnitudes of bottom currents are not well known.

Seven transparent heavy minerals chosen by the Principal Component Analysis were used in Q-mode factor analysis. In the study area, dominant heavy minerals are amphibole, garnet, and zircon. Less abundant are sphene, staurolite, epidote, and trace amounts of pyrite and rutile. The amphibole is highly abundant in the forms of green and brown hornblende (Appendix D), on the other hand pyroxene is less abundant and in the form of hypersthene.

In the study area, available samples were from within 15 km off-shore. The restriction of sample locations to a narrow, coast parallel band may have contributed to difficulty in interpretation of composition

gradients off the Eastern Shore compared to gradients within the Chesapeake bay-mouth area. Additional data are needed from near-shore and continental shelf depositional environments in order to get more information about sediment transport pathways. Results of this study may have the potential to help answer many questions relevant to the future explorations of economic placer deposits, the preservation of beaches and wetlands, sediment budget investigations, and an understanding of estuarine and near-shore sedimentary processes along the inner continental shelf of Virginia.

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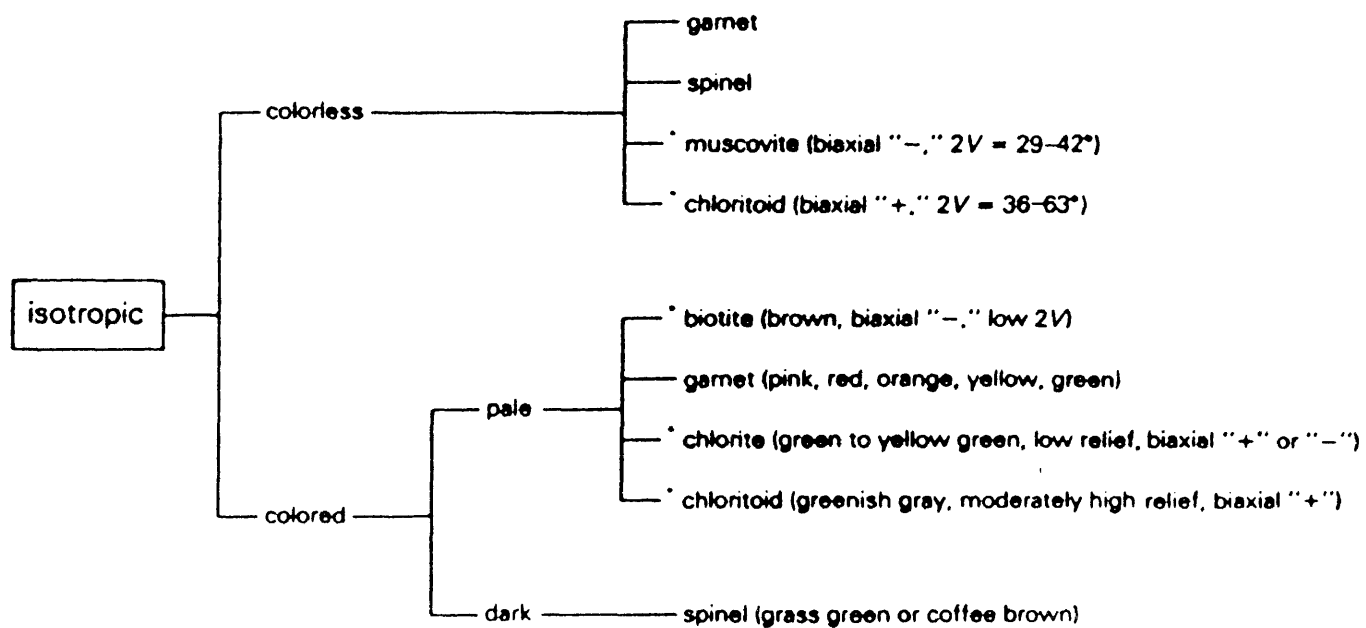
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APPENDIX A

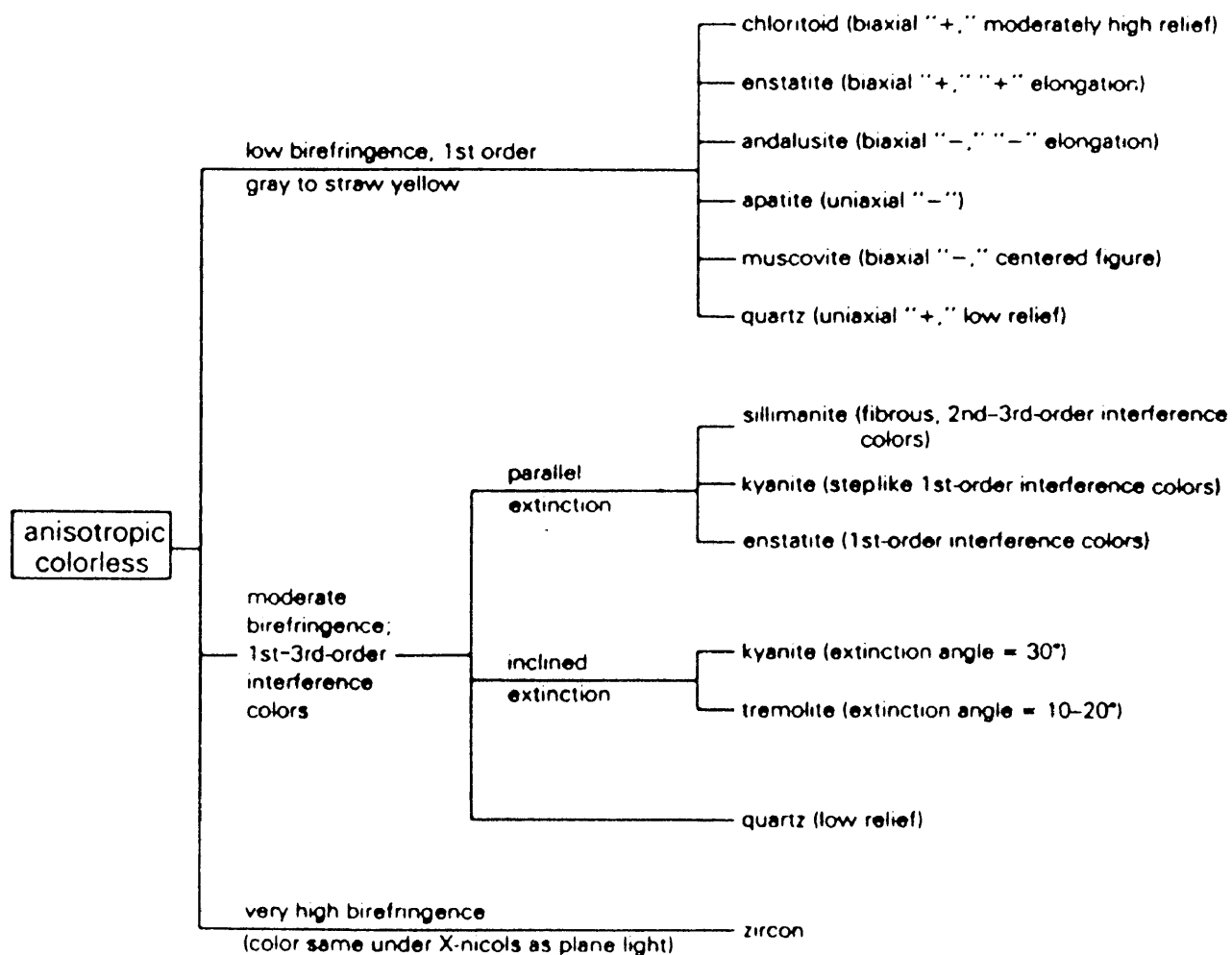
An identification key for isotropic minerals (Lindholm, 1987):



APPENDIX B

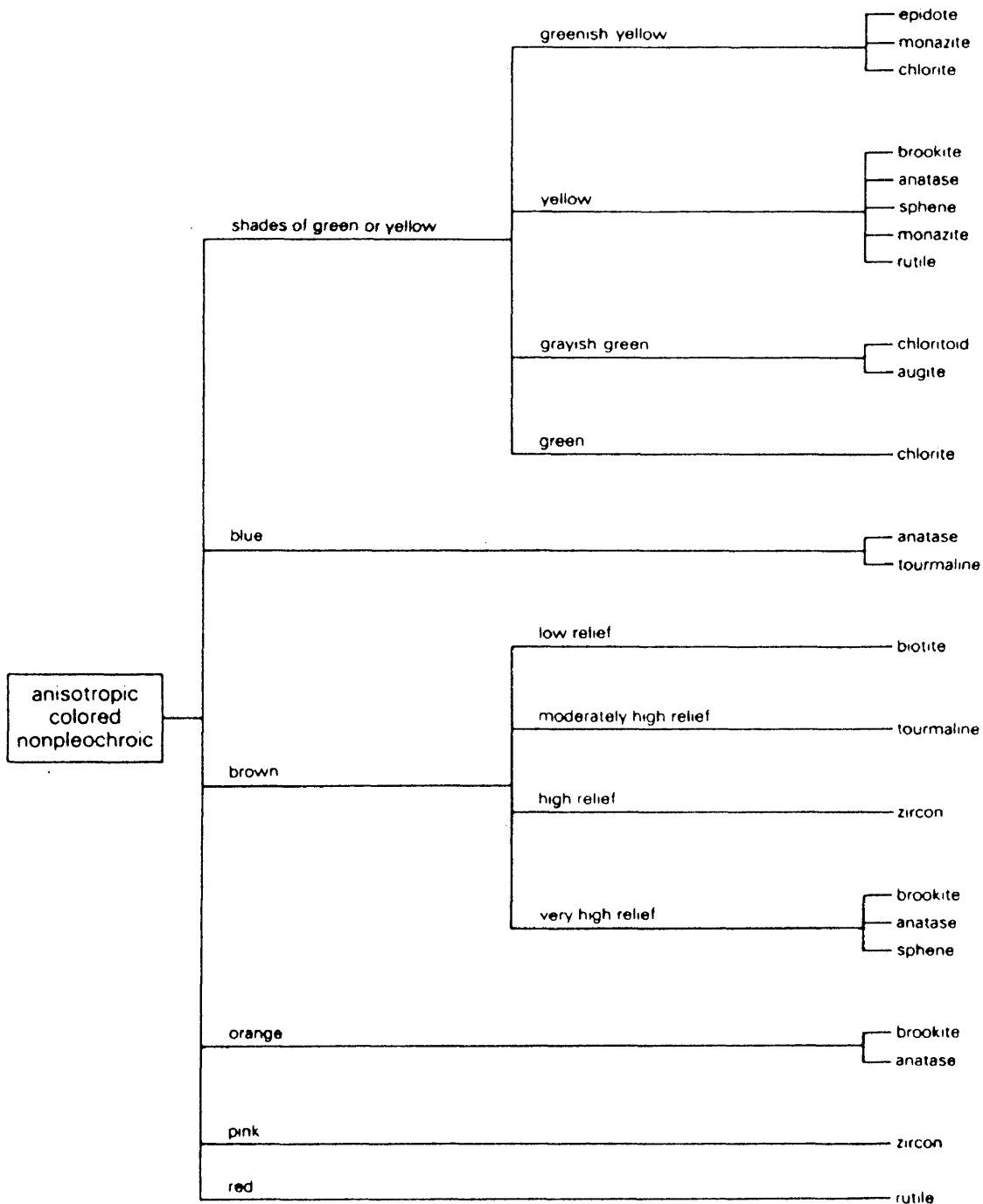
An identification key for colorless anisotropic minerals

(Lindholm, 1987):



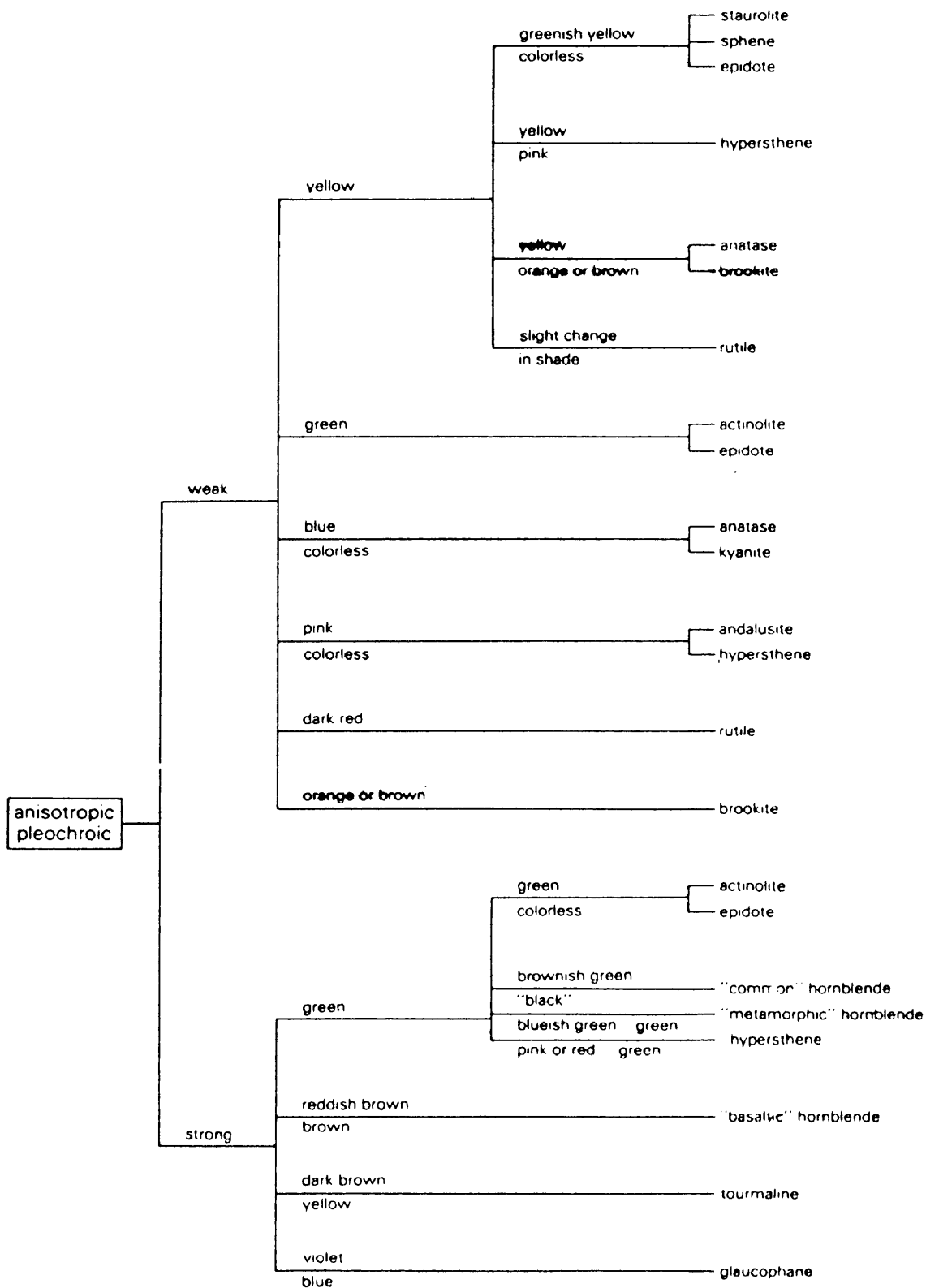
APPENDIX C

An identification key for colored nonpleochroic anisotropic minerals (Lindholm, 1987):



APPENDIX D

An identification key for pleochroic minerals (Lindholm, 1987):



APPENDIX E

Locations and compositions (grain %) of samples.

Coordinates are in degrees, minutes and tenths of minutes.

ZIRC: zircon; SPHN: sphene; AMPH: amphibole; EPID: epidote;

STAU: staurolite; PYRO: pyroxene; GARN: garnet.

<u>Sample</u>	<u>Lat.</u>	<u>Long.</u>	<u>ZIRC</u>	<u>SPHN</u>	<u>AMPH</u>	<u>EPID</u>	<u>STAU</u>	<u>PYRO</u>	<u>GARN</u>
C05	37.26.80	75.36.00	11.96	00.00	51.28	01.71	01.30	04.27	29.48
C06	37.26.50	75.36.20	12.18	00.42	48.74	02.10	01.26	03.79	31.51
C07	37.26.00	75.33.00	07.25	00.00	60.39	01.45	00.00	04.34	26.57
C08	37.23.40	75.38.50	13.75	00.42	48.75	00.83	00.00	07.92	28.33
C09	37.23.20	75.38.40	07.14	00.00	59.53	01.90	00.95	05.71	24.77
C10	37.23.10	75.37.30	04.55	00.90	56.82	01.37	00.45	05.00	30.91
C11	37.21.80	75.39.10	01.43	00.48	53.33	01.90	00.95	09.52	32.39
C12	37.19.30	75.40.10	08.73	00.00	55.46	03.06	00.87	04.37	27.51
C13	37.16.00	75.41.50	10.69	00.43	53.42	02.13	01.28	04.27	27.78
C14	37.06.00	75.47.00	06.31	00.00	60.68	01.94	00.49	07.77	22.81
C15	37.07.10	75.48.20	06.22	00.00	55.98	02.87	00.96	06.22	27.75
C16	37.06.60	75.47.90	04.76	00.00	57.14	03.33	01.91	05.24	27.62
C17	37.06.40	76.47.00	06.95	00.00	54.17	03.24	00.93	08.33	26.38
G01	37.03.00	75.51.70	02.87	01.64	47.13	07.38	00.00	16.39	24.59
G02	37.03.50	75.52.20	06.30	01.00	40.80	06.80	00.00	18.00	27.20
G03	37.06.00	75.51.00	02.30	00.90	45.60	11.20	00.00	17.20	22.80
G04	37.07.90	75.48.70	04.90	01.00	43.80	09.40	00.00	17.70	23.20
G22	37.36.70	75.33.00	07.11	00.00	51.19	01.42	00.47	09.01	30.80

APPENDIX E continued

<u>Sample</u>	<u>Lat.</u>	<u>Long.</u>	<u>ZIRC</u>	<u>SPHN</u>	<u>AMPH</u>	<u>EPID</u>	<u>STAU</u>	<u>PYRO</u>	<u>GARN</u>
G23	37.33.50	75.34.20	11.02	00.00	64.41	04.24	00.84	02.54	16.95
G24	37.32.50	75.34.60	25.78	00.78	36.72	02.34	00.00	00.00	34.38
G25	37.31.80	75.35.10	14.29	00.00	53.25	03.24	01.30	00.00	27.92
G27	37.31.90	75.30.00	21.94	01.02	44.39	01.02	00.00	04.59	27.04
G28	37.26.20	75.33.10	02.20	00.90	52.60	09.20	00.90	08.80	25.40
G29	37.26.50	75.35.20	05.49	00.00	68.68	02.75	01.10	05.49	16.49
G30	37.26.60	75.36.10	06.66	00.61	48.48	03.03	00.61	10.91	29.70
G31	37.26.80	75.37.30	09.79	00.00	53.10	01.54	00.00	07.22	28.35
G32	37.25.20	75.37.90	13.49	00.00	46.51	04.65	01.39	03.26	30.70
G33	37.23.40	75.38.50	03.20	00.90	42.30	11.70	00.40	08.10	33.30
G34	37.22.60	75.38.80	04.12	01.03	31.96	09.28	00.00	07.22	46.39
G35	37.07.20	75.51.50	03.44	02.59	49.57	07.76	00.43	11.64	24.57
G36	37.07.90	75.50.60	03.00	02.63	42.10	08.27	00.00	12.42	31.58
G39	37.07.30	75.48.50	05.00	00.50	43.30	10.90	00.50	11.40	28.40
G40	37.07.00	75.48.00	05.70	00.50	42.40	10.90	01.00	12.90	26.70
G41	37.06.60	75.47.70	04.55	01.51	42.05	12.50	00.00	15.15	24.24
G42	37.06.10	75.47.20	10.74	00.00	48.02	01.13	00.00	05.08	35.03
G43	37.08.00	75.41.70	03.50	00.40	43.50	13.00	00.90	17.80	20.90
G44	37.08.20	75.42.90	11.80	00.56	57.87	01.12	00.00	03.37	25.28
G45	37.08.50	75.44.30	00.47	00.00	42.72	14.55	00.00	19.72	22.54
G46	37.08.70	75.44.90	04.90	01.47	56.37	01.96	00.00	08.34	26.96
G47	37.10.30	75.45.40	03.40	01.40	45.70	08.60	00.50	13.00	27.40
G48	37.13.10	75.44.70	08.60	00.00	34.40	08.10	00.50	09.60	37.80
G49	37.13.70	75.42.80	02.69	01.61	43.01	06.99	00.00	16.67	29.03
G50	37.16.10	75.41.80	24.10	01.81	51.20	06.02	02.41	03.01	11.45

APPENDIX E continued

<u>Sample</u>	<u>Lat.</u>	<u>Long.</u>	<u>ZIRC</u>	<u>SPHN</u>	<u>AMPH</u>	<u>EPID</u>	<u>STAU</u>	<u>PYRO</u>	<u>GARN</u>
G51	37.16.40	75.43.30	09.04	01.13	46.89	07.34	01.13	05.66	28.81
G53	37.17.90	75.42.10	01.50	00.00	49.50	12.60	00.50	12.10	23.80
G54	37.19.40	75.40.30	14.06	00.00	41.67	03.65	00.00	00.00	40.62
G55	37.19.10	75.38.20	12.88	00.00	49.50	03.96	00.00	11.39	22.27
G56	37.21.90	75.39.30	13.18	00.00	47.73	00.45	00.00	10.46	28.18
G57	37.03.10	75.53.30	05.90	01.00	43.30	06.90	00.00	11.80	31.00
G58	37.00.50	75.53.20	03.77	02.15	41.93	09.14	00.00	15.59	27.42
G59	36.55.60	75.52.90	09.50	01.60	37.40	07.40	00.50	14.70	28.90
G60	36.55.60	75.55.40	01.69	00.42	50.21	08.01	00.00	18.57	21.10
G61	36.53.10	75.56.40	02.60	02.16	45.89	11.25	00.43	15.59	22.08
G62	36.52.80	75.58.30	03.49	00.50	60.70	08.95	00.99	11.44	13.93
G64	36.51.50	75.57.10	05.00	02.00	52.00	08.50	00.50	14.50	17.50
G65	36.51.10	75.54.80	08.20	01.09	54.64	10.93	02.19	14.21	08.74
G66	36.49.50	75.55.50	03.85	01.92	38.46	07.69	00.96	16.83	30.29
G67	36.48.50	75.49.80	17.10	00.37	48.33	03.72	00.74	13.38	16.36
G68	36.43.10	75.49.50	08.50	01.00	58.50	15.00	00.00	04.50	12.50
G71	36.44.40	75.51.50	04.95	01.10	44.51	12.64	00.55	17.57	18.68
G73	36.44.80	75.53.80	04.90	02.86	43.26	09.39	00.41	17.96	21.22
G74	36.45.20	75.56.10	06.50	00.44	48.92	06.06	00.86	11.25	25.97
G75	36.41.90	75.52.30	29.71	00.85	30.12	05.44	02.09	02.09	08.79
G76	36.40.30	75.53.20	17.30	02.00	34.20	11.40	00.00	16.30	18.80
G77	36.38.40	75.52.70	11.34	02.57	50.00	12.37	03.10	03.10	17.52
G78	36.37.90	75.50.40	33.47	00.42	23.73	07.20	04.24	06.36	24.58
G79	36.34.70	75.51.70	13.10	01.40	50.50	10.20	01.00	07.80	16.00
G82	36.34.30	75.50.00	30.60	01.60	25.90	06.70	01.60	03.60	30.00

APPENDIX E continued

Sample	Lat.	Long.	ZIRC	SPHN	AMPH	EPID	STAU	PYRO	GARN
G84	36.34.10	75.48.70	41.94	01.61	17.20	10.22	03.22	04.84	20.97
G86	36.32.70	75.46.40	12.30	01.90	41.50	09.40	02.40	10.40	22.20
G87	36.33.20	75.48.50	25.83	01.10	34.07	08.24	02.20	03.84	24.72
G89	36.33.40	75.49.80	04.28	02.14	51.70	08.11	02.56	11.97	19.24
G93	36.39.40	75.39.30	31.60	00.00	27.70	03.03	03.03	04.74	29.90
G95	36.39.80	75.41.50	12.74	01.12	41.20	07.49	04.12	04.87	28.46
G98	36.40.40	75.44.50	31.60	01.00	18.10	09.80	01.00	06.70	31.60
G100	36.41.00	75.47.90	13.61	01.18	26.63	17.16	04.14	07.10	30.18
G101	36.43.30	75.55.20	01.80	00.00	46.10	16.00	00.50	13.20	22.30
1103	37.00.50	76.03.30	14.21	00.00	50.00	05.26	05.26	00.53	06.84
1106	37.00.70	75.58.70	16.28	00.00	43.72	01.39	00.00	04.65	33.96
1107	37.02.30	76.01.00	11.16	00.45	46.88	02.23	00.45	06.25	32.58
1109	37.03.70	76.02.00	06.64	00.47	52.13	00.95	00.00	06.64	33.17
1111	37.05.60	75.59.80	12.79	00.00	44.75	00.91	00.00	05.94	35.61
1116	37.03.40	75.58.70	06.73	00.96	51.92	02.89	00.96	05.29	31.25
1119	37.01.50	75.56.60	05.99	00.00	48.39	00.92	00.00	04.15	40.55
1120	37.00.70	75.55.50	05.91	00.00	54.55	01.36	00.00	07.27	30.91
1121	37.01.60	75.54.30	08.33	00.00	45.83	01.85	00.47	03.70	39.82
1127	37.02.40	75.50.00	07.79	00.00	45.02	00.87	00.00	05.19	41.13
1129	37.03.70	75.46.80	03.25	01.30	53.90	02.60	00.65	06.49	31.81
1130	37.04.00	75.47.90	02.52	01.26	51.58	03.77	01.25	11.32	28.30
1131	37.04.70	75.49.30	15.92	00.00	46.76	02.99	00.50	04.48	29.35
1139	37.04.10	75.57.60	08.18	00.91	49.55	00.91	00.00	06.36	34.09
139	37.06.80	75.58.50	00.00	02.90	60.14	07.25	00.00	13.77	15.94
140	37.06.00	75.58.80	04.14	04.14	47.93	05.92	04.73	12.43	20.71

APPENDIX E continued

<u>Sample</u>	<u>Lat.</u>	<u>Long.</u>	<u>ZIRC</u>	<u>SPHN</u>	<u>AMPH</u>	<u>EPID</u>	<u>STAU</u>	<u>PYRO</u>	<u>GARN</u>
141	37.05.70	76.00.20	03.27	01.96	47.06	04.58	00.65	14.38	28.10
142	37.04.90	75.59.20	00.60	01.80	56.29	05.99	03.59	10.78	20.96
143	37.04.00	75.58.90	00.00	02.65	48.34	03.97	00.00	17.22	27.81
144	37.05.00	75.58.20	01.72	03.45	55.75	05.17	02.87	13.79	17.24
145	37.03.90	75.57.10	06.96	07.59	24.05	04.43	08.23	05.70	43.04
146	37.04.70	75.56.90	01.16	01.16	56.98	04.65	02.91	13.95	19.19
147	36.56.40	76.02.60	01.39	01.39	61.11	06.25	02.08	15.97	11.81
148	36.55.60	75.59.50	00.56	00.56	56.50	04.52	04.52	22.60	10.73
149	36.56.60	75.59.30	03.52	04.93	58.45	05.63	02.82	07.75	16.90
150	36.57.40	75.59.00	02.40	03.59	55.09	02.40	05.99	19.16	11.38
151	36.58.50	75.58.60	14.86	16.57	17.71	05.14	04.00	01.14	40.57
152	36.59.40	75.58.40	06.67	02.78	36.67	02.22	04.44	17.22	30.00
153	37.00.30	75.58.20	01.40	04.90	42.66	04.90	03.50	06.29	36.36
154	37.01.20	75.57.80	00.58	03.47	53.76	04.05	03.47	21.97	12.72
155	37.02.00	75.57.60	04.03	06.71	36.24	03.36	05.37	07.38	36.91
156	37.02.90	75.57.30	02.35	01.76	51.76	04.71	02.35	14.71	22.35
157	37.02.80	76.00.10	05.00	06.88	35.62	06.25	02.50	06.25	37.50
158	37.01.90	76.00.90	02.21	04.42	52.49	04.97	04.42	14.36	17.13
159	37.01.00	76.01.80	03.57	05.36	36.31	06.55	02.98	04.17	41.07
160	37.00.00	76.02.60	05.26	04.68	48.54	07.02	05.26	14.62	14.62
161	36.59.00	76.03.40	11.80	04.35	32.30	12.42	04.35	06.21	28.57
162	36.58.10	76.04.20	00.58	02.31	59.54	08.67	00.58	18.50	09.83
163	36.57.10	76.05.10	01.35	00.68	52.03	06.76	05.41	07.43	26.35
164	36.56.20	76.06.00	01.16	03.47	47.40	04.62	04.05	30.64	08.67
165	36.55.20	76.06.80	11.26	11.26	41.06	07.95	04.64	05.96	17.88

APPENDIX E continued

<u>Sample</u>	<u>Lat.</u>	<u>Long.</u>	<u>ZIRC</u>	<u>SPHN</u>	<u>AMPH</u>	<u>EPID</u>	<u>STAU</u>	<u>PYRO</u>	<u>GARN</u>
166	36.57.20	76.09.00	01.69	02.81	56.18	05.62	04.49	23.60	05.62
168	36.59.00	76.10.80	00.00	03.64	55.15	05.45	03.64	25.45	06.67
169	36.59.70	76.09.20	02.60	02.60	49.35	09.09	02.60	05.84	27.92
170	37.00.40	76.07.90	01.73	04.05	50.87	05.78	02.31	24.28	10.98
171	37.01.20	76.06.40	18.07	09.04	24.70	09.04	17.47	05.42	16.27
172	37.01.80	76.05.10	07.82	08.38	35.20	07.82	06.15	25.14	09.50
173	37.02.50	76.03.70	02.70	03.38	47.97	13.51	04.05	09.46	18.92
174	37.03.40	76.02.10	00.56	01.13	62.71	02.26	02.26	20.90	10.17
175	37.04.20	76.00.70	05.77	05.13	35.90	09.62	07.05	07.69	28.85
176	37.05.30	76.02.20	03.77	01.89	54.09	03.77	01.89	21.38	13.21
177	37.05.00	76.03.60	00.67	01.33	61.33	07.33	02.67	14.00	12.67

APPENDIX F

The oblique composition loadings matrix [D] from the output of EXQMODEL program (the amount of each factor in every sample):

<u>SAMPLE ID</u>	<u>FACTOR-1</u>	<u>FACTOR-2</u>	<u>FACTOR-3</u>
C05	0.46	0.18	0.36
C06	0.42	0.19	0.39
C07	0.56	0.09	0.35
C08	0.46	0.21	0.33
C09	0.58	0.09	0.33
C10	0.52	0.05	0.43
C11	0.52	0.00	0.48
C12	0.52	0.12	0.36
C13	0.49	0.16	0.35
C14	0.62	0.08	0.30
C15	0.54	0.08	0.38
C16	0.55	0.06	0.39
C17	0.55	0.10	0.35
1103	0.50	0.24	0.26
1106	0.35	0.25	0.40
1107	0.41	0.17	0.42
1109	0.47	0.08	0.45
1111	0.36	0.19	0.45
1116	0.48	0.09	0.43
1119	0.37	0.06	0.57

APPENDIX F continued

1120	0.51	0.07	0.42
1121	0.34	0.11	0.55
1127	0.34	0.10	0.56
1129	0.51	0.03	0.46
1130	0.56	0.02	0.42
1131	0.41	0.25	0.34
1139	0.43	0.11	0.46
139	0.75	0.00	0.25
140	0.61	0.08	0.31
141	0.54	0.04	0.42
142	0.67	0.00	0.33
143	0.57	0.00	0.43
144	0.72	0.02	0.26
145	0.11	0.15	0.74
146	0.71	0.00	0.29
147	0.81	0.02	0.17
148	0.85	0.00	0.15
149	0.69	0.06	0.25
150	0.80	0.04	0.16
151	0.00	0.34	0.66
152	0.44	0.12	0.44
153	0.40	0.00	0.60
154	0.81	0.00	0.19
155	0.33	0.06	0.61
156	0.64	0.03	0.33
157	0.30	0.09	0.61

APPENDIX F continued

158	0.70	0.04	0.26
159	0.27	0.05	0.68
160	0.69	0.11	0.20
161	0.33	0.27	0.40
162	0.85	0.00	0.15
163	0.57	0.02	0.41
164	0.89	0.02	0.09
165	0.52	0.25	0.23
166	0.91	0.04	0.05
168	0.92	0.00	0.08
169	0.52	0.04	0.44
170	0.83	0.03	0.14
171	0.34	0.52	0.14
172	0.72	0.22	0.06
173	0.63	0.07	0.30
174	0.86	0.00	0.14
175	0.40	0.14	0.46
176	0.77	0.06	0.17
177	0.80	0.00	0.20
G01	0.59	0.04	0.37
G02	0.51	0.11	0.38
G03	0.61	0.04	0.35
G04	0.58	0.09	0.33
G22	0.49	0.09	0.42
G23	0.64	0.16	0.20
G24	0.23	0.42	0.35

APPENDIX F continued

G25	0.45	0.22	0.33
G27	0.38	0.36	0.26
G28	0.58	0.03	0.39
G29	0.71	0.07	0.22
G30	0.50	0.09	0.41
G31	0.50	0.14	0.36
G32	0.40	0.22	0.38
G33	0.43	0.05	0.52
G34	0.20	0.06	0.74
G35	0.58	0.05	0.37
G36	0.46	0.04	0.50
G39	0.49	0.09	0.42
G40	0.50	0.11	0.39
G41	0.55	0.10	0.35
G42	0.40	0.15	0.45
G43	0.62	0.08	0.30
G44	0.53	0.17	0.30
G45	0.63	0.01	0.36
G46	0.57	0.05	0.38
G47	0.53	0.05	0.42
G48	0.30	0.15	0.55
G49	0.52	0.03	0.45
G50	0.55	0.42	0.03
G51	0.46	0.15	0.39
G53	0.60	0.03	0.37
G54	0.26	0.22	0.52

APPENDIX F continued

G55	0.54	0.21	0.25
G56	0.47	0.20	0.33
G57	0.46	0.09	0.45
G58	0.52	0.06	0.42
G59	0.43	0.18	0.39
G60	0.67	0.02	0.31
G61	0.61	0.05	0.34
G62	0.75	0.06	0.19
G64	0.67	0.09	0.24
G65	0.76	0.17	0.07
G66	0.47	0.06	0.47
G67	0.57	0.30	0.13
G68	0.68	0.17	0.15
G71	0.63	0.11	0.26
G73	0.60	0.10	0.30
G74	0.54	0.10	0.36
G75	0.29	0.57	0.14
G76	0.47	0.37	0.16
G77	0.56	0.23	0.21
G78	0.19	0.67	0.14
G79	0.59	0.25	0.16
G82	0.16	0.58	0.26
G84	0.12	0.86	0.02
G86	0.49	0.25	0.26
G87	0.30	0.49	0.21
G89	0.64	0.08	0.28

APPENDIX F continued

G93	0.18	0.58	0.24
G95	0.40	0.24	0.36
G98	0.08	0.65	0.27
G100	0.26	0.33	0.41
G101	0.60	0.05	0.35

VITA

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