# GEOLOGIC INTERPRETATION OF SELECTED ANOMALIES WITHIN THE MONROVIA QUADRANGLE, LIBERIA, USING AN INTERGRATION OF GEOPHYSICAL METHODS

Thesis for the Degree of M. S.

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ABSTRACT

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By

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In the tropics, because of the high degree of weathering, information from geophysical surveys are used in the making of geologic maps. Faults, geologic contacts, and structural trends, are often hard or impossible to detect solely on the grounds of surface geologic mapping. This is the case in Liberia.

In 1968 a joint magnetic and radiometric survey was flown over the entire country of Liberia by Lockwood, Kessler and Bartell (Behrendt and Wotorson, 1971a). A detailed gravity station network has been started in the Monrovia Quadrangle and will eventually cover the entire country. Rock samples were collected in the summer of 1972 and their densities and magnetic susceptibilities were determined and compared with the grativy and magnetic pattern in this study. In general these physical properties

show very little correlation with the gravity and magnetic patterns of the area.

The aeromagnetic data show that the Monrovia Quadrangle has primarily a north-east structural trend. Superimposed on this trend are north-west trending diabase dikes which occur in two zones: A coastal zone, and a zone beginning about 90 kilometers inland.

The Bouguer and Free-air anomaly gravity maps show a positive trend which runs parallel to the coast. From the bouguer anomaly map, a gradient of 3-4 milligal/km is associated with this feature. Behrendt and Wotorson (1972), felt that uplift of granulite and crustal thickening were both responsible for this feature, since the gradient is too steep to be explained by crustal thickening alone. The mean free air anomaly for the entire country is + 22 milligals which would mean that essentially, the area of Liberia is isostatically under compenstated. For the region of Liberia, a crustal thickness of about 32 km. was calculated using Woollard's curve (Woollard, 1957).

The total-count gamma radiation map shows that there is a positive correlation of felsic and mafic rocks with radioactivity. The felsic rocks have a greater radioactivity than the mafic rocks, which is due to their higher potassium content. The radiometric pattern of the quadrangle also reflects the Northeast and Northwest trends that are found on the aeromagnetic map.

In all, six anomalies within the Monrovia Quadrangle are interpreted in this discussion. In general, it would appear that the anomalies that occur in the coastal area are caused mainly by faulting, accompanied at times by the intrusion of diabase dikes. Where basins have resulted from the faulting, sediments have accumulated to substantial thicknesses. Those anomalies that occur inland are mainly caused by density contrasts of large rock bodies.

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# CHAPTER I

# INTRODUCTION

## Purpose of the Study

The purpose of this study is to integrate magnetic, gravity and radiometric data with recent geologic information, in order to interpret certain geophysical anomalies in the Monrovia Quandrangle, Southwestern Liberia. These anomalies are readily apparent on some or all of the geophysical maps of the quadrangle, but they are not all easily correlatable to features on the geologic map of the area.

It is hoped that an integration of the geophysical methods with the geologic information will place restrictions on the possible solutions, thus viable and geologically sound models for these anomalies might be suggested. Towards this end, samples were collected with the hope that they would add further restrictions to the models.

## Location of Study Area

Liberia lies on the south-west coast of west Africa, between 4 degrees and 9 degrees N. latitude and between 7 degrees and 12 degrees W. longitude. To the northwest is Sierra Leone. Guinea lies to the north and the Ivory Coast to the east. To the south and south-west is the Altantic Ocean. This thesis covers the Monrovia Quadrangle, which is one of several quadrangles that makes up the entire map of Liberia. The Monrovia Quadrangle is shown by the shaded area in Figure 1. The region has low relief near the coast, with a hilly interior. The highest point in the quadrangle can be found at Cape Mount. The region, like the rest of the country, lies in the tropical rain forest belt, and is therefore heavily forested. Due to the intense weathering, there are few outcrops from which to collect samples. In such a region, the outcrops that offered the best samples were those that were found in river beds, and those that were left exposed in road or railroad cuts.

## Previous Investigation

Previous investigations in this area consist of geological and geophysical studies. The geological studies were conducted by A. W. Leo and R. W. White (1969), whose contributions are mainly the Reconnaissance geology of western Liberia, mapping of both sedimentary and weathered crystalline rocks, and summarizing the age provinces of Liberia. L. V. Blade (1970) studied the geology of the Bushrod Island-New Georgia clay deposit near Monrovia. P. M. Hurley et al. (1971) were instrumental in dating and

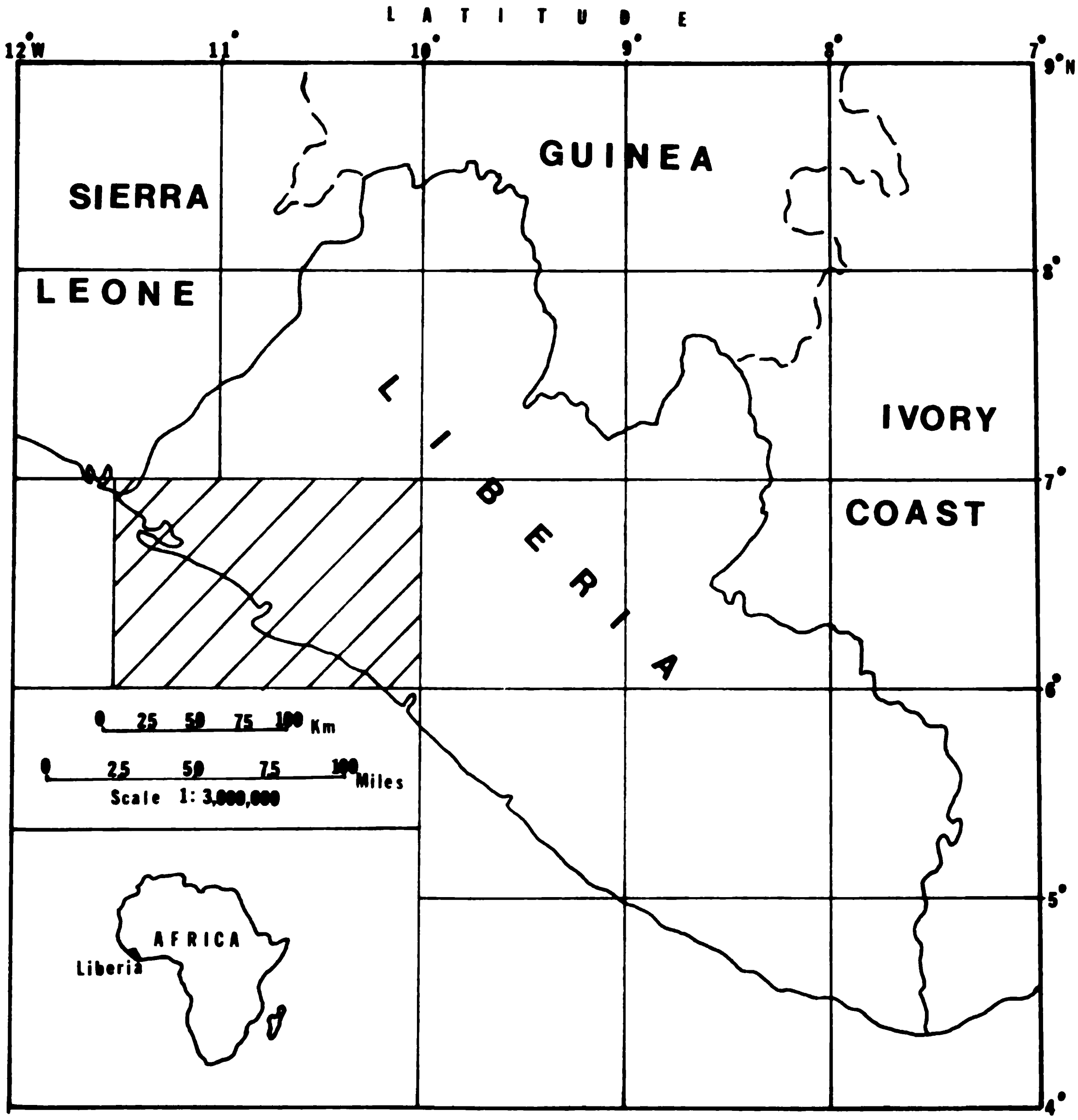


Fig. 1 Map Of Liberia — Shaded Area Is The Monrovia Quadrangle

classifying the various age provinces of Liberia. All previous geophysical work in the area which includes grativy, magnetics and radiometrics, have been done by J. C. Behrendt (U.S.G.S.) and C. S. Wotorson (L.G.S.) between 1968 and 1972.

## Geology of Study Area

The Quadrangle, like most of Liberia lies within the Guinea shield and is underlain by precambrian cristalline rocks mainly of granite composition. Rocks in the Quadrangle fall into two age provinces. The Pan-African and the Liberian Age provinces, have been dated as 500 M.Y. and 2700 M.Y. respectively (Hurley, et al., 1967). In the Liberian age province both the foliation of the gneiss and metasedimentary structural features trend northeastward. This is not the case in the Pan-Africa age province where the structural grain generally trend northwestward (White and Leo, 1969). Figure 2 shows the age provinces of the Monrovia Quadrangle.

### Metamorphic Rocks

The metamorphic rocks range in grade from the amphibolite to granulite facies, and there is considerable exposure of amphibolite, quartzite, schist, and metasedimentary iron formation found in the area. The amphibolite facies occurs mainly east-northeast of Monrovia, whereas, the granulite facies is found mainly from Monrovia towards the northwest and onward to the Sierra Leone border. The

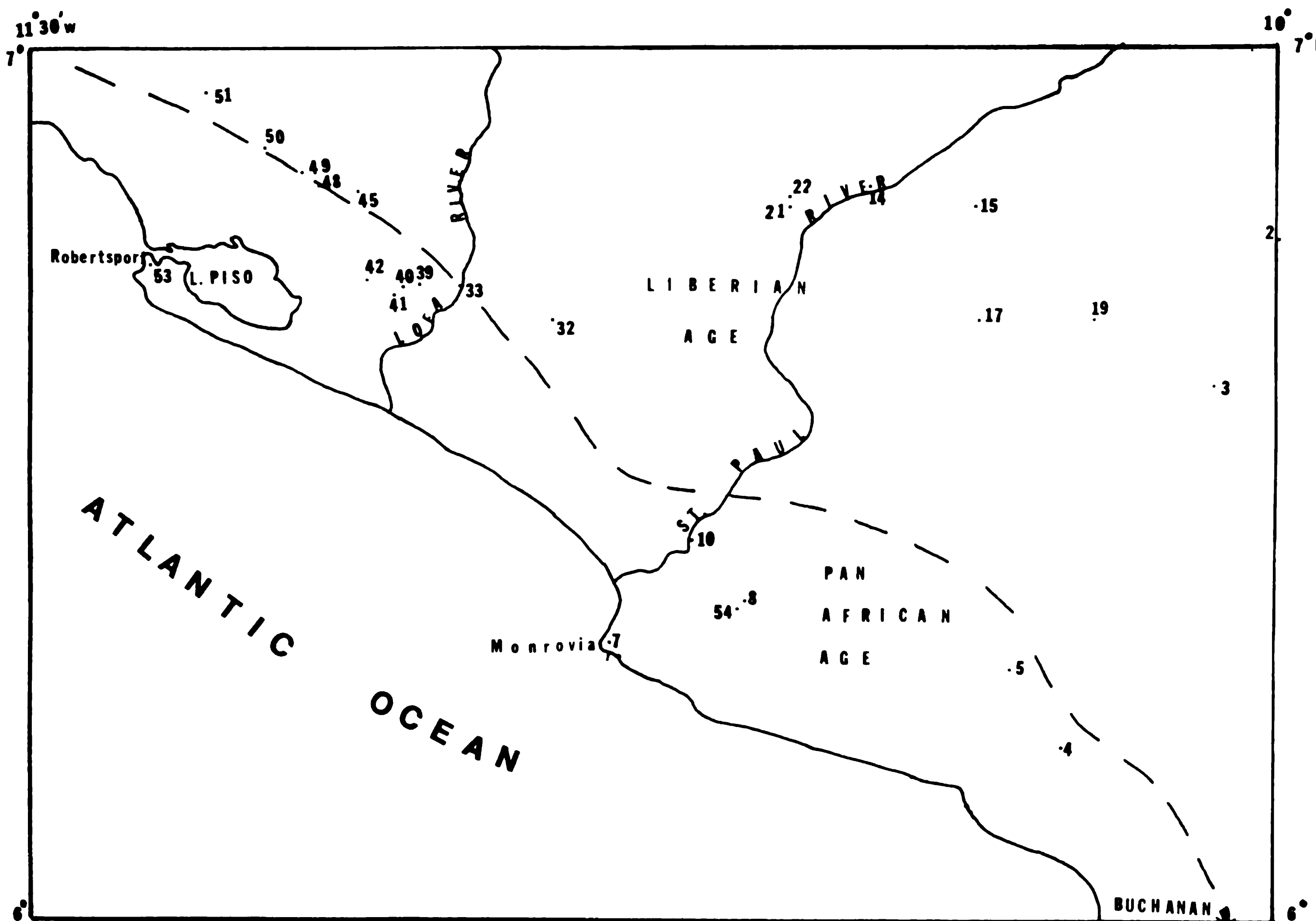


FIG. 2 Monrovia Quadrangle Showing Sample Location For Susceptibility Determiation

— — — Inferred Boundary Separating The Age Provinces amphibolite and other mafic rocks in Liberia are generally not as deeply weathered as the granitic rocks and schist, therefore they have a tendency to form ridges and divides (R. W. White, 1970).

The quartzite and schist are in many places associated with iron formations, as is the case in the Goe-Fantro Ranges. The schist in this region contains kyanite, quartz and muscovite. The metasedimentary iron formations, locally known as itabirite, are finely laminated rocks with grain size increasing with metamorphism (C. H. Thorman, 1972). Major deposits of this itabirite are found in the area of Bomi Hills and the Bong Range. The magnetite-itabirite is the most common although hematite-itabirite is also found (R. W. White, 1969-70).

The granulite facies crops out in a 15 mile wide belt which runs parallel to the coast from Monrovia toward Sierra Leone. Granulite of igneous and sedimentary origin occurs in this belt (R. W. White and G. W. Leo, 1969).

## Igneous Rocks

The igneous rocks are mainly intrusive in nature and include diabase, norite and pegmatite. Some granite is also found in the Quadrangle. The diabase appears mainly as vertical dikes having surface expressions that can be traced for tens of miles. The longest continuous dike, which occurs within an inland northwest trending dike zone, is the Gibi dike and can easily be seen on the aeromagnetic map of the quadrangle (Figure 6A in back folder). Another diabase dike zone strikes along the coast, and here, flat lying sill-like diabase bodies have been mapped (R. W. White and A. W. Leo, 1969). The norite which forms a prominent hill near Robertsport is believed to be a plug-shaped intrusive body (Brehrendt and Wotorson, 1971c). Its relationship with the granulite facies rocks in the area is not known since this hill is surrounded by unconsolidated sand on one side and the Atlantic Ocean on the other. Pegmatites appear sparsely in the Quadrangle and have been placed into two categories. These categories are (1) granite, quartz-muscovite-microcline-plagioclase rocks with minor hornblend or biotite, and (2) massive bull quartz, with minor amounts of feldspar and mafic minerals (C. H. Thorman, 1972).

## Sedimentary Rocks

In the Quadrangle, sedimentary rocks are found mostly between Monrovia and Buchanan. The sandstones lay unconformably on the metamorphics and are of Paleozoic, lower Cretaceous and Tertiary ages (J. C. Behrendt and C. S. Wotorson, 1969). They are mainly white sandstone which are heavily stained with iron in places, arkose, graywacke, siltstone, mudstones and conglomerates. The true thickness of this section is not known since from geophysical data (Behrendt and Wotorson, 1969) it has been shown that there is at least one major basis underlying a part of the area. Sedimentary rocks also crop out northwest of Lake Piso and at Gibi mountain (C. H. Thorman, 1972). Just north of Monrovia and in the area of Lake Piso there are large areas of thin unconsolidated sandy sediments. In these places they are slightly thicker than 15 meters (R. W. White, 1969-70).

# CHAPTER II

## PROPERTIES OF THE ROCK SAMPLES

### Introduction

More than sixty rock samples were collected during the summer of 1972 to determine general physical properties of these materials. The exact location of these samples are shown in Figure 3 and numbers on the map refer to the sample number in the Appendix. The samples were collected for several reasons which will be mentioned here and discussed more fully below. They were collected to identify the rock types, to determine their magnetic susceptibilities and densities and to identify and estimate the percentages of opaques.

The sampling scheme used in this study was based primarily on the accessibility of the outcrops and on the degree to which weathering had proceeded. With this in mind, those outcrops that were heavily weathered were passed over, and only those with relatively fresh rock were sampled. Because of the intense weathering problem, most of the rocks collected were mafic rocks rather than felsic rocks. In Liberia the former seem to be less

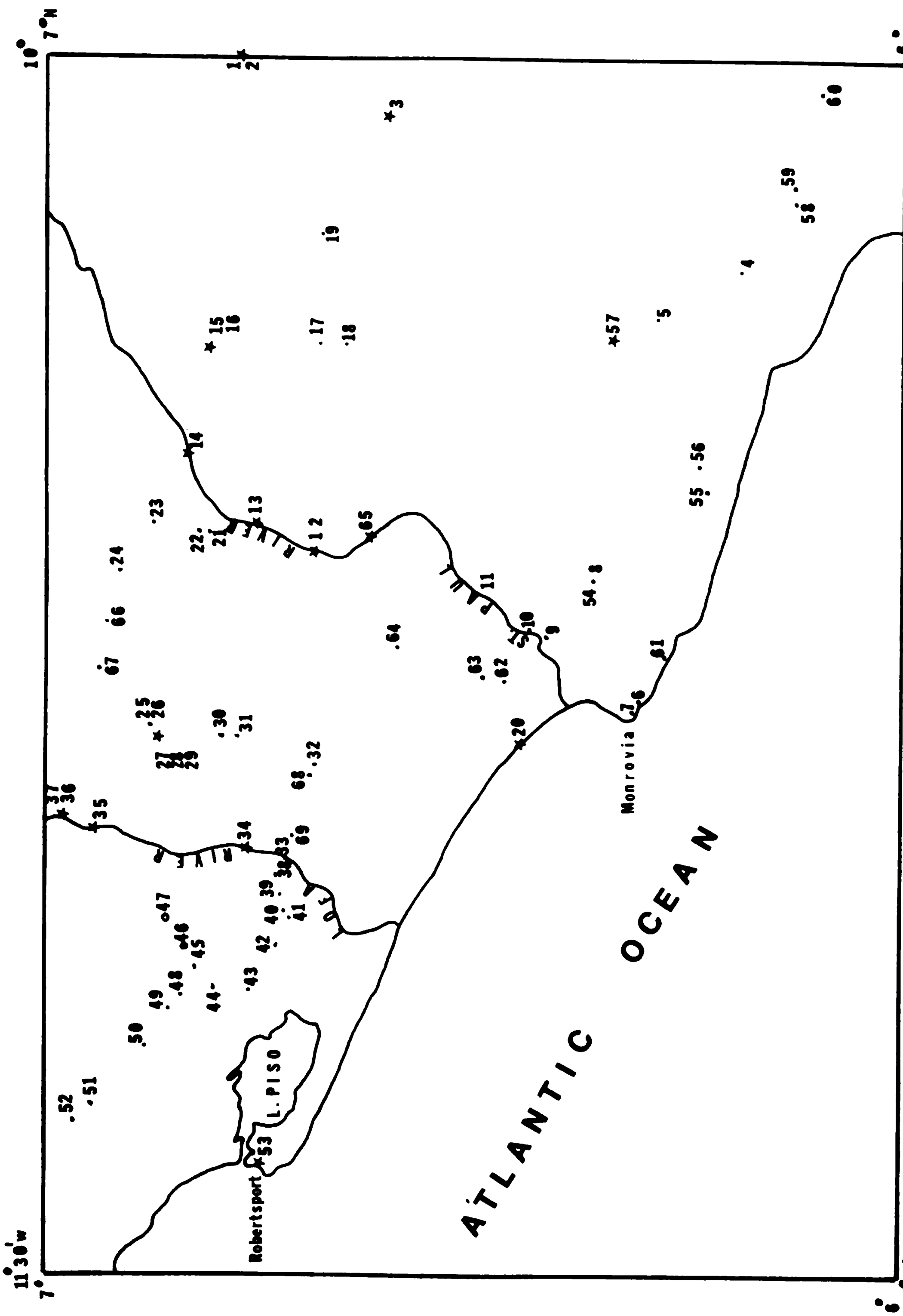


**Fig. 3** Monrovia Quadrangle Showing Sample Location
Numbers refer to sample number in Appendix

effected by the weathering than the latter. Several of the samples were collected by Mr. C. Thorman of the U.S.G.S. from outcrops in the Lofa and St. Paul River channels.

## Magnetic Susceptibility of the Rocks

The reason for measuring the magnetic susceptibility was to have base data that would give the range and magnitude of magnetic susceptibilities. It was felt that this information could probably be utilized in the interpretation of the magnetic maps.

The magnetic property of any material, including rocks, is due to both permanent and, or induced magnetization. Permanent or remanent magnetization refers to that portion of magnetism which remains fixed in the material or rock. If the rock is moved about or exposed to an external magnetic field, the permanent magnetization will be unaffected. However for a weakly, permanently magnetized rock, the permanent magnetization can change with time if the rock is placed in a different magnetic field. An ordinary bar magnet is a good example of permanent magnetization. A study of the remanent magnetization of these samples was not conducted therefore only the susceptibility is discussed in this study.

Induced magnetization refers to that portion of magnetism that is created when a material is placed in an external magnetic field, such as the magnetic field of the earth. When this external field is present, the material will behave like an ordinary bar magnet which is oriented with the external field. If the strength and direction of this external field is removed, the induced magnetization will disappear. An electromagnet is a good example of induced magnetization. The induced magnetization is proportional to the field through the constant k, where k is the magnetic susceptibility of the material. The magnetic susceptibility of a material therefore is a measure of the ability of that material to take on induced magnetization when it is placed in an external field.

The susceptibility of a rock is dependent upon several characteristics listed below.

1. Dependence on composition.--The variation in composition, of the magnetic mineral suite within rocks, can lead to variations in susceptibility. Since weathering produces oxides of iron from the primary magnetite, the relatively nonmagnetic oxides reduce the susceptibility. The formation of hematite from pre-existing magnetite, due to hydrothermal solutions, will cause a reduction in the susceptibility, whereas the formation of magnetite from the reduction of hematite, in highly metamorphosed sediments, will increase the susceptibility (Grant and West, 1966).

2. Dependence on field strength.--According to Strangway (1967), the susceptibility of a material will increase rapidly as the field strength approaches 150

oersteds, above this, the susceptibility starts to decrease. However, this factor is not important in the earth's relatively low magnetic field.

3. Dependence on state of magnetization.--The state of magnetization is very important to the susceptibility of a sample. If a sample has remanent magnetization its susceptibility will be different than if it had no permanent magnetization. According to Strangway (1967), it is found in general that susceptibility decreases with an increased remanence.

4. Dependence on grain size.--Experiments carried out on powdered samples of magnetite show that a decrease in the particle size greatly reduced the effective susceptibility (J. J. Jakosky, 1957). This means that plutonic rocks have generally higher magnetic susceptibilities than their volcanic equivalents.

5. Dependence on amount of magnetic minerals present. --Not only does magnetization depend on the type of magnetic mineral present, but also on the quantity present. Jakosky (1957), found that rocks which have widely dispersed magnetite show the lowest susceptibility. However, with increased grain size one might reasonably expect an increase in susceptibility.

6. Dependence on orientation.--Certain metamorphic rocks especially those that exhibit a platy, schistose or

gneissic texture will have different susceptibility values in different directions. As a general rule, the bulk susceptibility will be smaller in the direction perpendicular to the schistosity or gneissosity then in the direction parallel (Grant and West, 1965).

Other variations in the susceptibility values could have come from the following sources. Some of the samples were slightly below minimum size, and although a conversion factor was used, error might have been introduced in this conversion. Variations in five repeated measurements on the same sample were found to be less than 1 percent, which is the estimated error in Table 1.

Since some of the samples are metamorphic in origin, this might be a source of error in these samples. The samples measured might not be representative of the general rock type. For example, D. Sanderson (Ph.D. Thesis, 1972) showed that magnetic susceptibility is apt to change quite markedly from one location to another within the same rock body. Table 1 and the susceptibility values will be discussed in Chapter III.

Briefly, the magnetic susceptibility of a rock is measured by placing coils, referred to as the primary coil and the secondary coil, around the rock sample. When a current is passed through the primary coil, it causes a galvanometer, which is connected to the secondary coil, to be deflected (Dorbrin, 1960). This deflection is a measure

TABLE 1.--Magnetic Susceptibility Values According to Rock Type. Errors in the Repeatibility of These Readings is Less Than 1 Percent.

| Rock Type | Number of Samples | Susceptibility Range x $10^{-6}$ | Medium Value | Arithmetic Mean |
|---|---|---|---|---|
| Granite Gneiss | 8 | 117.0-1838 | 783 | 733 |
| Granite | 1 | 20.0 | . . | . . |
| Gneiss | 1 | 146.0 | . . | . . |
| Metabasic 1[a] | 2 | 2870-4210 | . . | . . |
| Diabase | 6 | 2188-5793 | 3990 | 3889 |
| Gabbro | 2 | 5099-5546 | . . | . . |
| Chlorite Schist | 1 | 158.0 | . . | . . |
| Norite | 1 | 1728 | . . | . . |
| Weathered-Quartzite | 1 | 756.0 | . . | . . |
| Metabasic 2[b] | 6 | 126-1678 | 192 | 376 |

[a]Metabasic 1--locally called amphibolite, is a dark gray, medium grained massive rock containing approximately equal amounts of plagioclase and hornblende.

[b]Metabasic 2--locally called granulite, is a reddish gray, medium to course grained massive rock containing pyroxene, plagioclase and often garnet.

Note: These values represent selected samples, and should not be taken as the susceptibility values, for the representative rock type in the Monrovia Quadrangle.

of the magnetic susceptibility of the rock. The magnetic susceptibility values determined in this study are given in Table 1 and the location of the samples used are shown in Figure 2. The susceptibility bridge used in this study was the model MS-3 made by Geophysical Specialities Company.

## Density of the Samples

The sample densities were determined to provide base information on the range and magnitude of the rock densities in the area. It was felt that this information would aid in the interpretation of the gravity survey data.

The densities of the samples used in this study were determined by dividing the weight in air by the loss of weight in water. For igneous and metamorphic rocks, this method presents no serious problems since the porosity of these rocks is very low. For sedimentary rocks, the density depends mainly on the amount of pore spaces and on the degree to which these pore spaces are filled with water.

Errors in the determination of densities of the samples could have come from one or both of the following sources.

1. Air bubbles were clinging to several of the rock samples when they were submerged for the measurements. The error due to this was minimized by allowing the sample to stay submerged for a period of time, during which time most of the bubbles broke loose from the sample and floated

to the surface. The bubbles that remained were removed with a small brush.

2. A few of the samples had surfaces that had developed a weathered crust. This problem was reduced mostly by chipping off the weathered surface with a rock hammer. Readings that might be in error due to this factor will appear with an asterisk to their upper right hand corner in the Appendix.

The estimated relative error based on five repeated measurements of the same sample, was found to be less than 1 percent. Densities obtained by the method described above are shown in Table 2 and for the location of samples used in the density determination refer to Figure 4.

## Opaques

The primary purposes for studying the opaques in the rocks were to look at the size of the magnetite grains, the degree to which these grains had altered, and the secondary minerals that had been produced by the alteration of the magnetite. It was hoped that these properties could be related to the magnitudes of the magnetic susceptibilities, and to the density ranges of the rocks studied.

The method chosen for this study was the point count method. The point count method, using transmitted light, allowed the estimation of the total opaques in the rock sample. The identification and degree of alteration

TABLE 2.--Density of Rocks in the Monrovia Quadrangle. The Estimated Relative Error Based on Repeatable Measurements is Less Than 1 Percent.

| Rock Type | Number of Samples | Density Range | Medium Density | Arithmetic Mean | Previous Investigator[b] |
|---|---|---|---|---|---|
| Granite Gneiss | 13 | 2.58-3.52[a] | 2.63 | 2.73 | 2.70 |
| Granite | 3 | 2.62-2.65 | . . | . . | 2.62 |
| Gneiss | 5 | 2.03*-2.86 | 2.81 | 2.63 | 2.68 |
| Metabasic 1[c] | 2 | 2.77-2.80 | . . | . . | 3.08 |
| Diabase | 8 | 2.92-3.42[a] | 3.04 | 3.08 | 2.97 |
| Gabbro | 2 | 3.05-3.07 | . . | . . | 2.94 |
| Chlorite Schist | 3 | 2.86-2.96 | . . | . . | . . |
| Hornblendite | 1 | 3.08 | . . | . . | . . |
| Norite | 1 | 3.00 | . . | . . | . . |
| Weathered-Quartzite | 1 | 2.95 | . . | . . | . . |
| Metabasic 2[d] | 12 | 2.96-3.23[a] | 3.03 | 3.05 | 3.07 |

[a]Value is unreliable.

[b]Samual Rosenblum (U.S.G.S.).

[c]Metabasic 1--locally called amphibolite is a dark gray, medium grained massive rock containing approximately equal amounts of plagioclase and hornblende.

[d]Metabasic 2--locally called granulite is a reddish gray, medium to course grained massive rock containing pyroxene, plagioclase and often garnet.

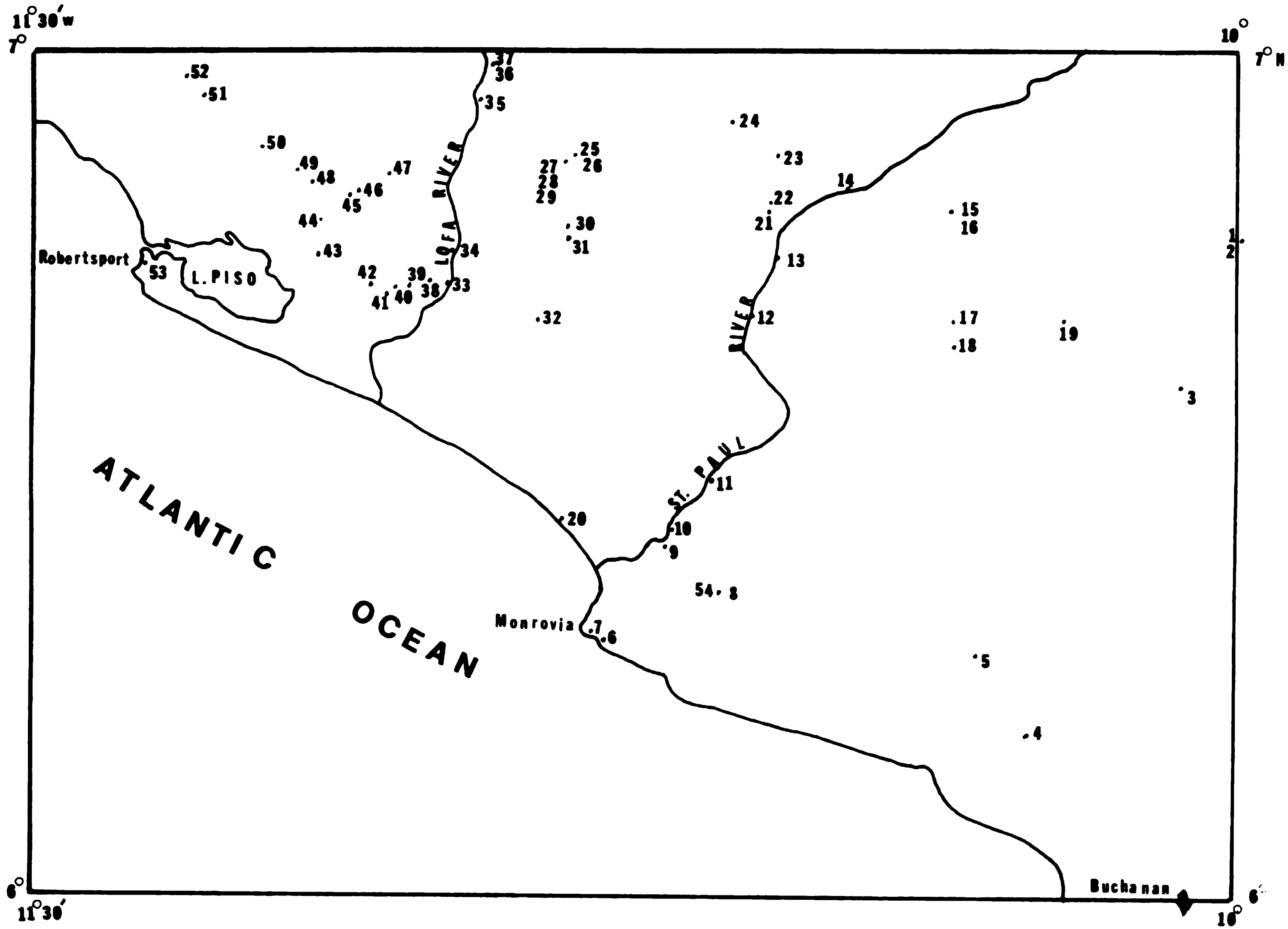


**Fig. 4** Monrovia Quadrangle Showing Sample Location Used In Density Determiations

of the opaques were then carried out using an ore microscope.

In the point count method both standard thin sections and thin sections made from rock cores were used in the estimation of the opaque percentages. Although the total average count for the core thin sections were about 750 as compared to 1000 for the standard thin sections, both results were placed on the same table.

After the counts were made, the thin sections were polished in order that the opaques be identified. The most abundant opaque identified was magnetite although in places it was almost completely altered to ilmenite. Ilmenite was the next in abundance followed by limonite or hematite. On one or two thin sections leucoxene was identified.

The quality of the standard thin sections, those made with Canadian Balsalm cement, deteriorated with polishing and therefore this made identification of the opaques harder. The polished thin sections made with epoxy cement were far superior for opaque identification.

This study shows that in general, the larger the grain size of the magnetite and the higher the total opaque percentage, the higher the magnetic susceptibility and density are likely to be. This does not appear to be a linear relationship since the ranges of densities and susceptibility differ widely with rock types. Specifically, the physical properties of individual rock samples may not individually correlate with gravity and magnetic fields, on the other hand, the ranges in the measured physical properties of these samples may be useful in the interpretation.

The percent opaques based on rock type can be found in Table 3 and Figure 5 shows the location of the samples used in this study. For the percentage of opaques of the individual rocks refer to the Appendix.

TABLE 3.--Percent Opaque According to Rock Type. Tr. is Less Than 1 Percent.

| Rock Type | Number of Samples | Range of Opaque Percentages | Medium Value | Arithmetic Mean |
|---|---|---|---|---|
| Granite Gneiss | 7 | Tr.-4.4 | .5 | 1.48 |
| Granite | 1 | Tr. | . . | . . |
| Gneiss | 5 | Tr.-3.0 | .2 | .78 |
| Metabasic 1[a] | 1 | 4.06 | . . | . . |
| Diabase | 10 | 1.9-9.4 | 3.82 | 3.88 |
| Gabbro | 2 | 8.68-8.80 | . . | . . |
| Chlorite Schist | 2 | Tr. | . . | . . |
| Hornblendite | 1 | .2 | . . | . . |
| Norite | 1 | 2.5 | . . | . . |
| Weathered-Quartzite | 1 | 6.58 | . . | . . |
| Metabasic 2[b] | 7 | Tr.-4.4 | .66 | 1.77 |

[a]Metabasic 1--locally called amphibolite, is a dark gray, medium grained massive rock containing approximately equal amounts of plagioclase and hornblende.

[b]Metabasic 2--locally called granulite, is a reddish gray, medium to course grained massive rock containing pyroxene, plagioclase and often garnet.

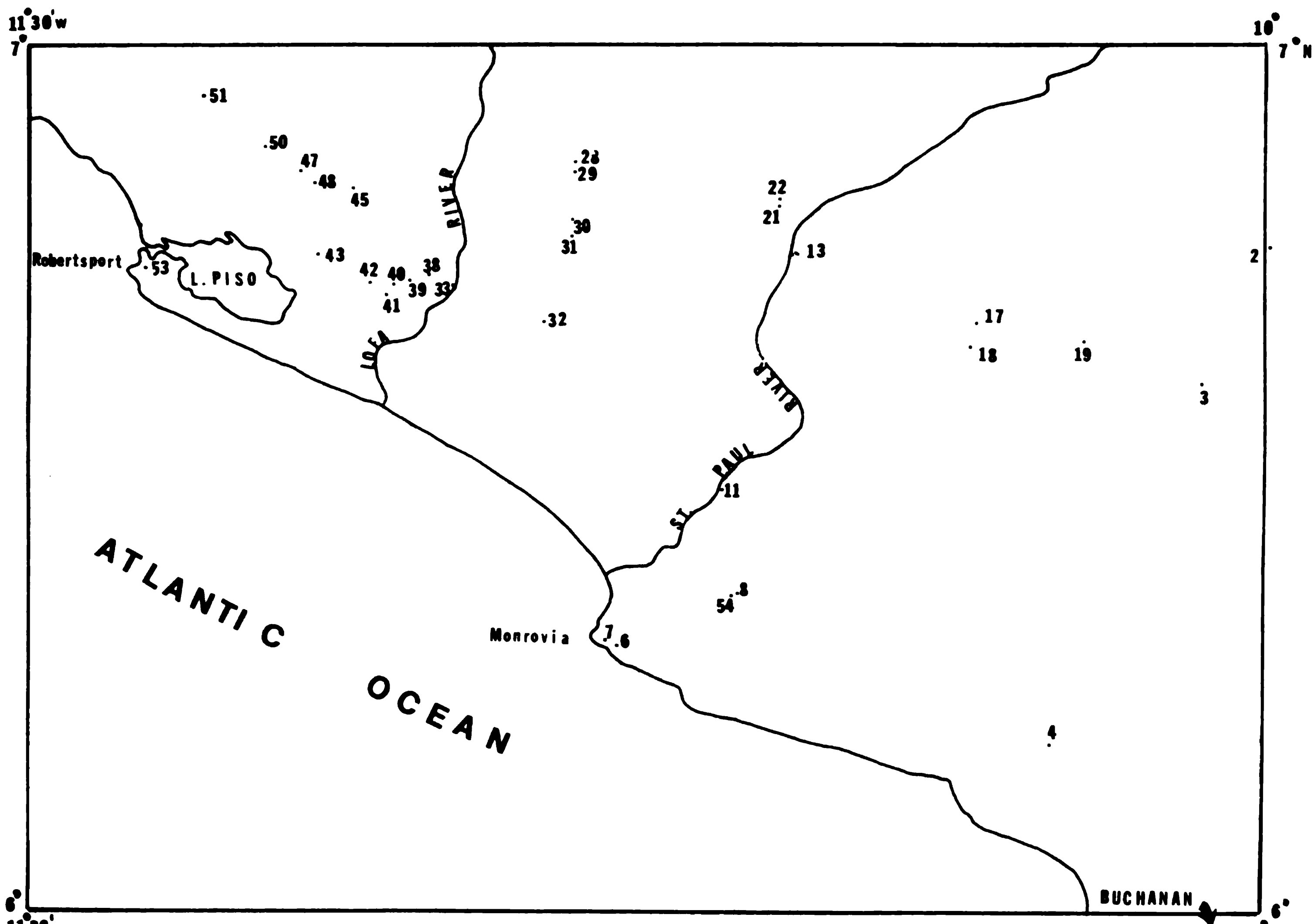


Fig. 5 Monrovia Quadrangle Showing Sample Location For Opaques

# CHAPTER III

# GEOPHYSICAL DATA

## Previous Geophysical Investigation

The geophysical data used in this study have been compiled and briefly discussed by J. C. Behrendt and C. S. Wotorson in several reports put out from 1969 to 1972. The geophysical work covered in these reports include magnetics, gravity and radiometrics. All of the geophysical maps with the exception of the residual bouguer anomaly map, which appear at the end of this study, have been taken from their reports. For the methods used in the reduction of the geophysical data and the compilation of the maps, refer to Behrendt and Wotorson (1969-1972). Some off-shore geophysical data was collected by the U.S.C.G.S. Discoverer in 1968 but will not be discussed in this study (Behrendt and Wotorson, 1972). For reference to the geophysical maps, see the back folder.

## Magnetic Survey of the Study Area

The aeromagnetic map of the Monrovia Quadrangle (Figure 6, back folder), can be divided into four provinces, based on the amplitudes of the magnetic anomalies in the areas. Two provinces have high magnetic amplitudes, one in the southeastern section of the quadrangle, and the other in the northern section. The third province is an area of rather low amplitude magnetic anomalies, and is found in the central portion of the quadrangle. The fourth province is off-shore and is characterized by reasonable high amplitude, very broad anomalies.

In the northern province the high amplitude, rather narrow magnetic anomalies lie mainly over the Bong Mines and the Bomi Hills mining districts. The trend of the iron formations is mainly east-west with a slight change to a north-eastern trend in the eastern part of the quadrangle. Most of the high amplitude anomalies are caused by the magnetite itabirite and not the ore itself (Behrendt and Wotorson, 1972). Due to these high east-west trending anomalies, the anomalies caused by the lower amplitudes northwest trending diabase dikes are not easily seen, and in many instances are completely lost in the anomalies caused by the itabirites. Within this province there are two areas of low amplitude anomalies, one just north of Bong mines, and the other north-west of the Bomi Hills.

The central province is characterized by rather low amplitude anomalies and here the north-west trending dikes can easily be observed since their amplitudes are higher than the background noise. It is in the eastern portion of this province that the Gibi dike can best be seen. This dike, passing through the Gibi Mountain, is the longest continuous dike in the country.

The most noticeable features in the southeastern province are the Goe-Fantro Ranges. Thorman (1972), described these rocks as being hematite and magnetite itabirites that are associated with quartzite, schist and amphibolite. Two low amplitude anomaly areas can be found in this province, one just south of the Fantro Range and the other just south of Roberts Field. On the western side of this province is an anomaly, called Anomaly A (Behrendt and Wotorson, 1971a). This anomaly is the longest north-east trending linear feature in this province. Northeast of the Goe Range there is a low amplitude northeast trending feature, which might be the continuation of Anomaly A on up through the central province and into the Gibi mountains. A large section of the Fantro Range has the same northeast trend and along with Anomaly A, these features might be controlled by a northeast trending fracture pattern in this area. In Chapter IV, portions of this area are more fully discussed.

The seaward province has reasonably high amplitude, rather broad anomalies. It is interesting to note, that there seem to be an equal distribution of high and low anomalies, having no preferred trends. Because of the broadness of these anomalies, their sources are probably rather deep. From the general pattern of these anomalies, and the fact that they have no preferred orientation, one might conclude that the basement is rather complexly faulted. There are no radiometric or gravity data available for this province. This province, will not be discussed hereafter.

## Residual Magnetic Map of the Area

The residual map (Figure 7) shows the effects of broad features and because of this, it tends to show only the effect due to the influence of deeper bodies. It is not surprising then, since the aeromagnetic map shows mainly shallow features, that these two maps are somewhat dissimilar.

Two rather small northwest trending features appear on the residual map just northeast of Monrovia. On the aeromagnetic map these are the two low amplitude linear features that appear in this area. Behrendt and Wotorson (1971a), attributed them to shallow diabase dikes. These features however are the only two diabase dikes that have a correlatable linear feature on the residual map. This might indicate that these dikes are either much deeper than previously believed, or that they are the single surface exposure of a dike swam that exist at depth. The low residual value in the area of Roberts Field corresponds to one of the low amplitude areas described above on the aeromagnetic map.

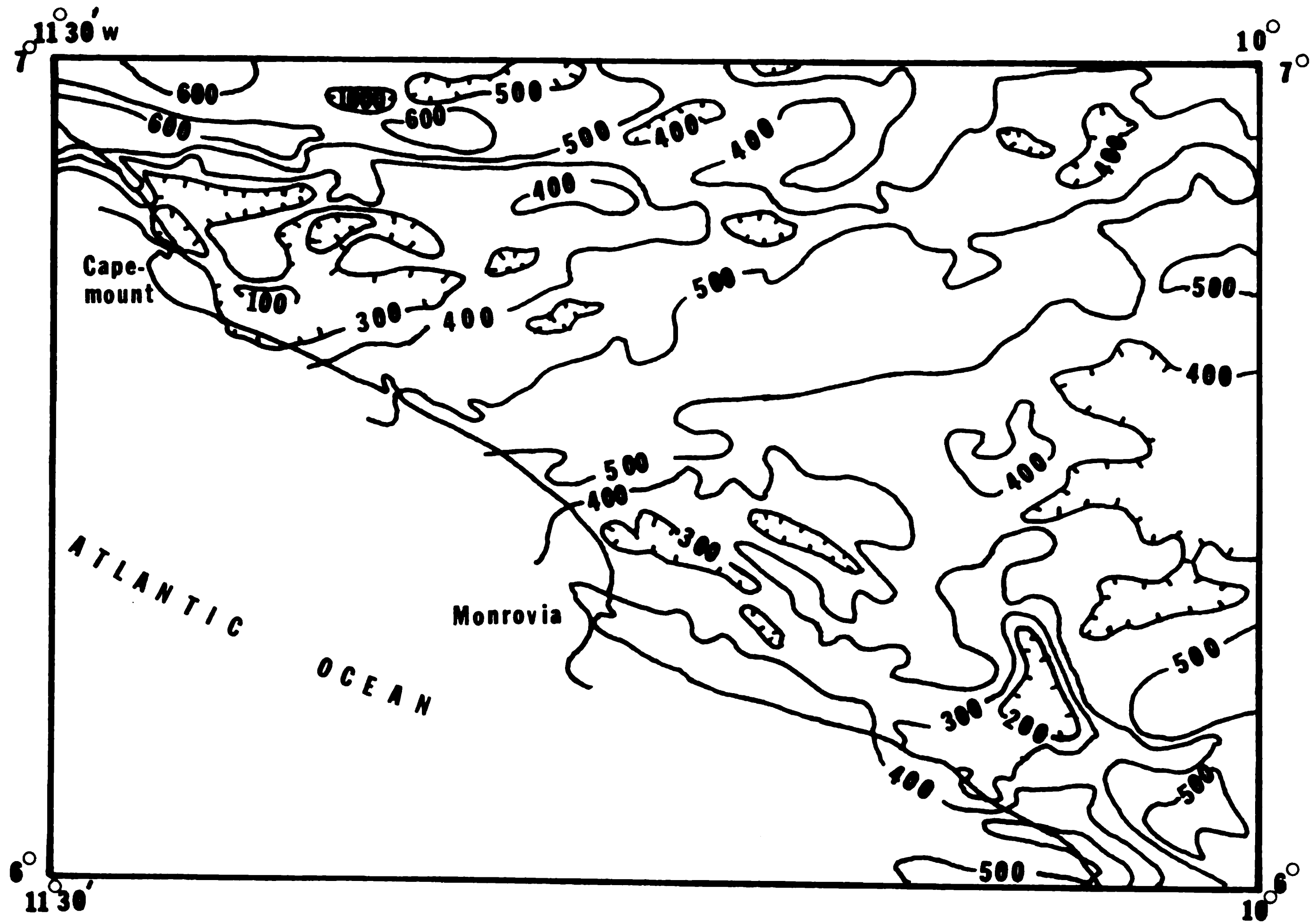


**Fig. 7** Residual Total Magnetic Intensity Map
From Behrendt and Wotorson, 1971a
Units In Gammas

In general, there are slight indications that the Northeast and Northwest trends that exist on the aeromagnetic map also exist on the residual map. This would indicate that these trends extend reasonably deep in the crust and are probably the reflection of gross tectonic patterns in the crust.

## Gamma Radiation Survey of the Area

The radiometric method is based on the detection of naturally occurring isotopes of K, U and Th. In general, the higher radioactive counts, those above 250 c.p.s., are in the area of the granite gneiss. This area is located toward the eastern portion of the quadrangle (Figure 8 back folder).

In areas where the rocks are mainly sedimentary, iron formations, granulites or other mafic rocks, the general count is less than 250 c.p.s. In the areas of low background counts, the low readings caused by the iron formations and dikes, are masked much like the high magnetic values of the dikes were masked by the even higher magnetic values of the itabirite.

The highest radiometric readings in the quadrangle, are those in the north central portion and those north of the Fantro Range. The high radiometric values that are north of the Fantro Range are in the vicinity of the lower portion of the broad gravity low that is found on the eastern side of the Bouguer Anamaly map (Figure 9 back folder). The rocks in this area would probably be high in feldspars and low in mafic minerals, since a highly feldspathic granite gneiss would tend to be less dense than granite gneiss containing amphibolites, thus explaining the low anomaly area on the Bouguer anomaly map.

The high north central values have been attributed to monazite and zircon by Behrendt and Wotorson (1971b). The high values north of the Fantro Range correspond to an area of low magnetic readings which might indicate that this area has highly felsic rocks.

The narrow anomalies that are seen along the St. Paul River and the local highs along the beach, have been attributed to clay deposits and black sands respectively (Blade, 1970; Behrendt and Wotorson, 1971b). The black sands contain zircon and monazite (S. P. Srivastawa, personal communication, 1971).

## Gravity Survey of the Study Area

The Bouguer anomaly map and the Residual Bouguer anomaly map can both be found in the back folder and are numbered Figure 9 and Figure 10 respectively. The Free air anomaly map Figure 11 is found below.

### Bouguer Anomaly Map

In the compilation of the Bouguer anomaly map, terrain corrections were not made because of the lack of topographic maps, but should be less than 1 mgal (Behrendt and Wotorson, 1972).

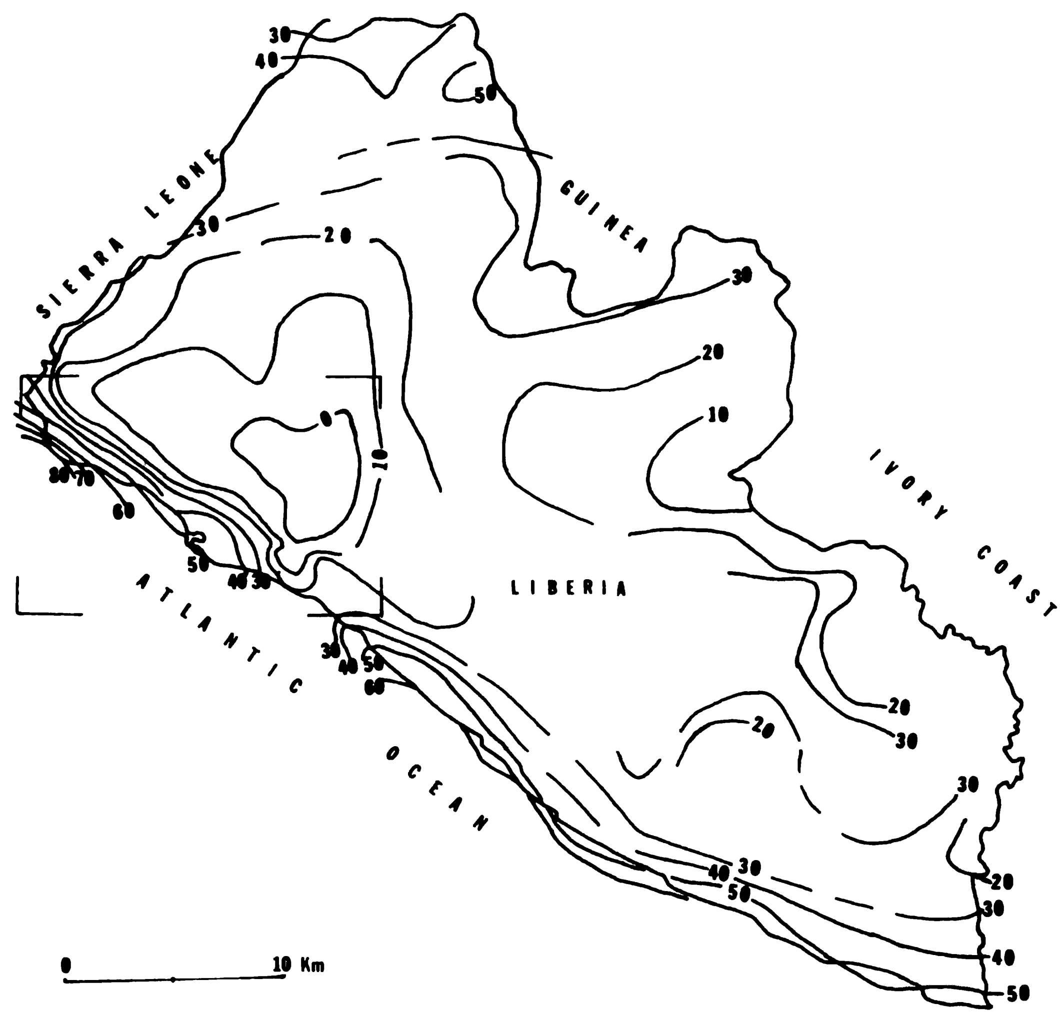


**Fig. 11** Free Air Anomaly Map Of Liberia
From Behrendt and Wotorson, 1972 Values In Milligals
[ ] Monrovia Quadrangle

There are four easily noticeable features on this map. The first is the 40 to 50 milligal feature which runs parallel to the coast all the way from Sierra Leone down through the southeastern section of this quadrangle and into the Ivory Coast. Behrendt and Wotorson (1971) wrote, "this feature has a gradient of 3 to 4 milligals / km, in the area between Sierra Leone and Buchanan, which is too steep to be more than partially the result of crustal thickening at the continental margins." This anomaly they feel is the result of uplift of granulite from deep within the crust.

A second area of notice is the broad low gravity area found on the eastern side of the quadrangle. The gravity data in this area of the quadrangle, are too sparse for one to come up with any definite conclusions as to the origin of this feature. However, it is probably the result of a granite gneiss which has a lower density than the surrounding rocks. The radiometric values in this area show that the rocks are probably highly felsic, and if these rocks are also low in density, they could be responsible for the lower portion of the broad, low Bouguer gravity anomaly. On the free-air anomaly map (Figure 11), this second area is coincidental with an area of relatively low contour values. The area is probably the only area in Liberia that is in isostatic equilibrium and this might also be due to the lower density granite gneiss.

The third feature that comes to ones' attention is the well defined gravity low that is known as the Roberts Basin. A model study of this structure (Behrendt and Wotorson, 1972) show that it is a down faulted basin filled, to a considerable depth, with cretaceous sediments.

The anomaly at Cape Mount is the fourth major anomaly found on the Bouguer anomaly map. This feature will be discussed in Chapter IV. There are several areas on the Bouguer anomaly map that show the contour widening or closing and a few of these areas will also be discussed later. Even though the station density is greater along the coast than inland, in general, it appears that the anomalies inland are broader than those along the coast. From this one might conclude that the sources producing the anomalies are shallower near the coast.

## Free-Air Anomaly Map

Free-air gravity anomalies are best suited for studying tectonic adjustments since they do not take into account the gravitional attraction due to the mass included between sea level and the elevation of the observation site. Therefore they become first approximations to the isostatic map. The Free-air anomaly map of Liberia (Figure 11) (Behrendt and Wotorson, 1972) shows that the coastal feature present on the Bouguer anomaly map is also present on the Free-air anomaly map. Behrendt and Wotorson (1972), found that the calculated mean free-air anomaly for the entire country is + 26 milligals, but because the coastal gradient might have biased the value, the area of steep gradient was left out and they came up with an average mean of + 22 milligals. This value of + 22 milligals would mean that although locally there might be isostatic equilibrium, for example the broad low free-air gravity area, the general area of Liberia is essentially isostatically under compensated. The reason for this might be that the uplifted basement material has not been compensated for at depth. Assuming that coastal adjustments to a free-air anomaly of 0 milligal requires a downward movement of approximately 500 feet, and that this calculation assumes a mantle density of 3.3 gm/cc, the resulting elevation after isostatic adjustment would be approximately 100 feet. This value corresponds to a coastal thickness of about 32 km based upon Woollard's curve (Woollard, 1959). The above calculation uses an estimated mean elevation for Liberia of 600 feet (Behrendt and Wotorson, 1972).

## Residual Gravity Map of of the Study Area

Many anomalies caused by near surface geologic bodies are often found superimposed on anomalies (or gradients) that are caused by large deep seated structural features. The magnitude and direction of the regional gradient depends entirely on depth, distance and configuration of the large structural features involved.

There are several sources of regional gravity variations. "In addition to large-scale geologic structures, there are density effects caused by intrabasement lithologic changes as well as isostatic variations which may often be indeterminate" (Dobrin, 1960).

In order to interpret near surface geology, the gravity anomalies caused by these features must somehow be removed from the regional background (Grant and West, 1965). Methods, such as the direct computation of the residual using a grid system, and graphical methods have been proposed for taking out the regional. The method chosen here, is a graphical method known as cross-profiling. For best results, one set of profiles should be drawn perpendicular to the direction of steepest gradient and the second set parallel to the gradient. In this study, the profiles were drawn along lines that represented reliable control points and not necessarily along lines that were perpendicular to each other.

The process involves smoothing out the profiles and being certain that where profiles cross the smoothed values are the same. According to Grant and West (1965), "This method has the merit of being highly flexible, since it allows the interpreter to incorporate into the process his personal judgment, or sense of 'rightness' about the forms of the residual anomalies."

More than 16 profiles were made, but only a few of them will be presented here. Figure 12 shows the

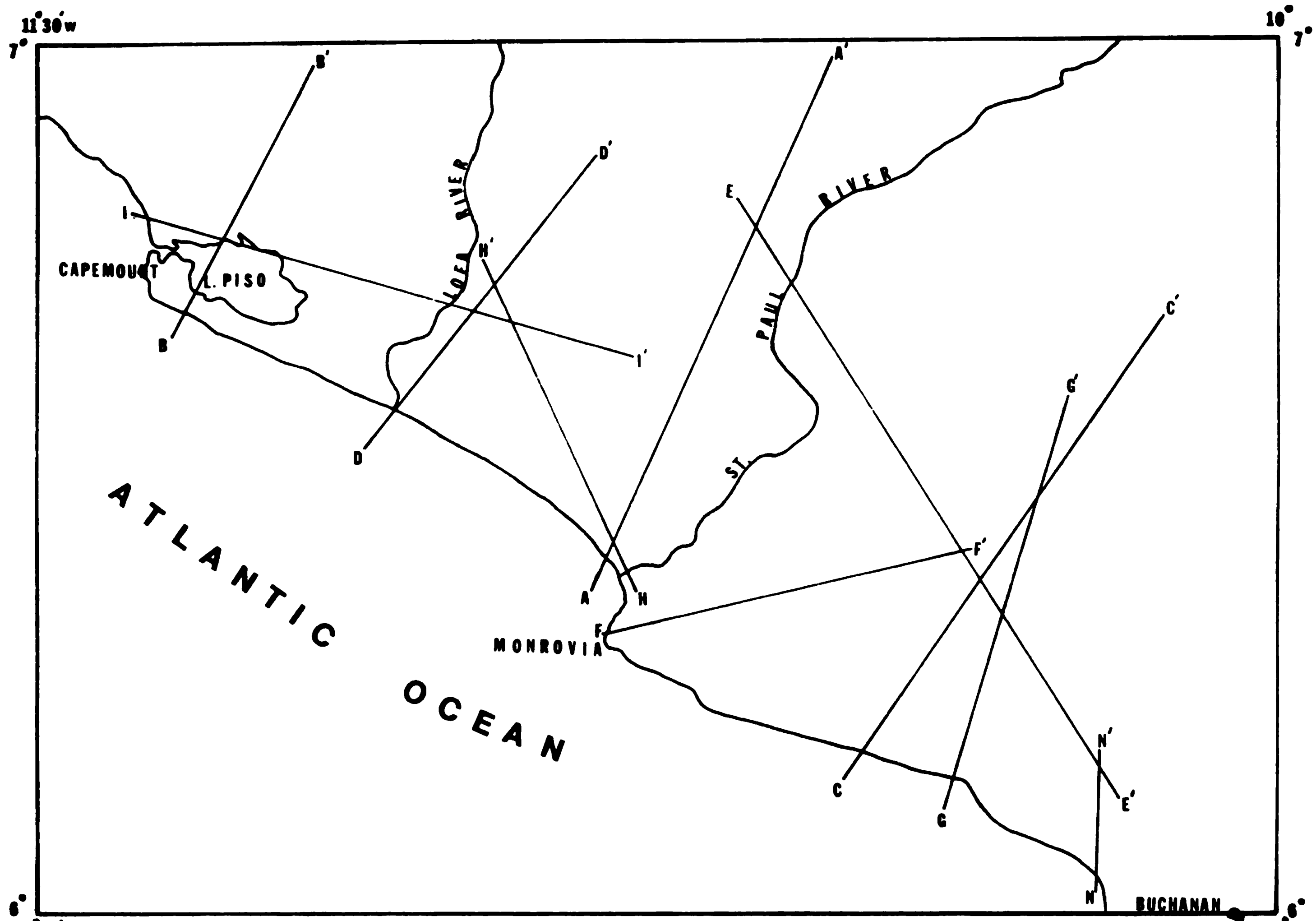


Fig. 12 Monrovia Quadrangle Showing Profiles Used In Making The Regional Gravity Map

location of the profiles presented in this study. In using results from the cross-profile method, one must always keep in mind that the removal of the regional is purely an interpretive process, and there is no unique solution. Because of this fact, the interpretation based on a residual obtained by this method, could be somewhat different than one obtained by another method. Admittedly this method might introduce error in the interpretation, therefore this must be kept in mind. Figure 13 through Figure 16 are profiles obtained by the cross-profiling method. The difference between the observed curve and the smoothed out curve was plotted and contoured to give the residual gravity anomaly map (Figure 10 see back folder).

The residual Bouguer gravity anomaly map has brought out several anomalies which are not readily apparent on the Bouguer anomaly map. An example is anomaly 3, Figure 10. This anomaly although slightly visible on the Bouguer anomaly map has been more definitely defined by the cross-profiling method. On Figure 10, the anomalies labeled 1 to 5 are interpreted in Chapter IV but those labeled A to E will be briefly discussed here.

Between the Roberts Basin and Robertsport, the steep gradient of the gravity contour on the Bouguer anomaly map, appears to have caused the anomalies that appear on the residual Bouguer anomaly map, to be shifted slightly northward from where they appeared on the Bouguer anomaly map. A good example is anomaly 3 which on the

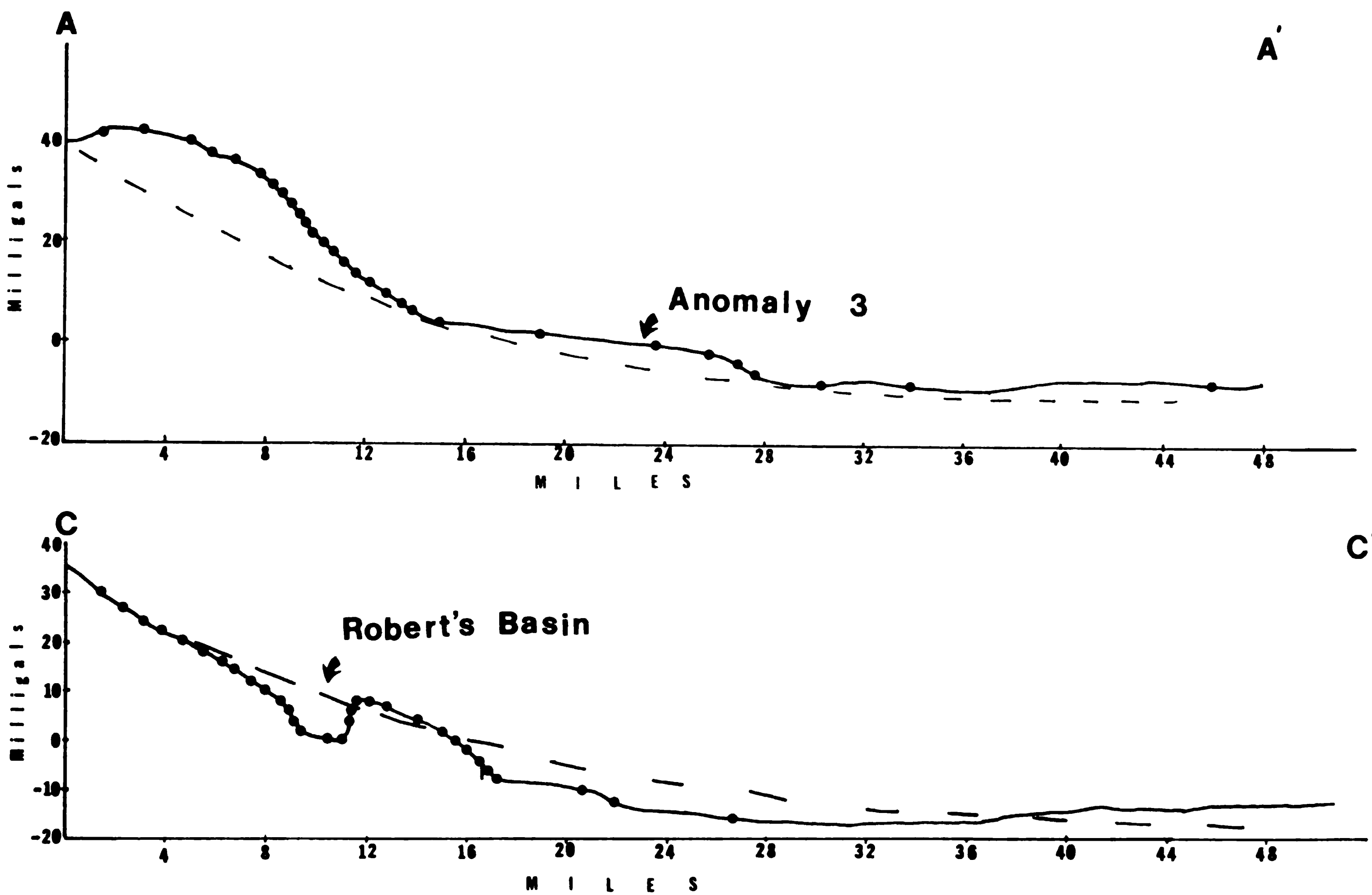


Fig. 13 PROFILES AA' and CC' --- Regional —— Observed

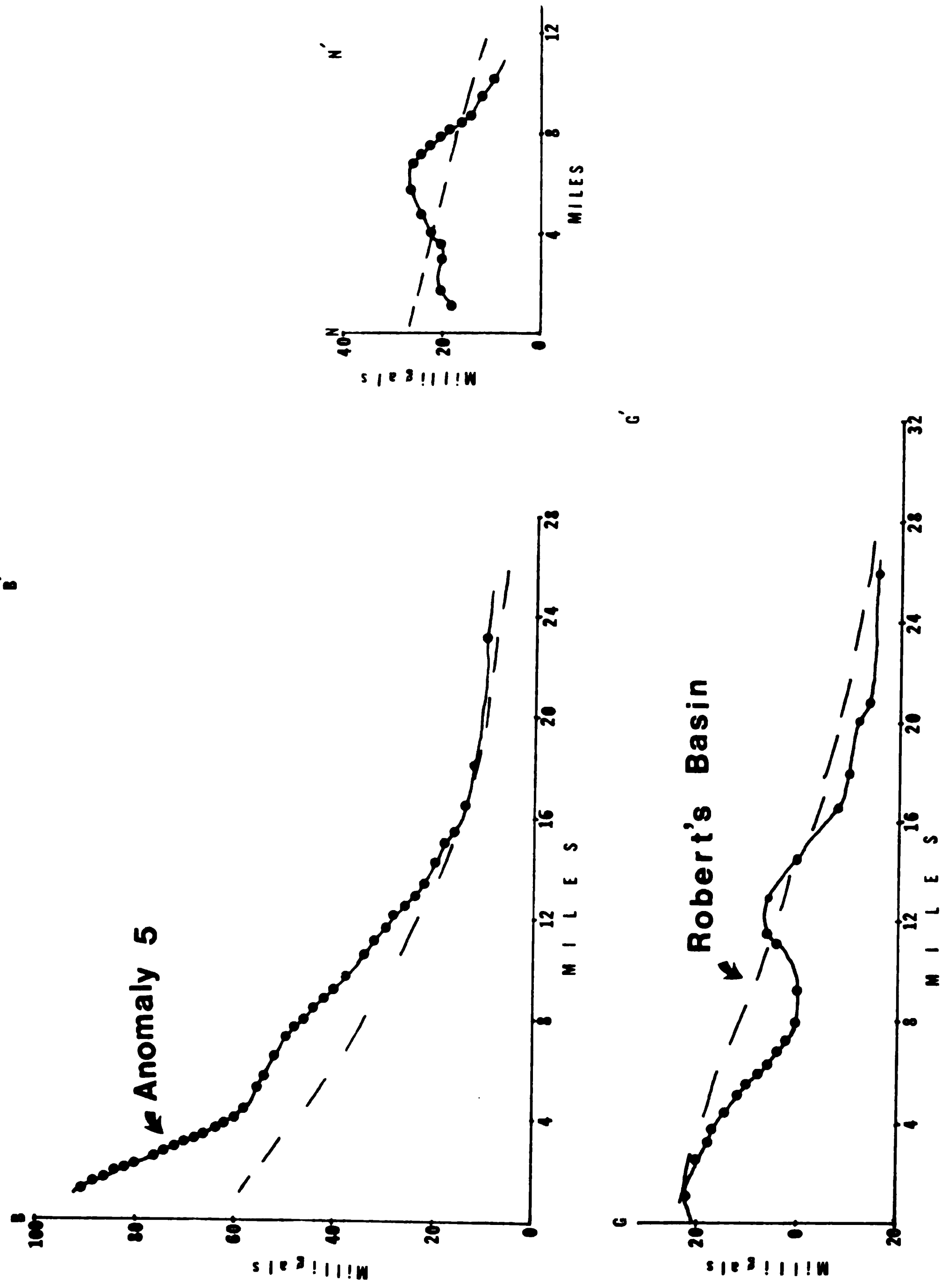


Fig-14 Profile BB', GG' and NN' — — — Regional ——— Observed

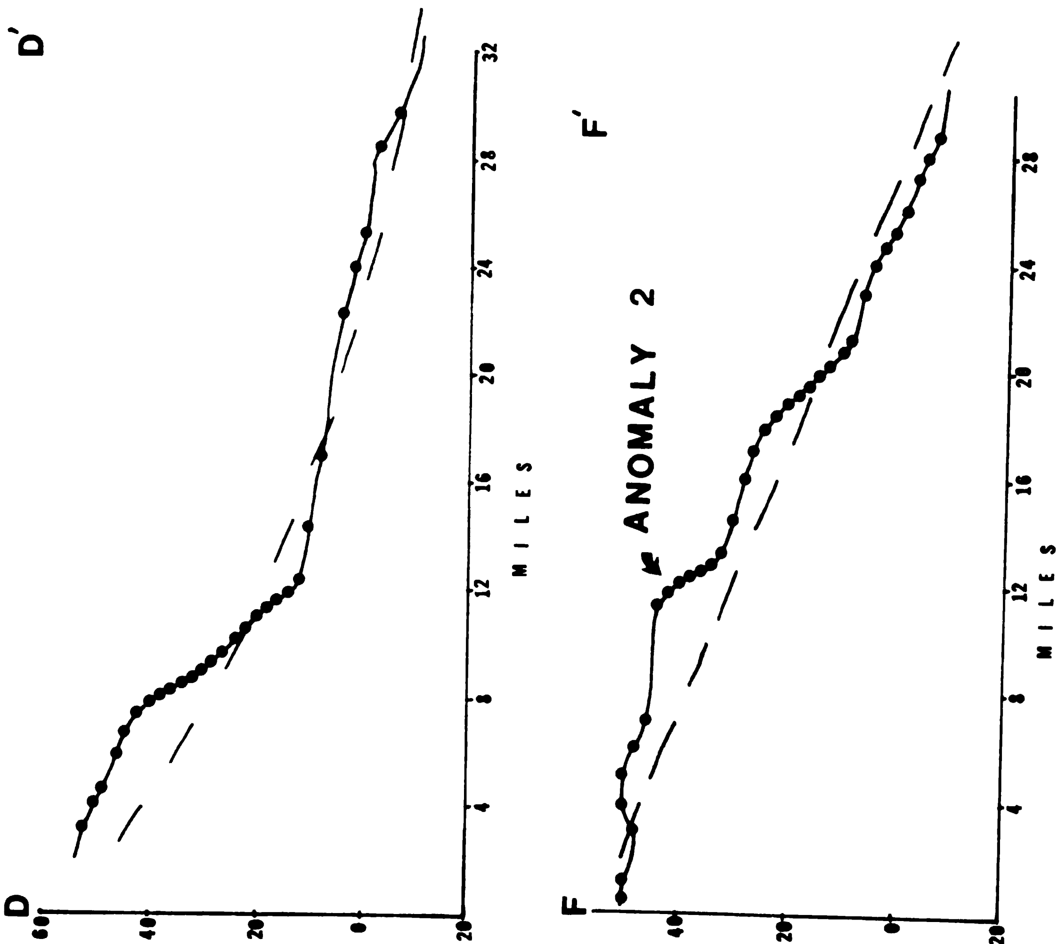


Fig. 15 Profiles DD' and FF'

— — Regional
—— Observed

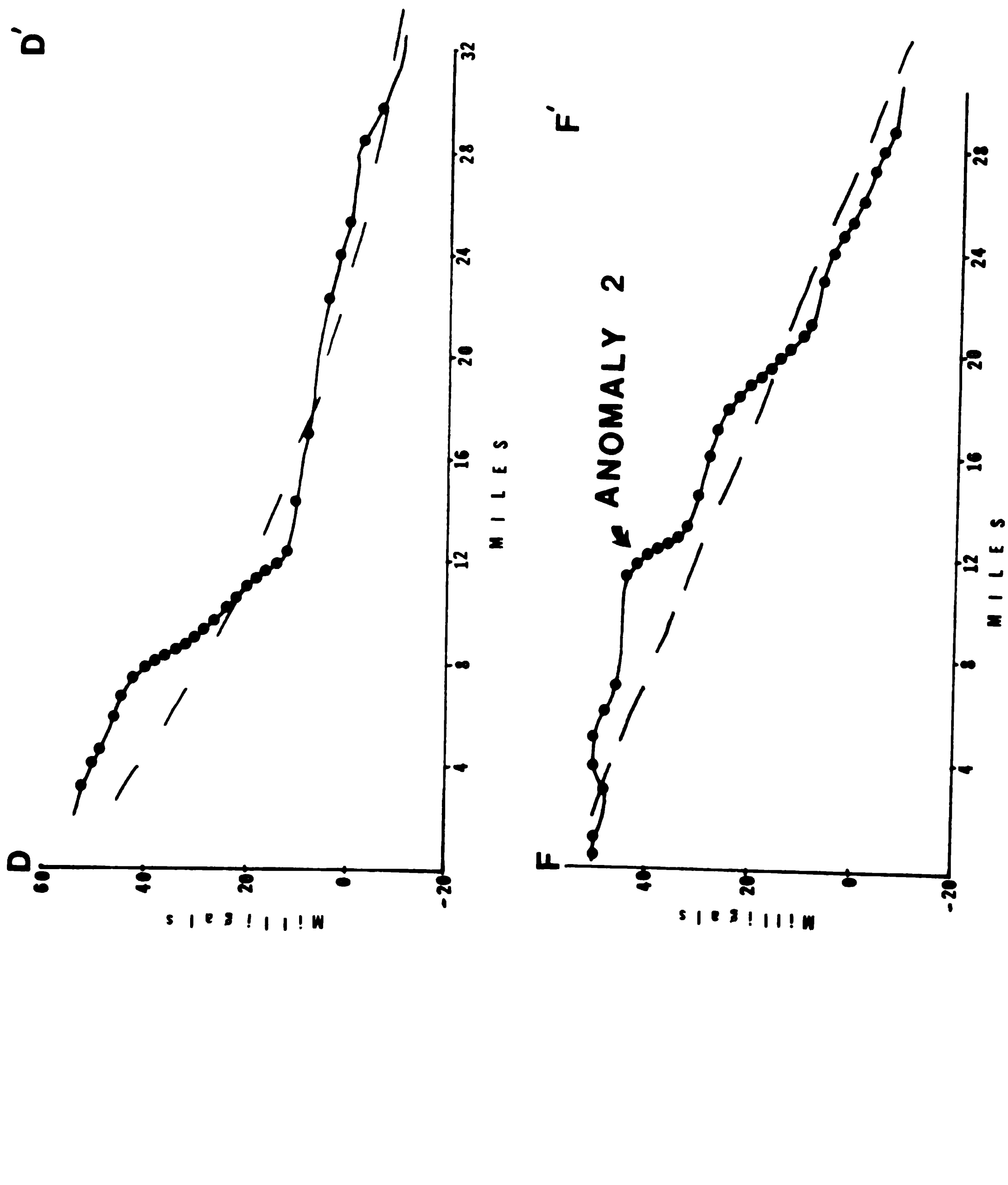


Fig. 15

Profiles DD' and FF'

— — Regional
—— Observed

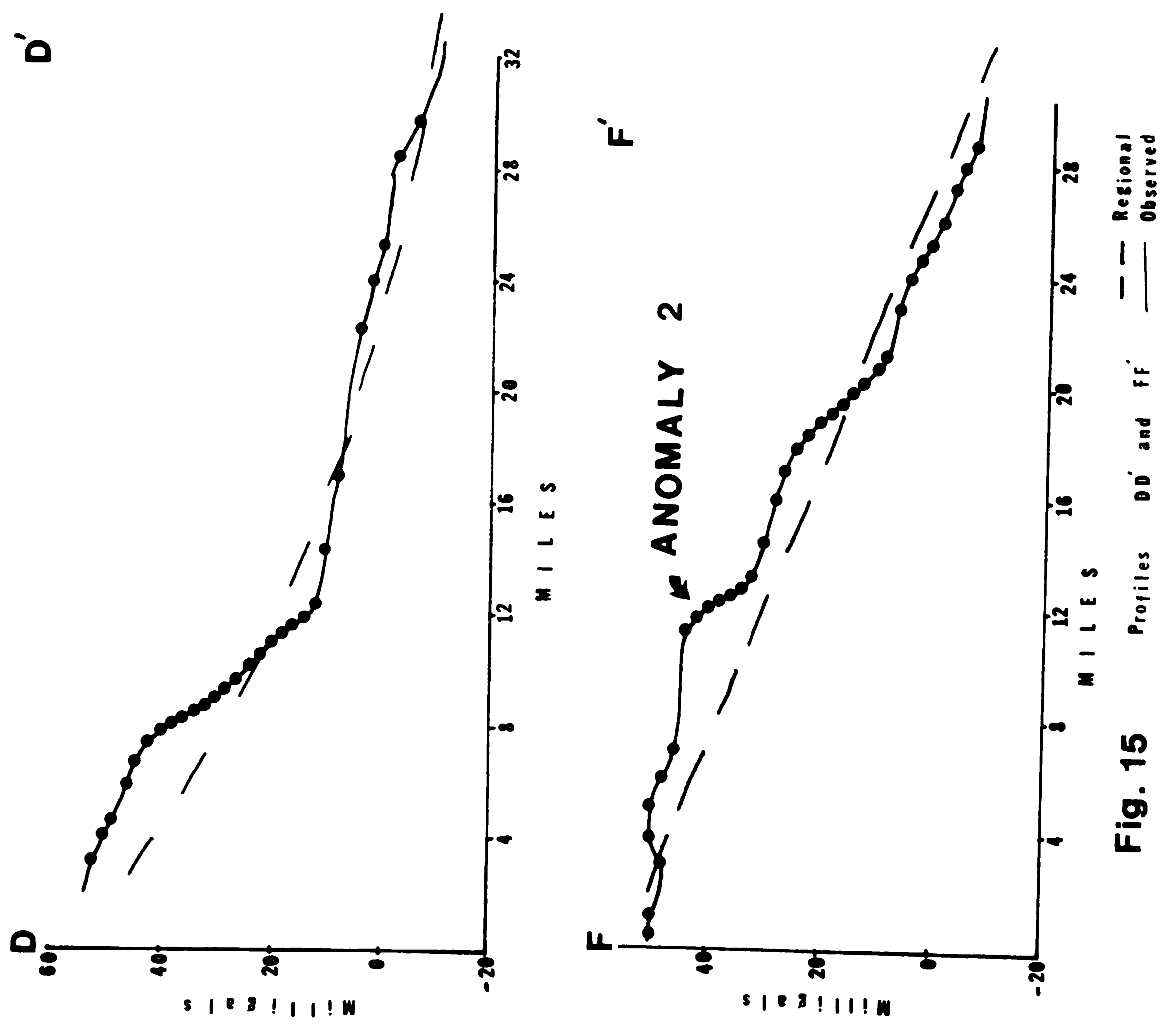


Fig. 15 Profiles DD' and FF'

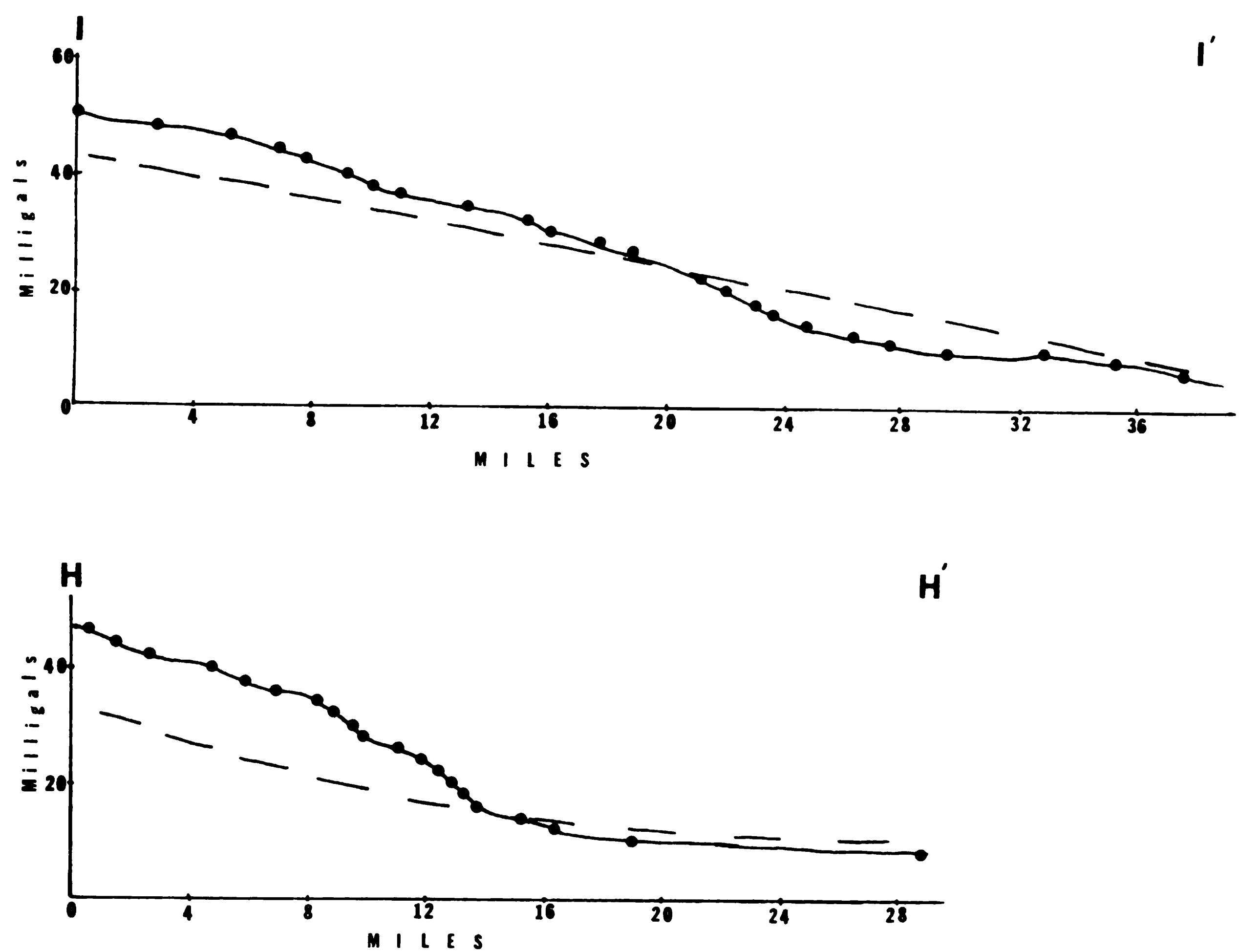


**Fig. 16** Profiles II′ and HH′ — — — Regional ——— Observed

Bouguer anomaly map is centered about 25 miles north of Monrovia whereas on the residual Bouguer anomaly map its center is almost five miles further north.

Anomaly A and B are two anomalies that are not visible on the Bouguer anomaly map. They are probably the result of an area within the granulite that have a slightly lower density. Anomaly C has been interpreted by Behrendt and Wotorson (1971c), as being caused by a down faulted block in which there has accumulated a large thickness of sediment. Anomaly D also like C, is probably caused by a down faulted block in which sediments have accumulated, but not to the thickness of those found at anomaly C. On the residual total magnetic intensity map of the area anomaly D is vaguely delineated by a small saddle in the contour lines. Anomaly E is found a few miles north of Monrovia and is probably another one of these down faulted sediment filled basins.

## Comparison of the Physical Properties Determined From the Rock Samples With the Aeromagnetic and Gravity Maps

In general the magnetic susceptibilities, densities and percent opaques for individual samples, did not correlate with the magnetic or gravity patterns in the study area. In the next two sections, these discrepancies and possible reasons for them are discussed.

Relationship of Opaques to Magnetic Susceptibility Values, and Magnetic Susceptibility Values to the Aeromagnetic Map

The values of magnetic susceptibilities are found in Table 1 and show the following relationships. The magnetic susceptibility values less than 1900 x $10^{-6}$ c.g.s. seem to be restricted to the granite gneiss and granulite zones. The granite gneiss zone on the aeromagnetic map is in the low amplitude central province. The lowest value of 20 x $10^{-6}$ c.g.s. is the measured susceptibility of a granite which is one of the host rocks at the Bong Mine iron mine. The granulites have susceptibilities that range from (125 to 1678) x $10^{-6}$ c.g.s. These rocks are the most uniform in their susceptibility values. This might explain why on the aeromagnetic map, the magnetic values are so smooth over the area that has been mapped as granulite (White and Leo, 1969). The magnetite in most of the granulites is highly altered, mostly to ilmenite. The grain size of the opaques are also relatively small compared with those of most of the diabases or gabbros. These two reasons probably explain the low susceptibilities of these rocks.

The amphibolites have an average susceptibility that is considerably higher than the granulite. The range is from (1668-4239) x $10^{-6}$ c.g.s. and it would seem that any model that would explain the origin of these rocks must also explain this difference. The grain size of some opaques in these samples are also larger than those in the granulite. The norite body at Cape Mount has a susceptibility of about 1728 x $10^{-6}$ c.g.s.

The highest values obtained in the susceptibility measurements were those from the highly mafic diabases and gabbros. The average values here were 4402 x $10^{-6}$ c.g.s. and 5685 x $10^{-6}$ c.g.s. respectively. It was among these rocks that the highest opaque percentages and largest magnetite grains were found. The scatter for the diabase was much greater than that for the gabbro. This is probably because the opaques in the diabase show a greater degree of weathering.

There are some correlations between the aeromagnetic map and the high and low susceptibility values. The best examples are found over the diabase dikes where aeromagnetic highs correlate with high susceptibilities. In places however, where there are low amplitude aeromagnetic anomalies, there are some high susceptibility values. Probably this is because the sample represents a very narrow diabase dike which, although large enough to provide an outcrop, is too small to give an aeromagnetic anomaly. Behrendt and Wotorson (1970), wrote, "Some exposed dikes have no magnetic anomaly due to their limited extent and many of the 'dikes' are shown where there are no known exposures." This statement might also explain why there are low susceptibility values where there are aeromagnetic highs. In general it was found that there was not as good a correlation of sample susceptibility and opaques, with the aeromagnetic map as was expected at the beginning of the study. However, the above observation by Behrendt and Wotorson may help to explain this discrepancy.

### Relationship of the Opaques to Density and Densities to the Gravity Maps

The density values obtained in this study (Table 2) show a good correlation with a similar study performed by Samuel Rosenblum of the U.S.G.S., however there does seem to be a difference in the densities determined for the amphibolites. His value of 3.08 gm/cc is probably more correct since he used many more samples than were used in this study. In general the samples with greater percentages of opaques (Table 3) had higher densities but since the degree of weathering of the opaques varies with rock type and even within the same rock type, the relationship of high opaque percentage with high density samples was found to be unreliable at times.

It was also found that in general sample densities show no correlation with high and low anomalies on the Bouguer and residual Bouguer anomaly maps. Some places where there are high density values there are low gravity anomalies and vice versa. Unlike the aeromagnetic anomalies, the anomalies on the gravity maps are broader and this is probably why the density values show poor correlation. For example, one sample might not represent the overall density of the rocks in an area. Another explanation for this inconsistency is that the surface rock type or density might differ from those at depth. For example, if a surface rock such as quartzite with a density of 2.68 gm/cc is underlain by a granulite with a density of 3.1, the gravity anomaly in this area would not be representative of what is expected of the quartzite. A third explanation for the inconsistency of the gravity maps with the rock densities is that the surface samples have had their densities decreased due to weathering.

## CHAPTER IV

## INTERPRETATION

### Introduction

Several anomalies within the Monrovia Quadrangle have been briefly discussed by Behrendt and Wotorson (1969 through 1972). These authors have discussed the Roberts Basin anomaly in detail but have hardly mentioned the others that are in the quadrangle. In this study, six anomalies labeled 1 through 6 in Figure 17, excluding the Roberts Basin anomaly have been studied and given a geological interpretation. All of the geophysical maps used in this study are found in the back folder.

### Anomaly 1

Anomaly 1 (Figure 17) is located on the Bouguer anomaly map (Figure 9, back folder) at latitude 6 degrees 30 minutes north and longitude 10 degrees 53 minutes west. On the Bouguer anomaly map anomaly 1 is recognized by a slight negative gravity nose facing a southerly direction. The nose is recognized by the spreading of the contour lines that form it. On the residual Bouguer anomaly map (Figure 10), anomaly 1 is more clearly defined by a

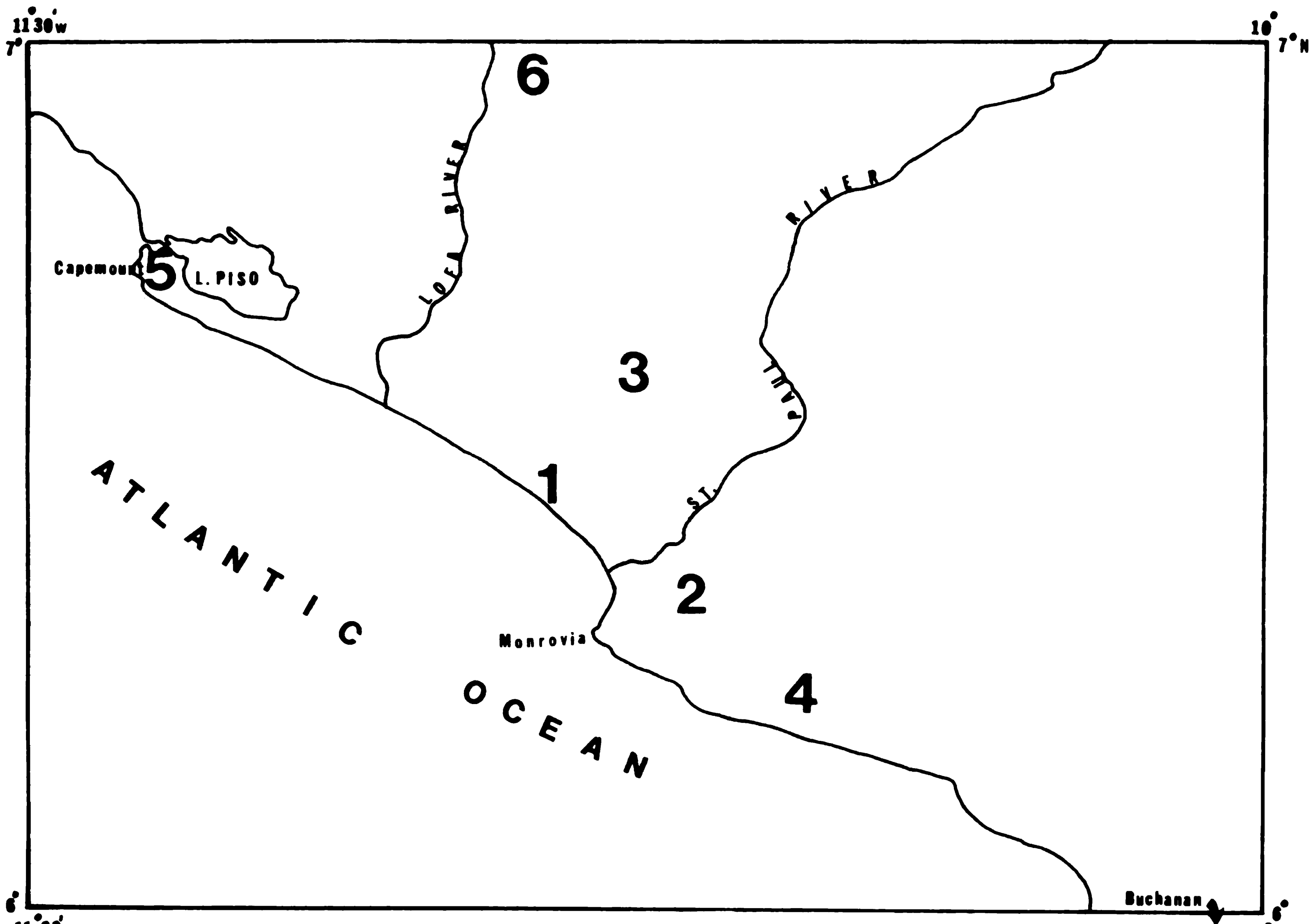


**Fig. 17** Monrovia Quadrangle Showing Anomalies Locations

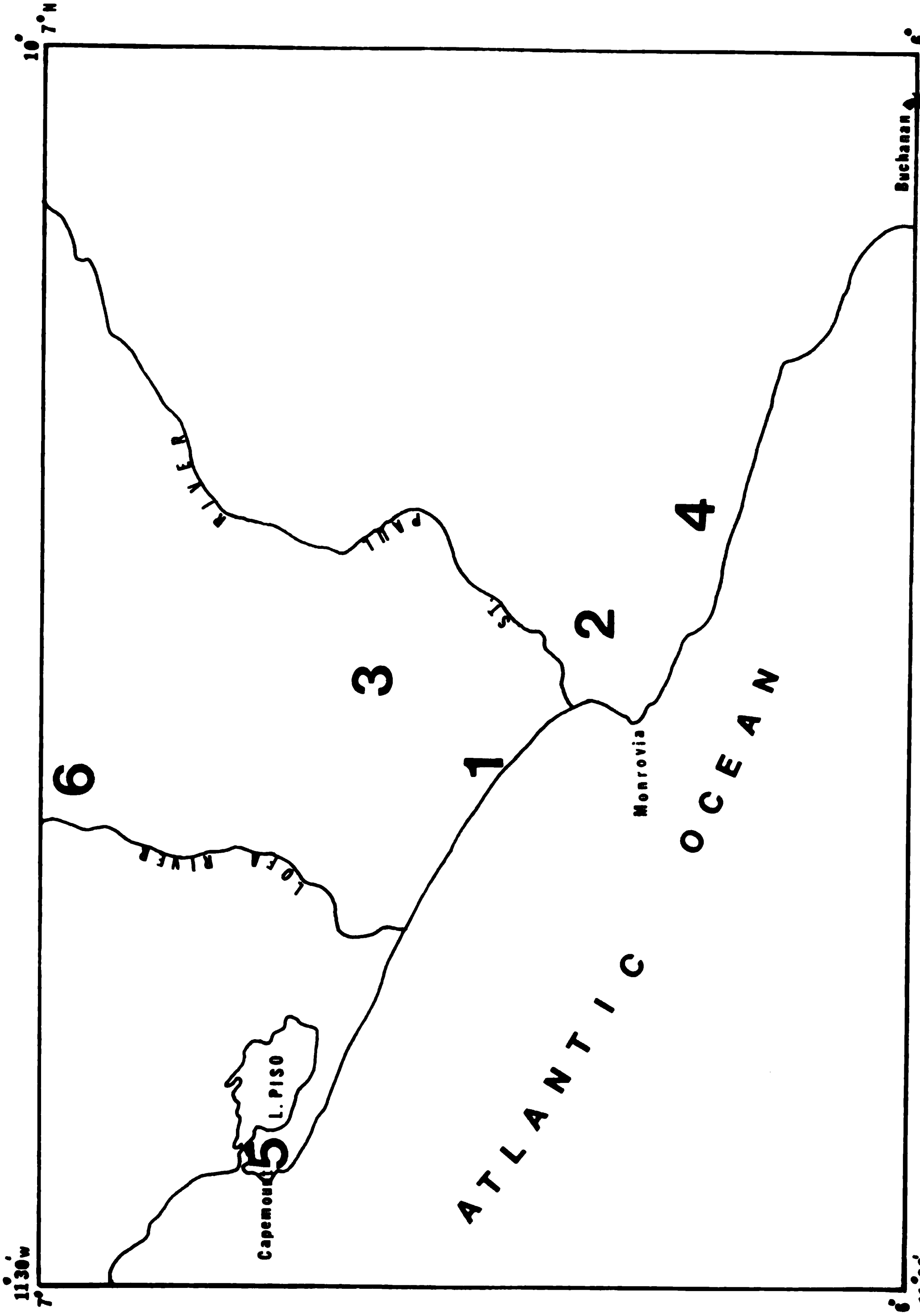


Fig. 17 Monrovia Quadrangle Showing Anomalies Locations

similar nose also facing in a southerly direction. Anomaly 1 is not represented either on the radiometric or residual aeromagnetic maps of the quadrangle.

On the aeromagnetic map, Figure 6A, anomaly 1 is represented by an area of relatively low magnetic relief, nowhere going much below 4600 or much higher than 4800 gammas. The 200 gamma difference is small compared with differences of 500 just outside the area. Off shore from anomaly 1 the magnetic contours widen considerably giving a rather smooth area, and then within six miles from the shoreline these contours take on a rather complex high and low appearance. Although this rather smooth magnetic area is slightly seaward of the location of anomaly 1, the structure causing this gravity anomaly is probably the same structure responsible for the smooth magnetic expression described above. According to Behrendt and Wotorson (1972), "Black faults are inferred in the pattern indicated along the coastal area and continental shelf." Anomaly 1 is therefore interpreted as being the result of a sediment filled basin similar to the Roberts Basin east of Monrovia (see Figure 9 and Behrendt and Wotorson, 1969). The interpreted basin, causing anomaly 1, was probably caused by the same tectonic forces that caused the formation of the Roberts Basin; their ages therefore might be similar.

## Anomaly 2

Anomaly 2 with its location shown on Figure 17 is seen on the Bouguer anomaly map (Figure 9), on the residual Bouguer anomaly map (Figure 10), but not on the radiometric map (Figure 8A). On both the Bouguer and residual Bouguer anomaly maps, anomaly 2 appears as a positive feature. On the residual Bouguer anomaly map the location of anomaly 2 seems to be shifted slightly northwest of its location on the Bouguer anomaly map. This slight difference in position is probably due to the effect of the steep gravity gradient that parallels the coast in the Monrovia quadrangle.

The aeromagnetic map (Figure 6A) shows two low amplitude northwest trending negative features in the approximate location of anomaly 2. The area adjacent to and between these two features is magnetically smooth just like the background in the adjacent areas.

The residual total magnetic intensity map (Figure 7) shows two northwest trending troughs in the location of anomaly 2. The southern most trough is in the exact location of anomaly 2 and is probably related to this gravity anomaly. From the aeromagnetic and gravity data, it would appear that the sources causing this anomaly on the respective maps might be different. On the aeromagnetic map, the source for the low amplitude magnetic anomalies, location 2, are interpreted as being shallow and probably the result of shallow diabase intrusions. The above mentioned troughs on the residual magnetic map are probably the results of the total effect of these diabase bodies.

On the gravity maps anomaly 2 is interpreted as being caused by a much deeper feature in the crust. The feature could be an upfaulted block of a denser rock type than those rocks adjacent to it.

## Anomaly 3

Anomaly 3 (Figure 17) appears on the Bouguer anomaly map (Figure 9, back folder) as a broading of the contour lines. Anomaly 3 is also visible on profile AA' (Figure 13) and on the residual Bouguer anomaly map (Figure 9), where it appears as a rather well defined 5 milligal closure. On the aeromagnetic map (Figure 6A) there is a cluster of narrow magnetic highs and lows in the general area of the anomaly. The narrowness of these features might indicate that their sources are near the surface.

On the southwest edge of anomaly 3, the radiometric map shows a pattern of moderate width and amplitude radiometric anomalies. From a background radiometric count of 125 c.p.s., just outside the area, this portion of anomaly 3 attains radiometric readings of 250 and 375 c.p.s. Geologic information from the area of anomaly 3 shows that the rock type is leucocratic gneiss containing rather large areas of amphibolites. This is not the case immediately outside the area covered by anomaly 3 where the rock type is generally granite gneiss.

Anomaly 3 is interpreted as being the result of a density increase of the rocks in the area caused by the increased density of amphibolities in the lencocratic gneisses. This model would give the observable gravity pattern and because of a possible increase in the ferro-magnesium minerals, due to the amphibolites, it could also explain the aeromagnetic pattern that is observed. The relative increase in potassium which might be associated with the leucocratic gneisses could explain the radio-metric pattern over anomaly 3.

## Anomaly 4

Anomaly 4 (Figure 17) is most prominently displayed on the aeromagnetic map (Figure 6A) of the Monrovia Quadrangle. On the aeromagnetic map it is marked "Anomaly A" (Behrendt and Wotorson, 1971a), and occurs as a north-east trending series of reasonably narrow, low amplitude, trough like features. The pattern for anomaly 4 is stronger near the coast than farther inland. The magnetic pattern disappears at the Goe Range but reappears, at a much lower amplitude further north near the Gibi Mountain where it continues on into the Bong Range (Figure 18).

On the Bouguer and residual Bouguer anomaly maps (Figure 9 and Figure 10 respectively), there are distortions in the contour lines along the lower portion of anomaly 4. The distortions on the residual Bouguer anomaly map tend to curve toward the seaward extension of the anomaly. Along anomaly 4 diabase sills were mapped but these sills are not different from other diabase intrusions in the area (White, 1969). Behrendt and Wotorson (1971a), felt that because of the seizable magnetic amplitude along this anomaly, these diabase bodies are not simple sills but may have considerable vertical extent.

Anomaly 4 is interpreted in agreement with Behrendt and Wotorson (1971a) as being a fault in the crust that has been accompanied by the emplacement of diabasic material. There appears to be two possible extensions of the trend of anomaly 4. The first is that anomaly 4 continues at a lower amplitude, past the Goe Range and up into the Bong Range (Figure 18). The second possible extension is that anomaly 4 is the continuation of the St. John's fault, along the St. John's river (Figure 18) and has been displaced to its present position along the Goe-Fantro Ranges.

### Anomaly 5

Anomaly 5 (Figure 17) has a 35 milligal gravity anomaly associated with it and is observable both on the Bouguer and residual Bouguer anomaly maps of the Monrovia Quadrangle. Gravity profile CC' (Figure 19) shows a rapid increase in gravity over the noritic body forming Cape

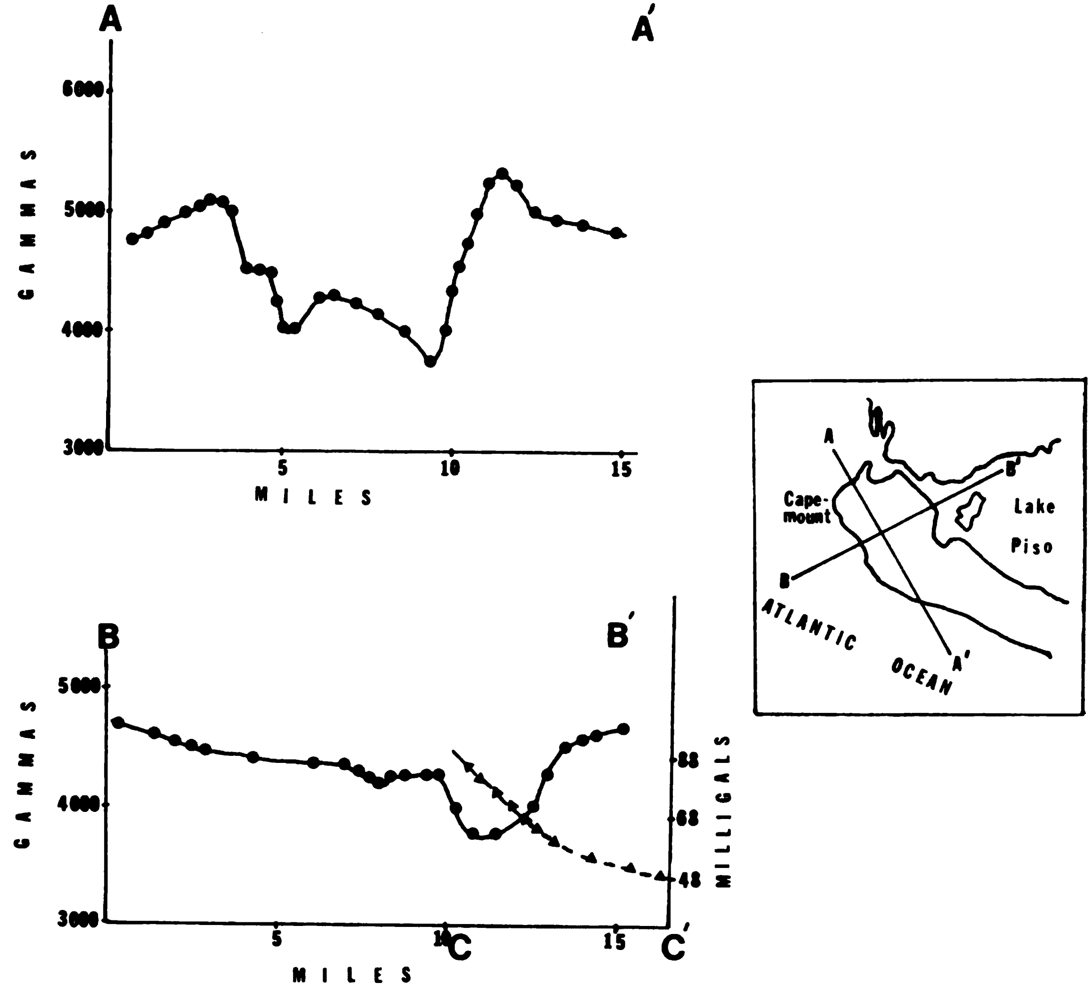


**Fig. 19** Magnetic Profiles AA' and BB', Gravity Profile CC' Over Cape Mount Anomaly

—●—●— Magnetic Profile  – ▲ – ▲ – Gravity Profile

Mount. There are no corresponding radiometric anomalies associated with anomaly 5, although on the radiometric map (Figure 8B) there are high radiometric counts in the vicinity of Cape Mount. This small radiometric anomaly is attributed to the black sands which contain monazite and zircon. These sands are not related to the norite body.

Anomaly 5 is interpreted in agreement with Behrendt and Wotorson (1971c) as being caused by a norite plug. These authors calculated that for a density contrast of 0.3 to 0.1 gm/cc, the thickness of the body would range from 1.6 km to 4.8 km respectively. Although the closest exposed bedrock to the norite body is found to be granulite it is difficult to explain the positive gravity anomaly since the granulites are higher in density than the norite. More probably, the country rocks surrounding the norite body is granite gneiss, which is of lower density than norite and thus the positive gravity anomaly would be consistent with the model. However, since granite gneiss has a lower susceptibility than norite it is difficult to explain the low magnetic anomaly except by assuming that the norite body has reversed polarization.

## Anomaly 6

Anomaly 6 (Figure 17) can best be seen on the radiometric map (Figure 8A,B) of the Monrovia Quadrangle. There are no gravity data available for this area therefore anomaly 6 does not appear on either the Bouguer or Residual

Bouguer anomaly maps. Off the coast of Liberia, and on line with the east-west section of anomaly 6, is a fracture zone which has only been observed off shore in the basement (Behrendt, personal communication, 1973). Anomaly 6 might be the landward continuation of this fracture zone. The increase in radiometric values along this zone could well be due to mineralization along the landward extension of the fracture zone. The recent geologic map of the Monrovia Quadrangle by Thorman (1972), does not however substantiate this interpretation. However, since the overall area shows intense weathering, the fracture could well be missed by surface geologic mapping.

The aeromagnetic data in the area of anomaly 6 is fairly linear and show several low trough like features that correlate with the location of anomaly 6. This fact might be used in the argument for the fracture zone interpretation since it is possible that the fracture zone has been intruded by diabase. Samples collected in this area, were found to be laterite and paragneisses containing 0.2 and 2 percent monazite and zircon respectively (Behrendt and Wotorson, 1972). These authors felt that the monazite and zircon were the cause of the high radiometric anomaly. Thorman (1972), shows that the area contains light colored, medium grained granite gneiss. This area is probably more structurally complex than has been assumed and only detailed geologic and geophysical mapping will lead to a better interpretation of this anomaly.

# CHAPTER V

# RECOMMENDATIONS, SUMMARY AND CONCLUSION

## Recommendations

1. Seismic data that have recently been collected off shore should be incorporated with the offshore aeromagnetic and gravity data so that sound interpretations can be made concerning the offshore structures. Maybe then by understanding these structures, the true origin of many features that occur on the geological maps will be found.

2. Some of the inferred "faults" that occurred constantly in Behrendt's and Wotorson's reports should be checked by geological ground mapping as their confirmation might help explain the tectonic history of Liberia. These faults could also have economical importance since some mineralization has occurred along fault zones.

3. A study of the magnitude and direction of remanent magnetization of the rocks in Liberia be made as this would help to explain many of the magnetic

anomalies. An example of this is the Cape Mount anomaly.

## Summary and Conclusions

1. The anomalies found in the coastal area of the Monrovia Quadrangle are caused mainly by faulting, accompanied at times by the intrusion of diabase dikes. Where basins have resulted from the faulting, sediments have accumulated to substantial thicknesses.

2. Anomalies found inland in the Monrovia quadrangle are caused mainly by density contrasts of large rock bodies.

3. The east-west radiometric anomaly at the upper margin of the quadrangle is probably caused by mineralization along a fracture zone.

4. In general, the magnetic susceptibility and density values of the samples did not correlate with the magnetic and gravity patterns of the quadrangle.

5. The broad magnetic low and high gravity anomaly at Cape Mount, is probably the result of the intrusion of a norite plug into granite gneiss. The magnetic pattern would indicate that the intrusion of the norite took place during a period of magnetic reversal of the present earth's magnetic field.

6. The area of Liberia is isostatically under-compensated for at depth, as is seen by the mean free air value of + 22 milligals for the entire country. Based on Woollard's curve (Woollard, 1957), a crustal thickness of about 32 km. was calculated for the region of Liberia.

7. A dominant northeastern and northwestern trend pattern is found on the magnetic maps and to a lesser degree on the radiometric maps. This pattern is probably tied to the tectonic history of Liberia.

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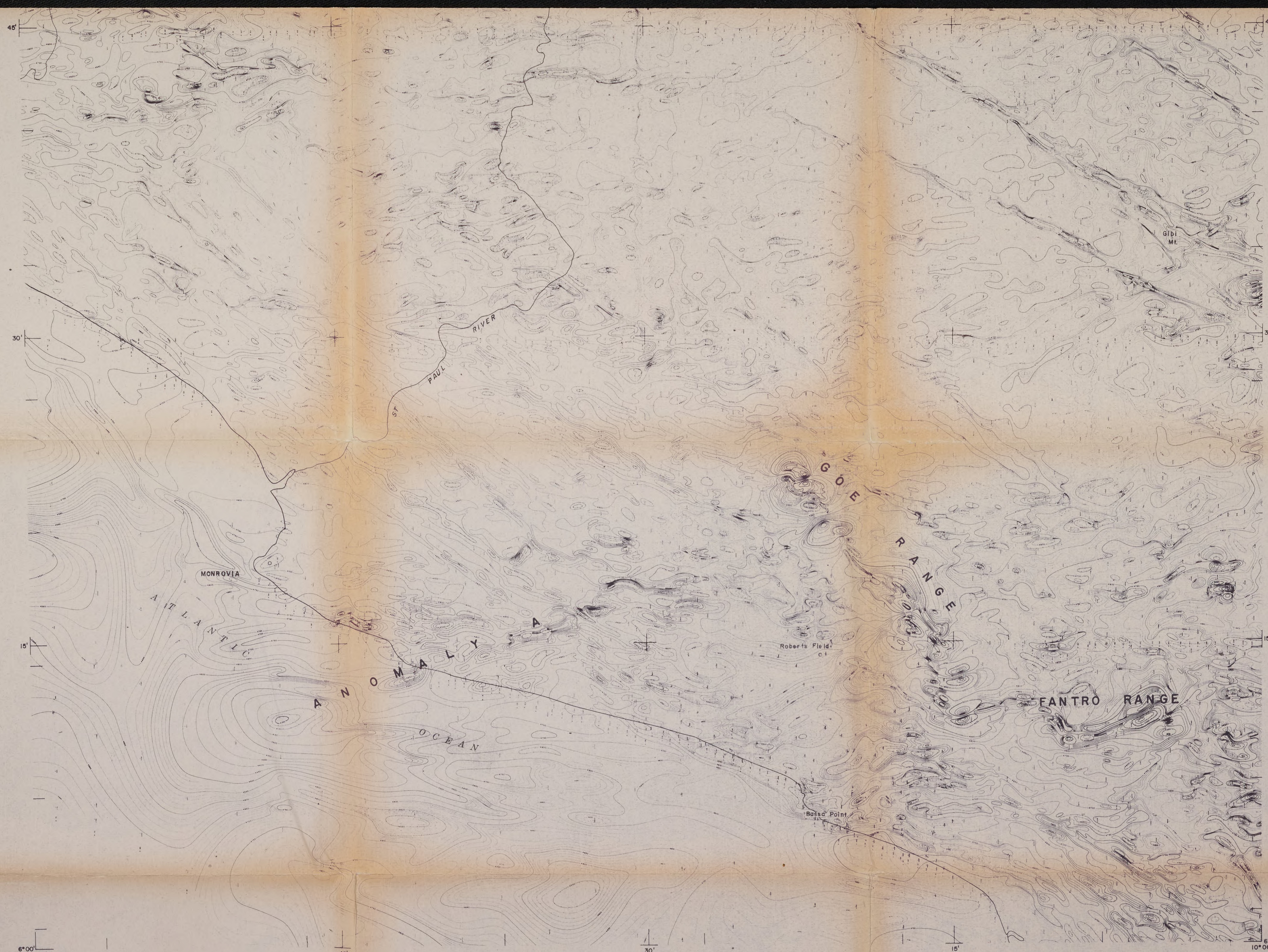
# APPENDIX

APPENDIX

| Map # | Sample # | Rock Name | Density | Susceptibility x $10^{-6}$ | Opaque % |
|---|---|---|---|---|---|
| 1 | TN95A | Granite Gneiss | 2.62 | 4 | |
| 2 | TN95B | Granite Gneiss | 2.75 | 1028 | .2 |
| 3 | TN36C | Granite Gneiss | 2.64 | 952 | .75 |
| 4 | NRF4 | Amphibolite | 2.77 | 2870 | 4.06 |
| 5 | NRF3 | Amphibolite | 2.80 | 4210 | |
| 6 | NRF1 | Diabase | 2.93 | | 3.55 |
| 7 | NRG2 | Diabase | 2.92 | 3023 | 3.8 |
| 8 | NRB4 | Diabase | 3.04 | 5793 | 3.84 |
| 9 | NRA1 | Granulite | 3.03 | | |
| 10 | NRA3 | Diabase | 3.04 | 2188 | |
| 11 | NRA4 | Gneiss | 2.84 | | 3.0 |
| 12 | TN77G | Granite Gneiss | 2.49 | | |
| 13 | TN75-G | Granite Gneiss | 2.60 | | Tr. |
| 14 | TN68B | Granite Gneiss | 2.63 | 614 | |
| 15 | TN100C | Granite | 2.63 | 20 | |
| 16 | TN100B | Granite | 2.62 | | |
| 17 | NRB1 | Gabbro | 3.07 | 5099 | 8.8 |
| 18 | NRB2 | Diabase | 3.42* | | 1.9 |
| 19 | NRB3 | Diabase | 3.10* | 3877 | 5.3 |
| 20 | TN92C11 | Granite Gneiss | 2.59 | | |
| 21 | NRD4 | Granite Gneiss | 2.58 | 117 | 4.3 |
| 22 | NRD3 | Diabase | 3.11 | 4352 | 6.0 |
| 23 | NRD2 | Hornblendite | 3.08* | | |
| 24 | NRC4 | Float Ore (Fe) | 3.68* | | |
| 25 | NRC4 | Iron Ore | 4.94 | | |
| 26 | NRC4 | Iron Ore | 5.08 | | |
| 27 | TN9rB-3 | Granite Gneiss | 2.70 | 528 | .5 |
| 28 | TN94B-1 | Chlorite Schist | 2.86 | | Tr. |
| 29 | TN94B-2 | Chlorite Schist | 2.86 | | Tr. |
| 30 | NRC2 | Gneiss | 2.62 | | .2c |
| 31 | NRC1 | Gneiss | 2.03* | | .44 |
| 32 | NRH3 | Granite Gneiss | 3.52* | 1838 | Tr. |
| 33 | NRI1 | Granulite | 3.20 | 190 | 1.84 |
| 34 | TN92B-3 | Granite Gneiss | 2.58 | | |

| Map # | Sample # | Rock Name | Density | Susceptibility x $10^{-6}$ | Opaque % |
|---|---|---|---|---|---|
| 35 | TN91A-3 | Chlorite Schist | 2.96 | | |
| 36 | TN90E-3 | Granite Gneiss | 2.61 | | |
| 37 | TN90E-5 | Granite Gneiss | 2.72* | | |
| 38 | NRI2 | Granulite | 3.04 | | 6.4 |
| 39 | NRI3 | Granulite | 2.99 | 147 | .35 |
| 40 | NRI4 | Granulite | 3.00 | 193 | .66 |
| 41 | NRI5 | Diabase | 3.05 | 4104 | 9.4 |
| 42 | NRJ3 | Gabbro | 3.05 | 5546 | 8.68 |
| 43 | NRJ4 | Gneiss | 2.86 | | .2c |
| 44 | NRJ6 | Granulite | 3.01 | | |
| 45 | NRL1 | Weathered Quartzite | 2.95 | 756 | 6.58 |
| 46 | W1016R | Granulite | 2.96* | | |
| 47 | W1010R | Granulite | 3.03 | | |
| 48 | NRK1 | Granulite | 3.10 | 126 | Tr. |
| 49 | NRK2 | Gneiss | 2.81 | 146 | Tr. |
| 50 | NRK3 | Granulite | 2.97 | 1678 | 1.4 |
| 51 | NRK4 | Granulite | 3.23 | 226 | 3.3 |
| 52 | NRK5 | Granulite | 3.13 | | |
| 53 | TN101A2 | Norite | 3.00 | 1728 | 2.5 |
| 54 | NRB5 | Granite Gneiss | 2.97* | 985 | 4.4 |
| 55 | NRF4 | Diabase | | | 7.54 |
| 56 | NRH1 | Diabase | | | 3.55 |
| 57 | NRD1 | Diabase | | | 2.90 |

*Values that are unreliable.




EXPLANATION

| | |
|---|---|
| CONTOUR INTERVAL | 10 OR 50 GAMMA WHERE APPROPRIATE |
| 10 GAMMA CONTOUR | |
| 50 GAMMA CONTOUR | |
| 250 GAMMA CONTOUR | |
| 1000 GAMMA CONTOUR | |
| MAGNETIC LOW | |
| SURVEY ALTITUDE | 150 M |
| FLIGHT LINE NUMBER, FLIGHT PATH AND POSITIONING PHOTO NUMBERS | P-80 — 50 — 100 |
| FLIGHT LINE SPACING | 0.8 Km |

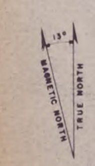
REGIONAL MAGNETIC GRADIENT NOT REMOVED
TOTAL INTENSITY BASED ON ARBITRARY DATUM

SHEETS AND COORDINATES BASED ON HOTINES RECTIFIED SKEW ORTHOMORPHIC PROJECTION, U.S. COAST AND GEODETIC SURVEY PUBLICATION, 1956

SCALE 1:250,000

5 0 5 10 Miles

5 0 5 10 15 Kilometers




APPROXIMATE MEAN DECLINATION, 1968
ESTIMATED TOTAL INTENSITY OF FIELD · 32,300 GAMMAS
MEAN INCLINATION −7.8°

AEROMAGNETIC SURVEY
REPUBLIC OF LIBERIA
BUREAU OF NATURAL RESOURCES & SURVEYS

GEOLOGICAL EXPLORATION & MINERAL RESOURCES APPRAISAL
JOINT PROJECT
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Syosset, New York    Pasadena, California
FLOWN : NOV. 1967 - JANUARY 1968    L.K.B. PROJECT 7630

123
276
T45
Fig. 6A



# AEROMAGNETIC MAP OF THE MONROVIA QUADRANGLE, LIBERIA (Sheet I) FIG. 6A

By
John C. Behrendt and Cletus S. Wotorson

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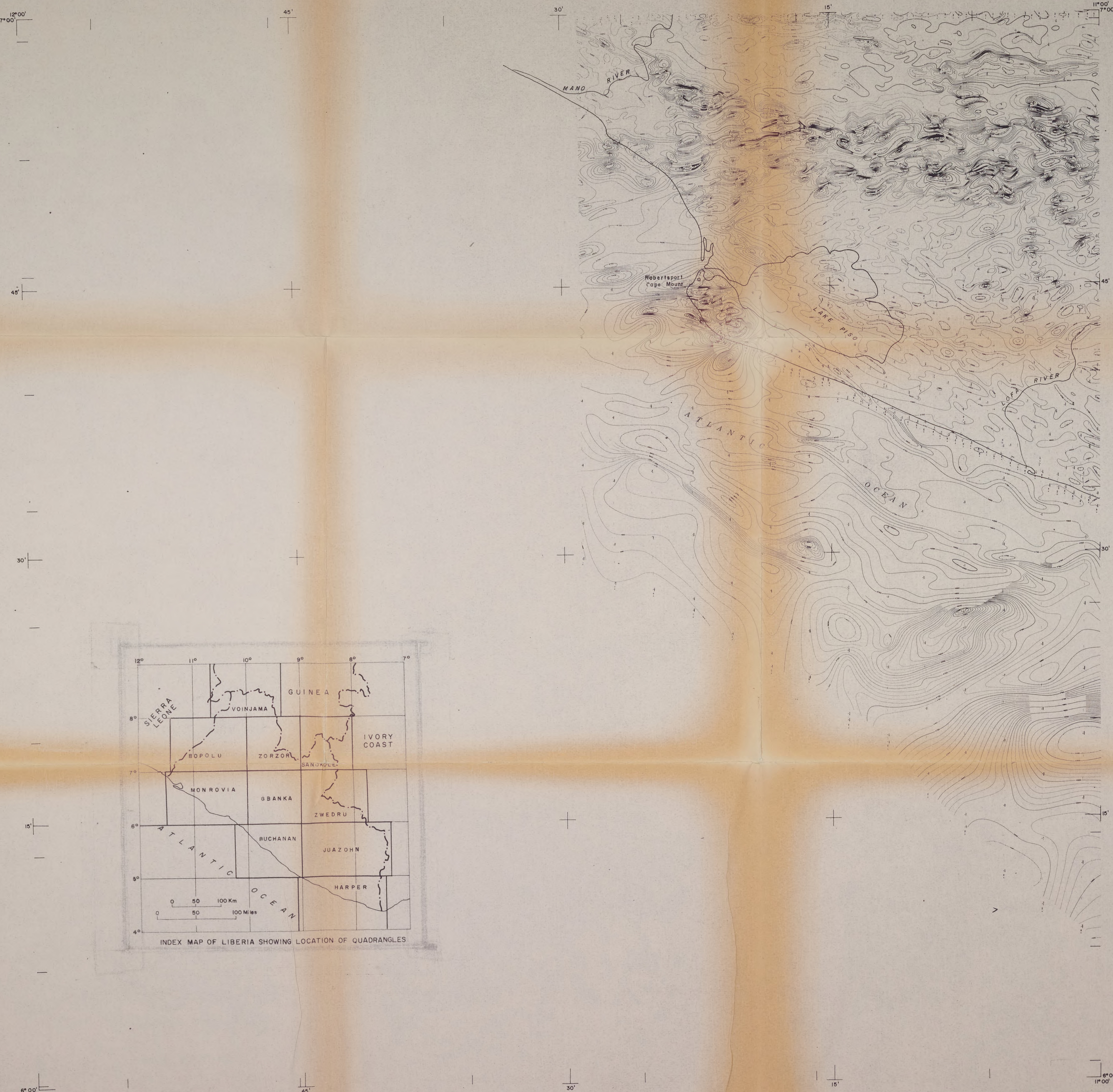


INDEX MAP OF LIBERIA SHOWING LOCATION OF QUADRANGLES

### EXPLANATION

CONTOUR INTERVAL ........ 10 OR 50 GAMMA WHERE APPROPRIATE
10 GAMMA CONTOUR
50 GAMMA CONTOUR
250 GAMMA CONTOUR
1000 GAMMA CONTOUR
MAGNETIC LOW
SURVEY ALTITUDE 150 M
FLIGHT LINE NUMBER, FLIGHT PATH AND POSITIONING PHOTO NUMBERS P-80 —O— —O— (50, 100)
FLIGHT LINE SPACING 0. 8 Km
REGIONAL MAGNETIC GRADIENT NOT REMOVED
TOTAL INTENSITY BASED ON ARBITRARY DATUM

SHEETS AND COORDINATES BASED ON HOTINES RECTIFIED SKEW ORTHOMORPHIC PROJECTION, U.S. COAST AND GEODETIC SURVEY PUBLICATION, 1956

SCALE 1: 250,000

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# AEROMAGNETIC MAP OF THE MONROVIA QUADRANGLE, LIBERIA (Sheet 2) FIG. 6B

By
**John C. Behrendt and Cletus S. Wotorson**

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U. S. DEPARTMENT OF STATE

UNITED STATES DEPARTMENT OF THE INTERIOR
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REPUBLIC OF LIBERIA
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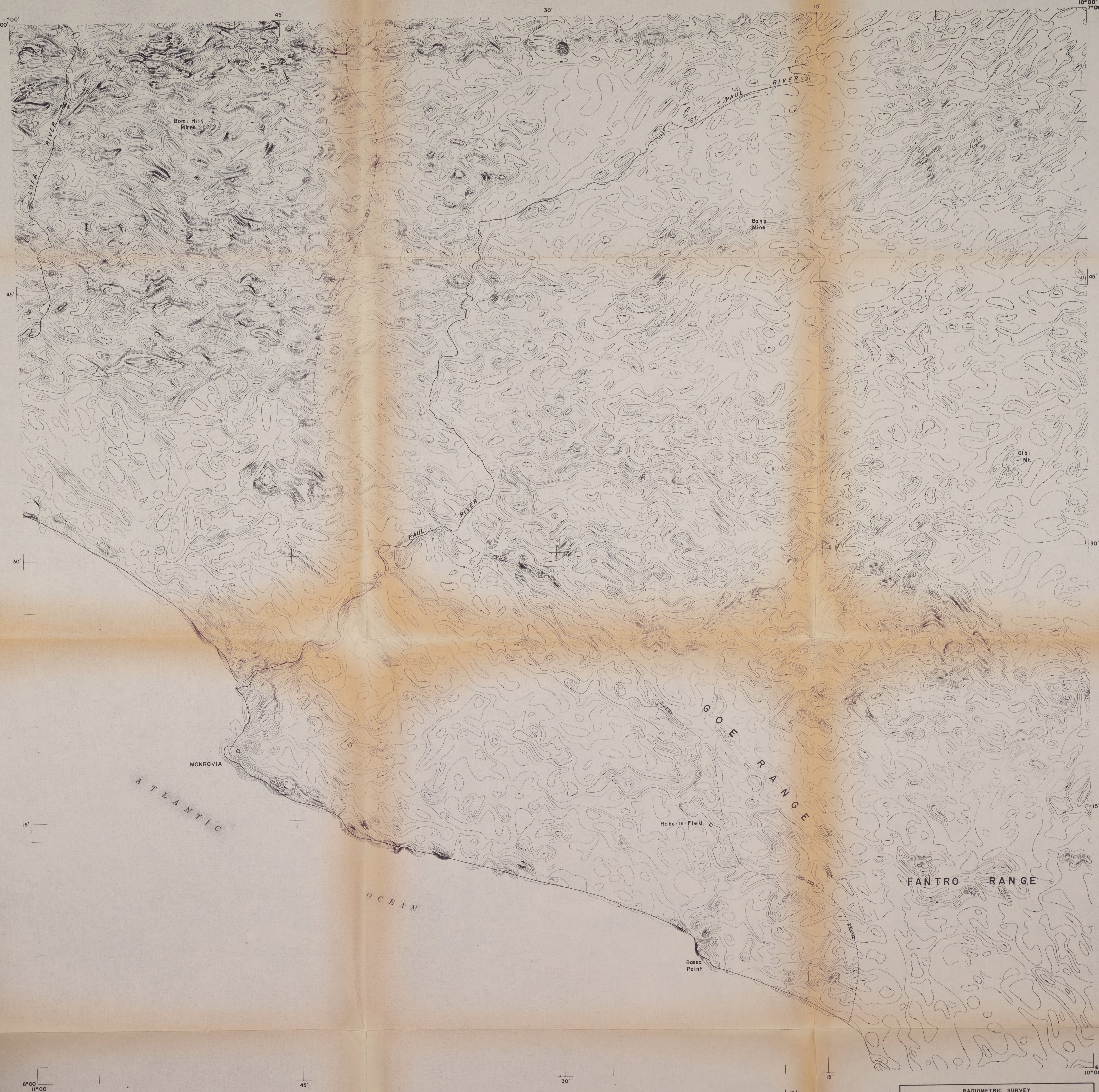
USGS OPEN-FILE REPORT (IR) LI-66 D




EXPLANATION

| | |
|---|---|
| CONTOUR INTERVAL | 50/25 COUNTS PER SECOND |
| 25 CPS CONTOUR | |
| 125 CPS CONTOUR | |
| RADIOACTIVITY LOW | |
| SURVEY ALTITUDE | 150M |
| FLIGHT LINE SPACING | 0. 8Km |

FOR FLIGHT PATH INFORMATION SEE CORRESPONDING MAGNETOMETRIC SHEET

ALL DATA ADJUSTED TO 220 M ABOVE TERRAIN

SCALE 1: 250,000

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# TOTAL-COUNT GAMMA RADIATION MAP OF THE MONROVIA QUADRANGLE, LIBERIA (Sheet I) FIG. 8A

By

John C. Behrendt and Cletus S. Wotorson

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U. S. DEPARTMENT OF STATE


EXPLANATION

CONTOUR INTERVAL 25 COUNTS PER SECOND
25 CPS CONTOUR
125 CPS CONTOUR
RADIOACTIVITY LOW
SURVEY ALTITUDE 150M
FLIGHT LINE SPACING 0. 8Km
FOR FLIGHT PATH INFORMATION SEE CORRESPONDING MAGNETOMETRIC SHEET
ALL DATA ADJUSTED TO 220 M ABOVE TERRAIN

SCALE 1:250,000

APPROXIMATE MEAN DECLINATION, 1968

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# TOTAL-COUNT GAMMA RADIATION MAP OF THE MONROVIA QUADRANGLE, LIBERIA (Sheet 2) FIG.8B

By
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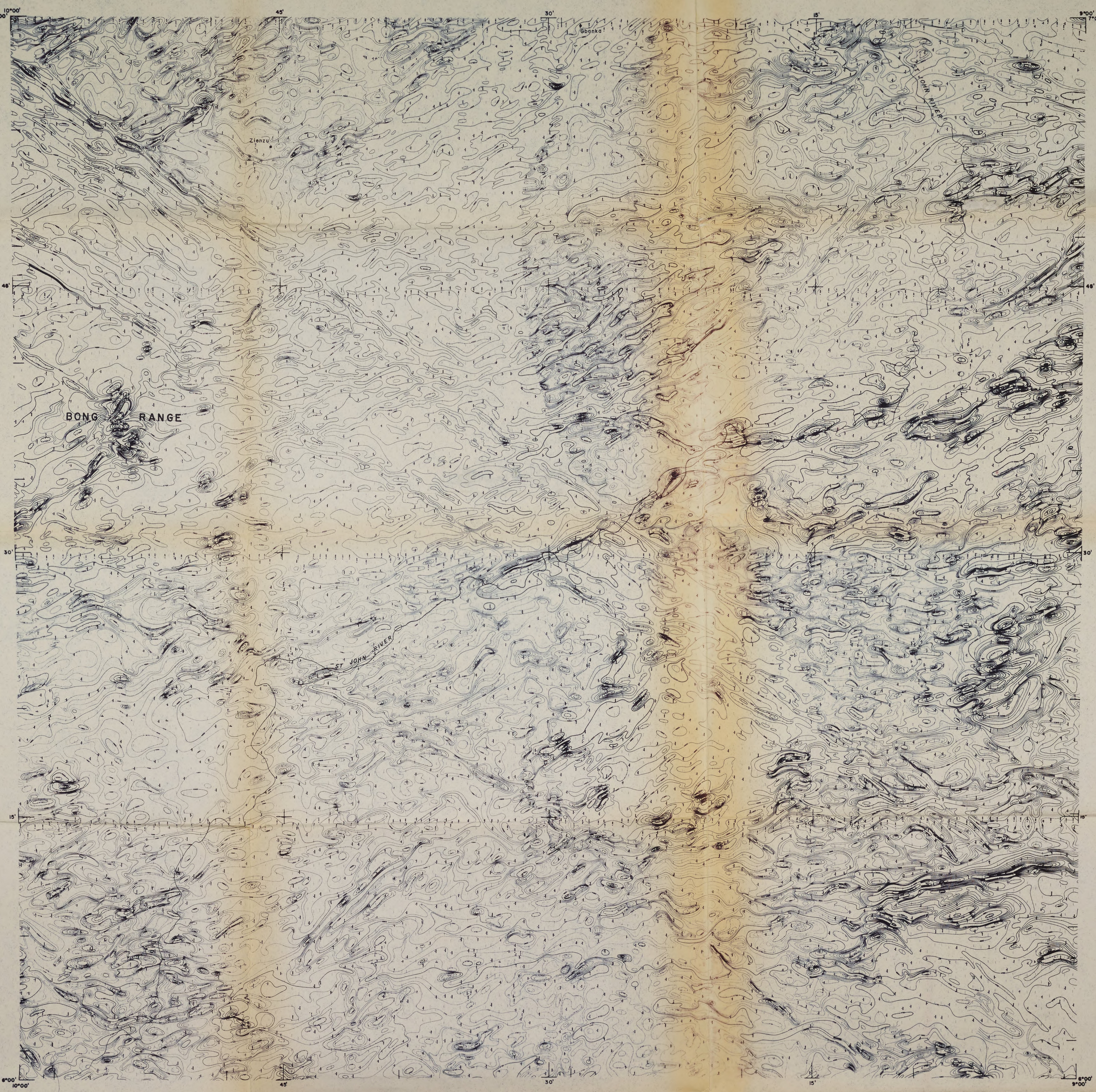


EXPLANATION

- CONTOUR INTERVAL .......... 10 OR 50 GAMMA WHERE APPROPRIATE
- 10 GAMMA CONTOUR
- 50 GAMMA CONTOUR
- 250 GAMMA CONTOUR
- 1000 GAMMA CONTOUR
- MAGNETIC LOW
- SURVEY ALTITUDE .......... 150 M
- FLIGHT LINE NUMBER, FLIGHT PATH AND POSITIONING PHOTO NUMBERS .......... P-80 — 50 — 100
- FLIGHT LINE SPACING .......... 0. 8 Km
- REGIONAL MAGNETIC GRADIENT NOT REMOVED
- TOTAL INTENSITY BASED ON ARBITRARY DATUM

SHEETS AND COORDINATES BASED ON HOTINES RECTIFIED SKEW ORTHOMORPHIC PROJECTION, U.S. COAST AND GEODETIC SURVEY PUBLICATION, 1956

SCALE 1: 250,000

13°
MAGNETIC NORTH
TRUE NORTH

APPROXIMATE MEAN DECLINATION, 1969
ESTIMATED TOTAL INTENSITY OF FIELD : 32,300 GAMMAS
MEAN INCLINATION - 7.8°

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123
276
THS
Fig. 18

# AEROMAGNETIC MAP OF THE GBANKA QUADRANGLE, LIBERIA

FIG. 18

By
John C. Behrendt and Cletus S. Wotorson

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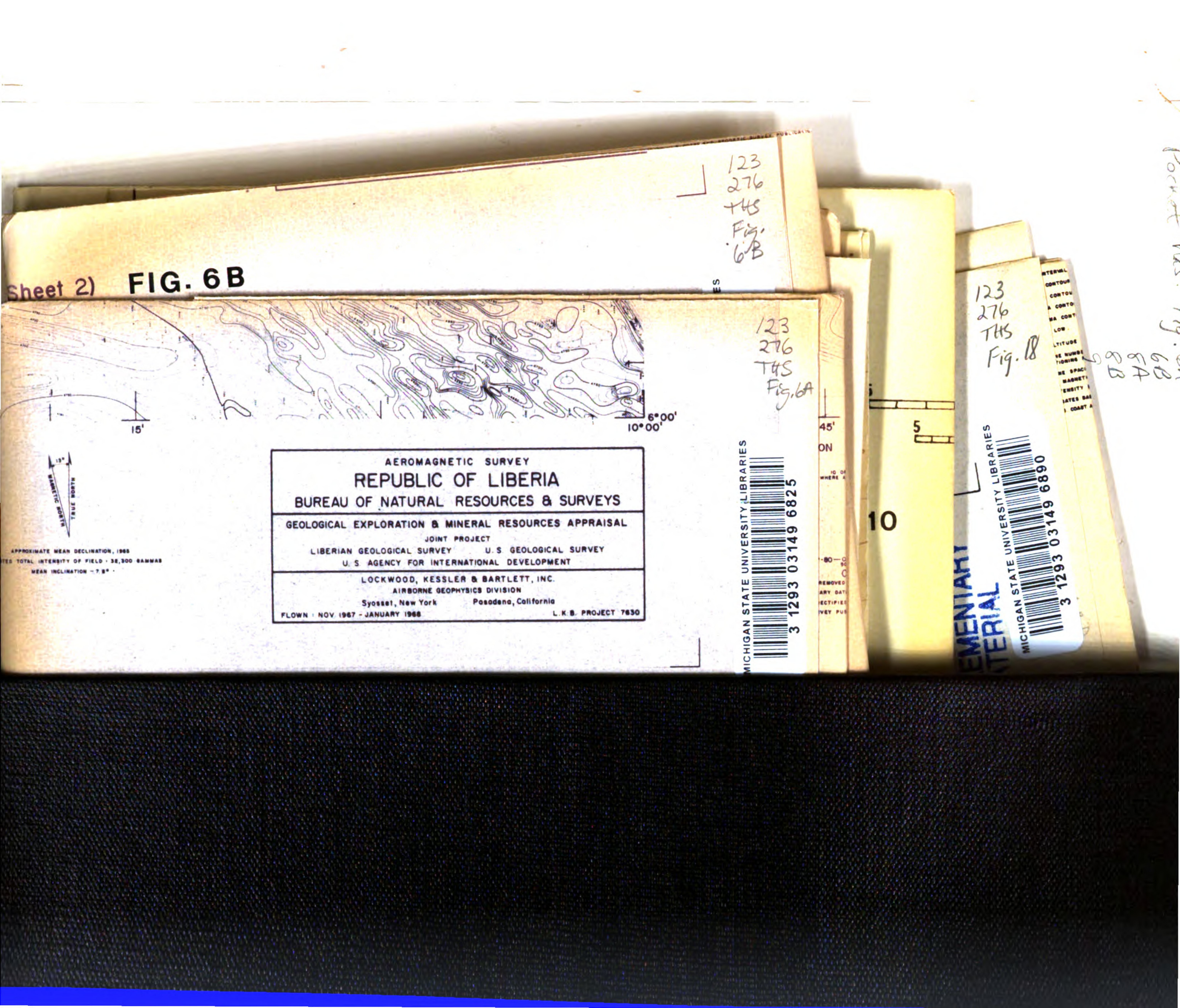

Sheet 2) FIG. 6B
123
276
THS
Fig. 6B
123
276
THS
Fig. 6A
15'
6°00'
10°00'
AEROMAGNETIC SURVEY
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TRUE NORTH
MAGNETIC NORTH
MICHIGAN STATE UNIVERSITY LIBRARIES
3 1293 03149 6825
45'
10
5
123
276
THS
Fig. 18
MICHIGAN STATE UNIVERSITY LIBRARIES
3 1293 03149 6890
6B
8A
8B