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TECTONIC MAP OF LIBERIA BASED ON GEOPHYSICAL AND GEOLOGICAL SURVEYS

by

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CONTENTS

ILLUSTRATIONS

Figures

ILLUSTRATIONS

Figures (cont'd)

Plates
/In pocket/

Table

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by

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ABSTRACT

Interpretation of the results of aeromagnetic, total-gamma radioactivity, and gravity surveys combined with geologic data for Western Liberia from White and Leo(1969) and other geologic information allows the construction of a tectonic map of Liberia. The map approximately delineates the boundaries between the Liberian(ca. 2700 m.y.) province in the northwestern two-thirds of the country, the Eburnean(ca. 2000 m.y.) province in the southeastern one-third, and the Pan-African (ca. 550 m.y.) province in the coastal area of the northwestern two-thirds of the country. Rock foliation and tectonic structural features trend northeastward in the Liberian province, east-northeastward to north-northeastward in the Eburnean province, and northwestward in the Pan-African age province. Linear residual magnetic anomalies 20-80 km wide and 200-600 gammas in amplitude and following the northeast structural trend typical of the Liberian age province cross the entire country and extend into Sierra Leone and Ivory Coast.

Theoretical bodies thicker than ten kilometers, having apparent susceptibility contrasts in the range of 0.0026 to 0.0043 emu are required to fit the highest amplitude(600γ) anomaly which exceeds 50 km in width. These anomalies are of unknown origin but are possibly associated with the shear zones of Liberian age, as similar associations are known elsewhere. The long-wavelength anomalies were only slightly modified by the Eburnean and Pan-African thermotectonic events and can be correlated with similar anomalies reported by others in Sierra Leone, Ivory Coast, the Guyana shield area in South America. Thus, the Pan-African thermotectonic event merely imprinted older rocks and did not generate new crust in the area of Liberia. As temperatures in these rocks exceeded the Curie isotherm during the Pan-African activity, the anomalies must be due to induced magnetization; therefore they probably are indicative of variations in the amount of magnetite in the underlying rocks.

A zone of diabase dikes, about 80-120 km wide, can be traced by means of magnetic data; it is about 90 km inland, and extends parallel to the coast from Sierra Leone to Ivory Coast. Another zone of diabase dikes having two dates of 176 and 192 m.y., is at least 70 km wide, and is located along the coastal area and beneath the continental shelf northwest of Greenville. These dikes probably were intruded during tectonic activity that preceded the separation of the continents at the southern end of the North Atlantic. The magnetic data suggest basins of sedimentary rocks possibly 5 km thick on the continental shelf, deposited after sea floor spreading had commenced.

The magnetic map indicates magnetic anomalies of amplitudes greater than 600 gammas; some reach amplitudes as great as 18,000 gammas over iron-formation and about 1800 gammas over mafic and ultramafic intrusive bodies.

The radioactivity data adjusted to an altitude of 220 m have a background level less than 100 cps (counts per second; relative to 180 cps=1 μr/hr) over mafic granulite-facies rocks and unmetamorphosed sedimentary rocks in the coastal area. Granitic rocks including granitic gneiss show the greatest variation. The central area of the country has the highest background radiation level, large areas showing more than 250 cps; the eastern one-third of the country is low. In general most of the areas having a background level above 150 and all areas above 250 cps are areas of granitic rocks.

Diabase sills having radiation levels of 100-200 cps show marked contrasts with granulites and sedimentary rocks. The contact between the coastal granulite zone and granitic gneiss inland is apparent in the radioactivity data. Metasedimentary iron-formation and mafic metamorphic rocks within the predominantly granitic gneiss terrane are easily delineated. The radioactivity map shows many anomalies above 500 cps; some reach amplitudes of more than 750 cps. Total-count radiation levels have a significant correlation with the percent of K_2O analysed in bedrock samples, but anomalous amounts of Th and U must be present to account for the highest amplitude anomalies. A few specific anomalies have been correlated with concentrations of monazite and zircon in bedrock as well as in beach deposits.

A regional gravity survey covers the country along the coast and available roads and along tidewater rivers in western Libera. A 50-60 mgal positive Bouguer anomalous area extends along the coast from Sierra Leone to Ivory Coast. This anomaly correlates with mafic granulites in the Monrovia region, where the gradient is too steep to be entirely due to crustal thickening at the continental margin. The only major break in this positive anomaly above basement rocks along the entire coast of Liberia is above granitic gneiss adjacent to (and presumably underlying) the only onshore basins on the Liberian coast. Local negative Bouguer anomalies exist over two Cretaceous basins in the coastal area. The high mean free-air anomaly of +22 mgal (exclusive of the coastal anomaly) suggests that the approximately 200-m mean elevation of Liberia is not compensated, at least over the Liberia region. A linear regression, showing a significant correlation of elevation with Bouguer anomaly, has a zero elevation intercept of +18 mgal, again indicative of an isostatic anomaly. The standard deviation of ± 14 mgal from the Bouguer anomaly-elevation regression line is indicative of the amplitude range of local geologic anomalies. These include a 30-mgal anomaly above an ultramafic intrusion near Juazohn and an approximate 30-mgal anomaly associated with a mafic intrusion at Cape Mount. A suggested crustal model computed to fit observed marine and land Bouguer anomalies shows an abrupt thickening at the continental margin, several kilometers of sedimentary rock on the continental slope, uplifted dense lower crustal rocks at shallow depths beneath the continental shelf southeast of Greenville, and a high mean crustal density.

A suggested sequence of events indicates thermotectonic activity in the periods ca. 2700 m.y.(Liberian age) and ca.2000 m.y.(Eburnean age); faulting along north-northeast trends in the apparent structures and lineation; intrusion of diabase dikes in northern Liberia during a period of reversed magnetic field; thermotectonic activity ca. 550 m.y. ago(Pan-African age) in the western coastal region; uplift and exposure of deep crustal rocks; deposition of Paleozoic(?) sediments; intrusion of dikes and sills (176-192 m.y. ago) prior to the separation of Africa and South and North America, during a period of normal magnetic polarity in approximately the present field direction; uplift and exposure of the coastal dikes and enclosing crystalline rocks and Paleozoic(?) sandstone; deposition of Cretaceous and Tertiary(?) sedimentary rocks on the continental shelf and coastal area, accompanied by subsidence, block faulting, and active sea floor spreading; basaltic extrusion on the spreading sea floor and sedimentary deposition on the continental slope; and uplift of Liberia to mean elevation of about 200 m without apparent isostatic compensation.

INTRODUCTION

The Liberian Geological Survey and the U. S. Geological Survey have completed a cooperative program of reconnaissance geologic mapping of Liberia, under the auspices of the Government of Liberia and the Agency for International Development, U. S. Department of State. The work leading to this report was done under AID/PASA No. AFR(IC) 11-00. To assist in this program, an aeromagnetic and a total-count gamma radiation survey were flown over Liberia in 1967-68. The U. S. Army Topographic Command participated in a gravity survey with the U. S. 72d Engineering Detachment, and provided a gravity meter. We have discussed various aspects of the results of the geophysical investigations in previous reports (Behrendt and Wotorson, 1969a; 1970a, b, and c; 1971 a-s). The observed total magnetic intensity and total-count gamma radiation data have been published at 1:250,000 scale in 20 quadrangle sheets (Behrendt and Wotorson, 1971a-r; Wotorson and Behrendt, 1971a-c). This report is an attempt to integrate the geologic work with the geophysical data; these results are shown on plate 1. The geological and geophysical interpretations presented here are provisional and may be revised on the basis of future field investigations.

White and Leo (1969, 1971) and White (1969-70) summarized the geology of Liberia as it is known at the time of this writing. We have used these papers extensively in the preparation of this report. The geologic map of western Liberia (White and Leo, 1969) should be used to supplement the data presented here.

Acknowledgments

We thank our colleagues in the Liberian Geological Survey and the U. S. Geological Survey for their assistance in this study. In particular, R. W. White, W. L. Coonrad, and Sam Rosenblum provided many helpful suggestions and criticisms. W. R. Bromery was instrumental in planning the airborne surveys prior to our participation in the program.

SUMMARY OF GEOLOGY

The geology of Liberia is difficult to study because of the scarcity of roads, and dense rain-forest vegetation resulting from a humid tropical climate (annual precipitation in certain coastal areas may exceed 500 cm), and thick laterite soils mostly of Tertiary age or older(R.W. White, written commun., 1970). The terrain is rolling and the mean elevation of the country is moderately high(about 200 m)(see fig. 1). The more resistant rocks, such as iron-formation, ultramafic rocks, mafic amphibolite, and diabase, form steep ridges. Local relief in the Nimba and Wologizi Ranges is about 800 m, and these two highest ranges in Liberia have maximum elevations of 1380 and 1420 m, respectively.

Hurley and others(1967; 1971) divided Liberia into age provinces, (pl. 1): the Liberian age province(ca.2700 m.y.) occupies the inland western two-thirds of the country; the Eburnean age province(ca. 2000 m.y.) includes approximately the eastern one-third; a narrow zone along the coast in the western two-thirds of the country is referred to as the zone of Pan-African age (ca. 550 m.y.) thermotectonic activity. The limits of these areas as shown on plate 1 are based in part on aeromagnetic data and in part on age determinations for samples analyzed by radiometric methods (Hurley and others, 1971).

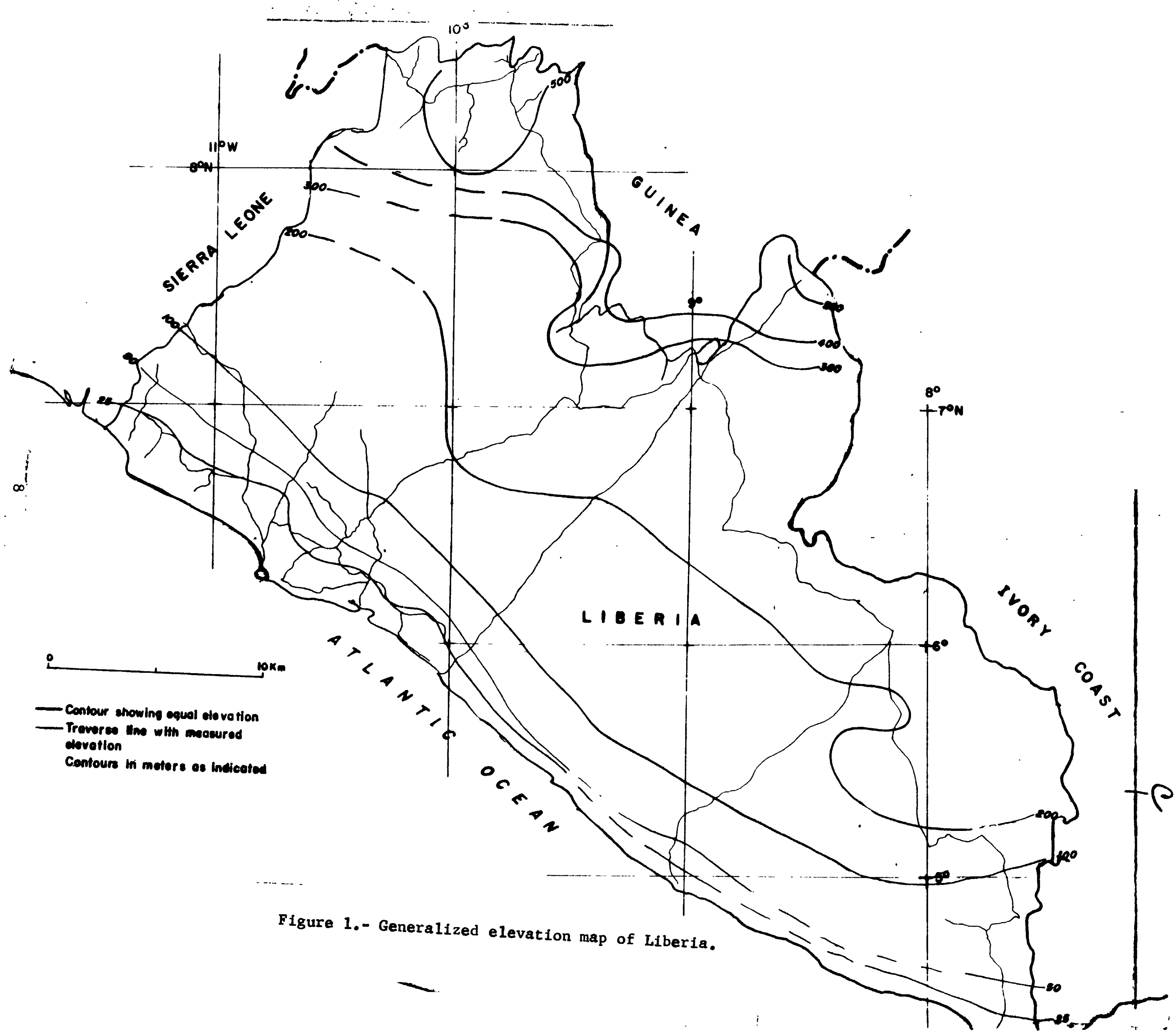

Figure 1.- Generalized elevation map of Liberia.

Figure 2 shows the relative abundance of various rocks in western Liberia. The abundances were calculated from measured areas of geologic units shown on White and Leo's geologic map(1969); granitic rocks are dominant over most of the area, but the Pan-African province contains abundant granulite.

Liberian age province

The following summary is taken largely from White and Leo(1971) who describe the Liberian age province (ca. 2700 m.y., Precambrian) as consisting of gneissic rocks of granitic composition. Massive granitic rocks are known only in northernmost Liberia(White and Leo, 1969). Elsewhere only small isolated bodies of granite are within the gneissic terrane. Metasedimentary rocks including pelitic schist, quartzite, and amphibolite in the lower part of the sequence, and oxide and silicate iron formation in the upper part overlie the gneissic basement. These rocks were deposited on the original gneissic basement and metamorphosed during the Liberian tectonic event(ca. 2700 m.y.); they form relatively narrow, elongate synclinal structures within granitic gneiss. Many of the synclinal structures are readily apparent as anomalies on both the total magnetic intensity map(pl. 2) and on the aeroradiometric map (pl. 4). They are not distinguished from other major linear structures in plate 1.

Isolated bodies of amphibolite, and minor areas of paragneiss, schist, and quartzite have an unknown age relationship to the surrounding gneissic terrane. Small bodies of peridotite and serpentinite cut the metasedimentary rock and granitic gneisses and thus are younger.

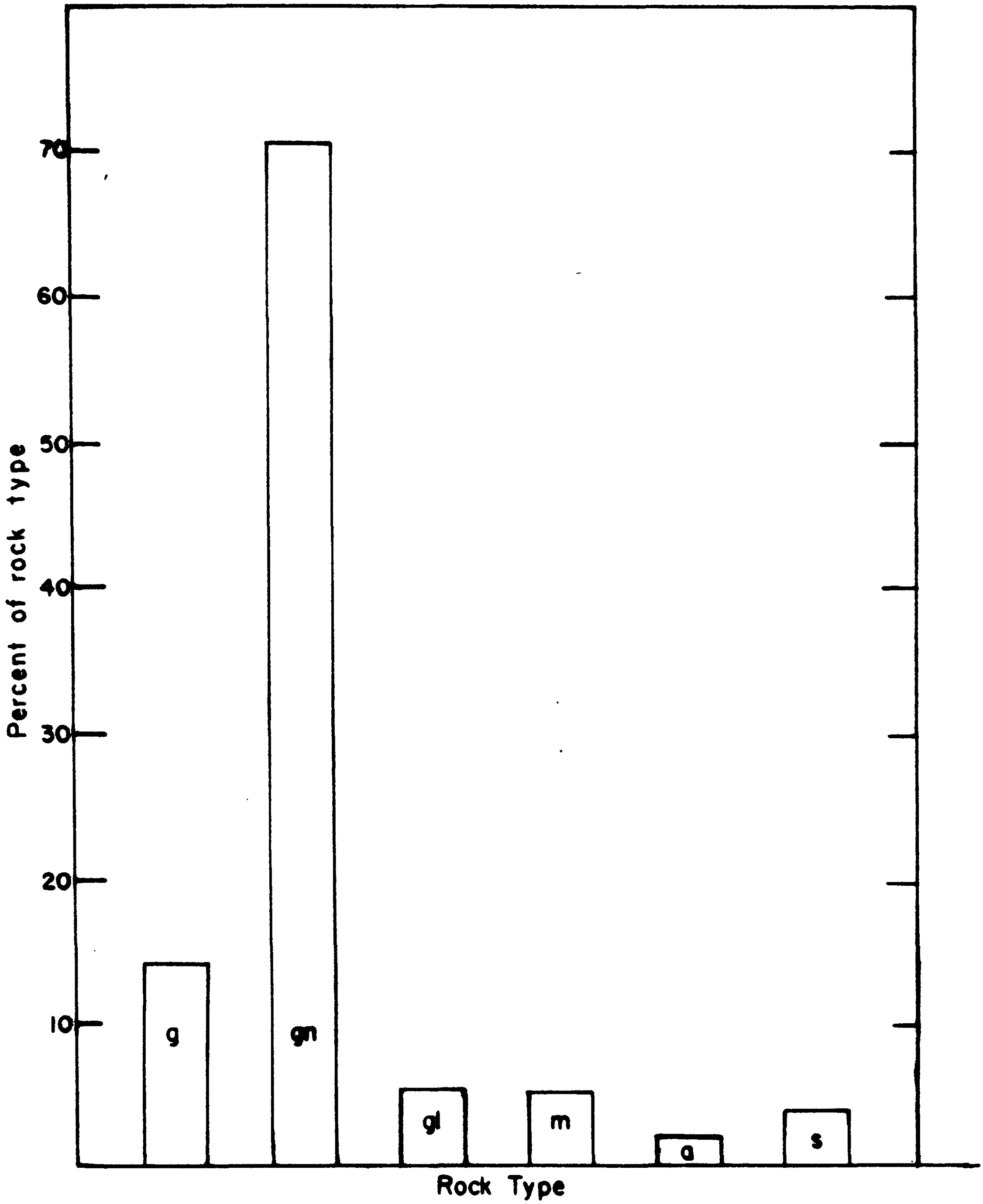

Figure 2.- Histogram showing relative amount of rock type in Liberia west of 9°W., as calculated from the geologic map of White and Leo (1969). Percentages are approximate but the preponderance of granitic gneiss (gn) over relatively unfoliated granitic rocks (g), granulite (gl) (limited to Pan-African age province), metasedimentary rocks (m), amphibolite (a), and sedimentary rocks (s) is apparent. Diabase dikes are not included because estimated quantity is too small to be shown in diagram. Eastern Liberia (Eburnean age province) contains substantially more metasedimentary rock.

Both foliation of the gneiss and metasedimentary structural features trend northeast in the Liberian age province. The foliation and tectonic lineation trends continue into Guinea and Ivory Coast(White and Leo, 1969). The residual total magnetic intensity map(pl. 3) reflects these trends quite prominently among the broader-scale features.

White and Leo(1969), on the basis of mineral assemblages and textures in the granitic rocks, suggest metamorphic recrystallization under amphibolite facies conditions. Because of the presence of sillimanite and andalusite, (White, 1970) infers a relatively low pressure, high-temperature metamorphic facies series. Undeformed granitic rocks are rare in the Liberian age province, and the magnetic data reveal short wavelength linear anomalies generally associated with foliation in most of the granites mapped by White and Leo(1969).

Eburnean age province

Geologic information is relatively sparse for the Eburnean age(ca. 2000 m.y. Precambrian) province as compared with the Liberian province. Our summary is taken largely from data presented by Van Greithusen(1971), White(1969-70), and White and Leo(1971), and from information by Sam Rosenblum(USGS, written, commun., 1970). The area contains less granitic gneiss than the Liberian age province(White and Leo, 1971) and extensive areas are underlain by isoclinally folded biotite-rich paragneiss and migmatite. Some iron-formation (but less than in the Liberian province), and amphibolite also are present, and undeformed intrusive granite and pegmatite are present along the coast. P. Dion(oral commun., 1970) observed evidence of faulting along the geologic boundary shown as trending generally northeastward from Greenville(pl. 1). Dion and Van Griethuysen(written commun., 1970) also reported that granphite-bearing paragneiss is associated with some of the migmatite.

The trend of shortwavelenth magnetic anomalies indicate that rock foliation and the structural trends of the folded paragneisses and migmatite curve northeast to north-northeast as shown on plate 1. The layers dip 40^{o}-70^{0} to the southeast(P. Dion and H. Van Griethuysen, oral commun., 1970), and the structural trends of the folds can be traced for long distances on the magnetic maps(for example, pl. 2). H. J. Van Griethuysen and P. Dion (oral commun., 1970) observed prominant layering in traverses normal to the structural grain. They also reported some evidence of rock foliation within the basement rocks parallel to the inland dike zone in areas where the Eburnean province is cut by the dike zone.

Pan-African province

Much of the Pan-African age (ca. 550 m.y.) province(pl. 1) is underlain by mafic and pelitic rocks metamorphosed to the granulite facies(White and Leo, 1969, 1971); amphibolite, biotite-garnet paragneiss, pelitic schists, iron-formation, and granitic gneisses are also present. Some migmatite, pegmatite, and massive granitic rocks are also present in this zone, but the proportion of felsic rocks is much less than in the Liberian age province. This can be deduced from generalized radiometric data (compare pl. 1 & 4) which generally show a lower radiation level in the Pan-African province. White and Leo(1969) note that the differences in average composition between rocks of the Pan-African and Liberian age provinces indicate that the original crystalline Pan-African rocks were unlike the presently exposed rocks in the Liberian province. The Pan-African granulites have not been retrogressively remetamorphosed, possibly because of deep burial in the crust where insufficient water was available. The structural grain in the Pan-African belt in general trends northwest, in contrast to the northeast trends in the Liberian age province.

Sedimentary rocks

White(1969) has divided the unmetamorphosed sedimentary rocks along the coast between Monrovia and Buchanan(pl. 1) into Paleozoic(?) Paynesville sandstone, Lower Cretaceous Farmington River Formation, and Tertiary(?) Edina Sandstone. The Paynesville sandstone, less than 1 km thick, occurs in faulted basins near Robertsfield, and on the coast near Long Reef Point. It is overlain by graywacke, arkose, and conglomerate of the Farmington River Formation, which in turn is locally overlain by the Edina Sandstone. The basins probably subsided during the deposition of the Lower Cretaceous rocks. They were discovered during the study of the aeromagnetic survey data for the continental shelf(Behrendt and Wotorson, 1969a). The discovery stimulated petroleum exploration on the shelf, and extensive seismic reflection surveys have been made by private companies; exploratory drilling started in 1971.

Diabase dikes

Diabase dikes are the most common of the various mafic intrusive rocks in Liberia. White and Leo(1969) and White(1969-70) mapped the dikes in three zones: a northern zone in the Voinjama-Zorzor region; an inland northwest-trending zone parallel to the coast, and a coastal zone extending from Sierra Leone to the vicinity of Greenville. The aeromagnetic data indicates many dikes in these zones, as shown in plate 1. The northern zone trends roughly east; the inland zone, about 80-120 km wide, can be traced from Sierra Leone to the Ivory Coast border; and the coastal zone has been inferred(Behrendt and Wotorson, 1970c) to extend beneath the continental shelf. Two sills associated with the coastal dike zone have been dated at 176 and 192 m.y.(White and Leo, 1969). Behrendt and Wotorson, (1969a) have suggested that these sills were intruded during tectonic activity associated with the beginning of the separation of Africa from South and North America(see fig. 3). No reliable ages have been determined for the dikes about 90 km inland, but magnetization directions(S. Gromme, written commun., 1969) suggest that they may be similar in age to the dikes of the coastal zone.

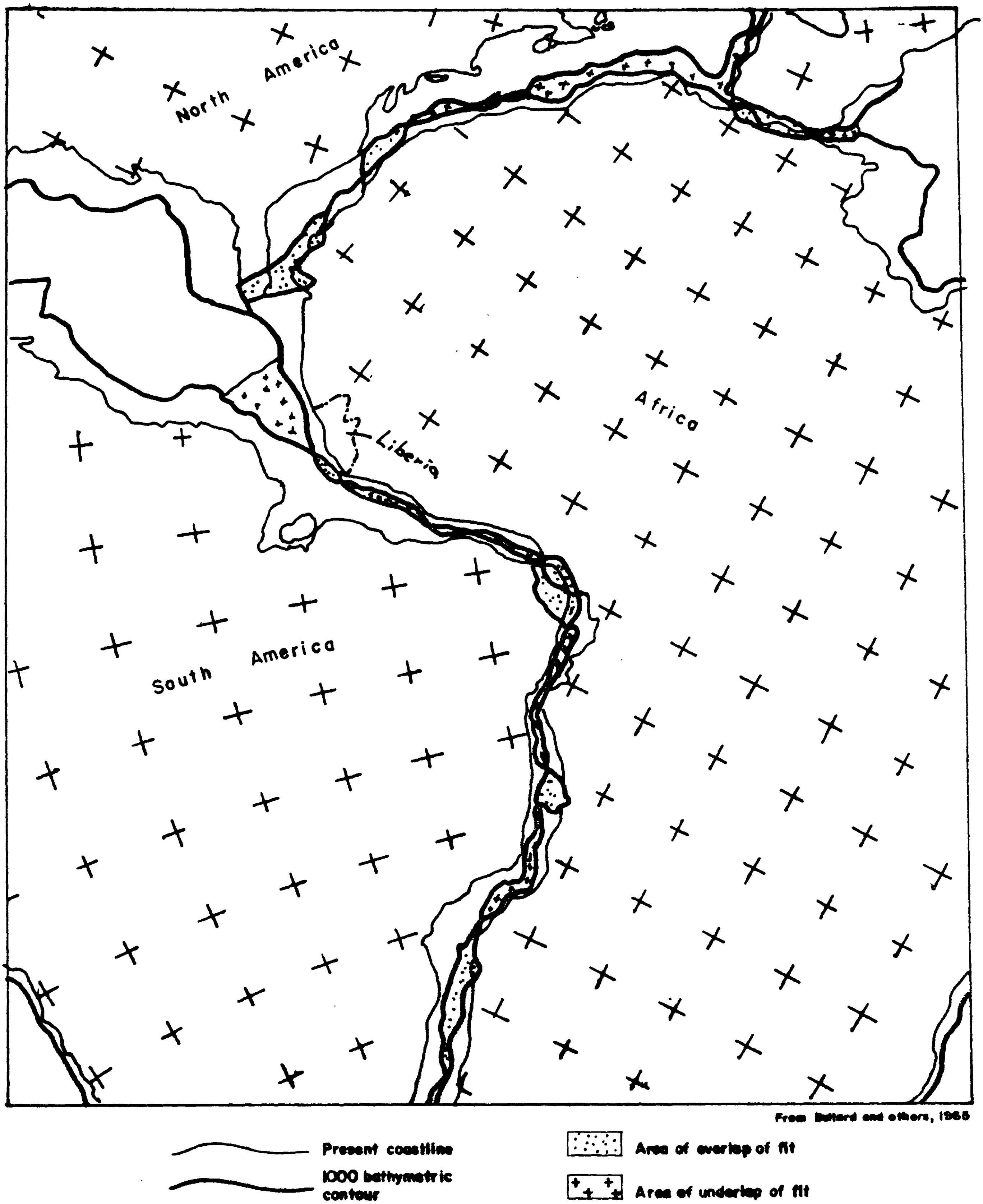

Figure 3. Reconstruction of predrift configuration of parts of continents around the Atlantic, taken from Bullard and others (1965). Note the good fit in the eastern third of Liberia and the poorer fit in the western two-thirds. The coastal zone of diabase dikes in Liberia does not continue along the eastern one-third of the coast.

Most observed dikes are vertical and commonly are between 5 and 30 m thick, but the thickness ranges from a few centimeters to about 100 m (White and Leo, 1969; White, written commun., 1970). The dikes in the coastal zone and those about 90 km inland(pl. 1) are strongly magnetic, and are associated with negative magnetic anomalies. Preliminary results indicate remanent magnetizations that average 0.001 and 0.0034 emu in the present field direction for the coastal and inland zones, respectively, and that have negligible susceptibility(S. Gromme, written commun., 1969). Six dike samples from the coastal zone, however, have reversed magnetization(without negative magnetic anomalies). Diabase sills in the coastal area commonly intrude the Paynesville Sandstone(White, 1969). Other bodies, which appear to be sills at the surface, must have substantial vertical extent to cause the several-hundred-gamma magnetic anomalies(fig. 6) associated with them(Behrendt and Wotorson, 1969a).

White and Leo(1969) report a number of thin short kimberlite dikes of unknown age that trend north-northeast, cutting obliquely across the foliation of the gneissic rocks in westernmost Liberia. These dikes have no apparent associated magnetic anomalies.

GEOPHYSICAL SURVEYS

Aeromagnetic and total-count gamma radiation surveys, flown simultaneously during the 1967-68 dry season, consist of approximately 140,000 km of traverse, mostly along north-south lines 0.8 km apart over land and 4 km apart over the continental shelf(pl. 2) Continuous photography and Doppler navigation provided horizontal control. Flight altitude was 150 m above terrain. Individual quadrangle maps showing the aeromagnetic data and the aeroradioactivity data at 1:250,000 scale have been released (Behrendt and Wotorson, 1971a-q; Wotorson and Behrendt 1971 a-c.).

Aeromagnetic survey

Time variations in the magnetic field measured with a fluxgate magnetometer were removed by adjustment at crossings of east-west control lines. Variable contour intervals of 10, 50, 250, and 1,000 gammas were used, depending on horizontal gradient. The data were compiled at 1:40,000 scale and reduced to various scales.

Subsequent to compilation of the survey, we digitized the 1:40,000-scale maps on a one-minute grid. USNS *Kane* absolute total-intensity data(Lowrie and Escowitz, 1969), overlapping our survey over the continental shelf, allowed a datum adjustment of +25,980$\pm$ 35 gammas to our survey, neglecting secular change(the two surveys were made about 6 months apart). With the assistance of Gordon Andreasen and Paul Zabel of the U. S. Geological Survey, we removed Cain's "Field G"(Cain and others, 1965) and automatically contoured the residual maps at 1:250,000 scale. These were joined at 1:500,000 scale, and the contours generalized over the entire country at a 100-gamma interval. The very high amplitude anomalies were eliminated in this compilation. Plate 2 shows the total magnetic intensity map and plate 3 presents the residual total magnetic intensity map, both at a scale of 1:1,000,000.

Discussion

Short-wavelength anomalies.--Steep gradients associated with the shallow magnetic basement are apparent over most of the area in plate 2. The predominant northeast magnetic grain associated with the Liberian age province changes to a generally northwest trend in the coastal area over the Pan-African age rocks; thus the magnetic pattern parallels the structural grain in these provinces. The boundary between the Liberian and Pan-African provinces (pl. 1) also is apparent on plate 2 as shown by the change in foliation direction from northeast in the Liberian province to northwest in the Pan-African.

We interpret that the prominent break in the magnetic fabric that extends northeast from the vicinity of Greenville represents the western limit of sediments deposited in a trough immediately prior to the Eburnean event. This magnetic break would be a good marker to aid in predrift reconstructions if it could be identified in South America. The dividing line between the Liberian and Eburnean age provinces is probably 50-60 km farther northwest, as suggested by Hurley and others(1971), but has no obvious magnetic expression. Any of several small changes in the magnetic pattern may be indicative of the Liberian-Eburnean province boundary.

A band of northwest-trending anomalies about 90 km inland clearly delineates the dike zone, which can be traced from Sierra Leone to Ivory Coast(for example, fig. 4). The diabase dikes in the coastal area also are clearly indicated in plate 2 by northwest-trending linear anomalies. The magnetic maps(Behrendt and Wotorson, 1969a) indicate that these dikes extend seaward beneath the continental shelf. The magnetic anomalies associated with dikes in the coastal zone become sparse southeast of Greenville and apparently cease to exist beyond Sasstown, although it would be difficult to detect them in this area of the high-amplitude northeast-trending anomalies. Geologic traverses along the beach revealed only one dike east of Greenville(about 7 m wide near 8°30'W)(White, written commun., 1970). We suggest that the coastal diabase dikes are more closely associated with the opening of the southern extremity of the north Atlantic than with the later(perhaps 130-150 m.y. B.P.) opening of the south Atlantic. White(written commun., 1970) collected limestone beach pebbles near Monrovia which he says ".....are definitely lacustrine, and are tentatively dated at Late Jurassic to Early Cretaceous. They place a maximum age on the marine transgression of roughly 150 m.y." The coastal dikes predate the limestone, and if they are associated with rifting in the North Atlantic, they were probably precursors to active drift and separation of the continents. The reconstruction of Bullard and others(1965) of the continents around the Atlantic(fig. 3) shows a poor fit in the area of the Liberian coast where the edge of the continent, as indicated by the 200-meter bathymetric contour(pl. 1), curves from a southeast trend to an east trend into the Gulf of Guinea east of Libera. We suggest that this point, where the trend changes, is the southern limit of intrusions associated with the early opening of the north Atlantic in this area of Africa.

Small positive anomalies associated with the east-west dikes in the northern part of the country suggest a reversed field direction that would indicate a different age from the other dikes; many associated anomalies are easily located on large-scale magnetic maps. The weak metamorphism and alteration of some dikes in this zone(White, 1969-70) suggest they may be older than the others.

The character of the magnetic field changes dramatically offshore over the shallow water on the continental shelf in the area northwest of Greenville. We have interpreted this as the effect of fault-bounded basins containing sedimentary rocks of Cretaceous and Tertiary age, in which depth to magnetic basement is as great as 5 km. Contours showing depth to magnetic basement are shown on plate 1.

Figures 4 through 9 are large-scale maps of parts of the magnetic map of plate 2 that illustrate some of the features discussed in this report. Figures 10 and 11 show the radiometric data overlapping figures 4 and 6, respectively. Figure 4 shows northwest-trending anomalies that are associated with the inland dike zone where it crosses northeast-trending anomalies associated with iron-formation. Figure 5 shows the anomaly caused by the mafic intrusion near Cape Mount and a portion of the magnetic field offshore. Figure 6 shows a portion of the field in the coastal area near Monrovia. The northwest-trending linear anomalies are due to the coastal dike zone. The other high-amplitude anomalies are also the result of diabase intrusions(Behrendt and Wotorson, 1969a). The effects of the deepening magnetic basement offshore is quite apparent. Figure 7 shows the magnetic field over the Nimba range iron ore deposits. Figure 8 illustrates the magnetic anomalies caused by a structure(fault?) associated with magnetic metasedimentary rocks. Figure 9 shows the strongly linear magnetic field over the isoclinally folded and faulted(?) paragneiss in the Eburnean age province.

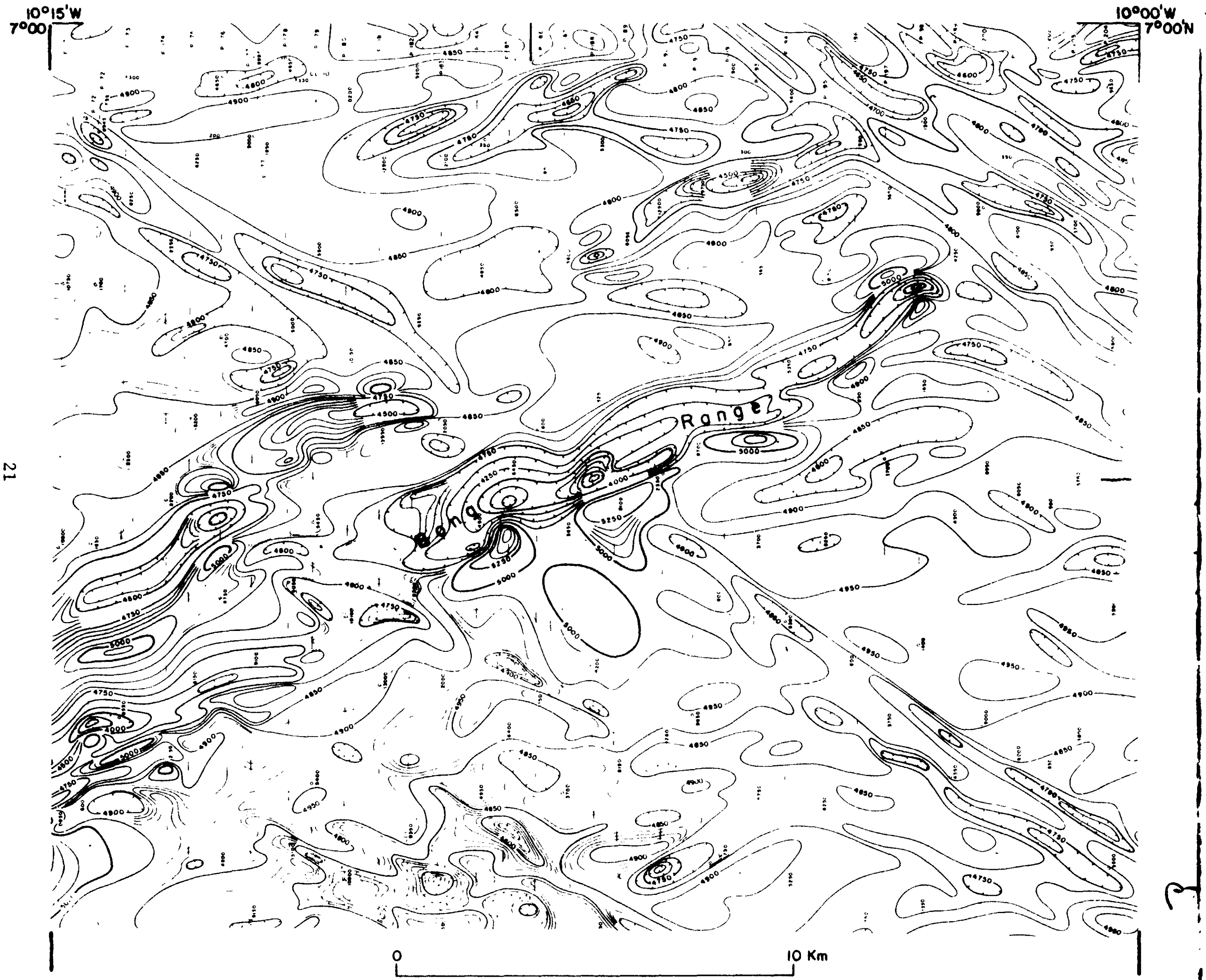

Figure 4.- Aeromagnetic map of the Bong Rang■ region. Note northwest-trending magnetic anomalies due to diabase dikes crossing northeast-trending iron-formation of the Bong Range. Contour interval in the southwest is 10 gammas and in the northeast 50 gammas. Flight line tracks including east-west control lines (eg. CL 10), numbers, and position locations are indicated.

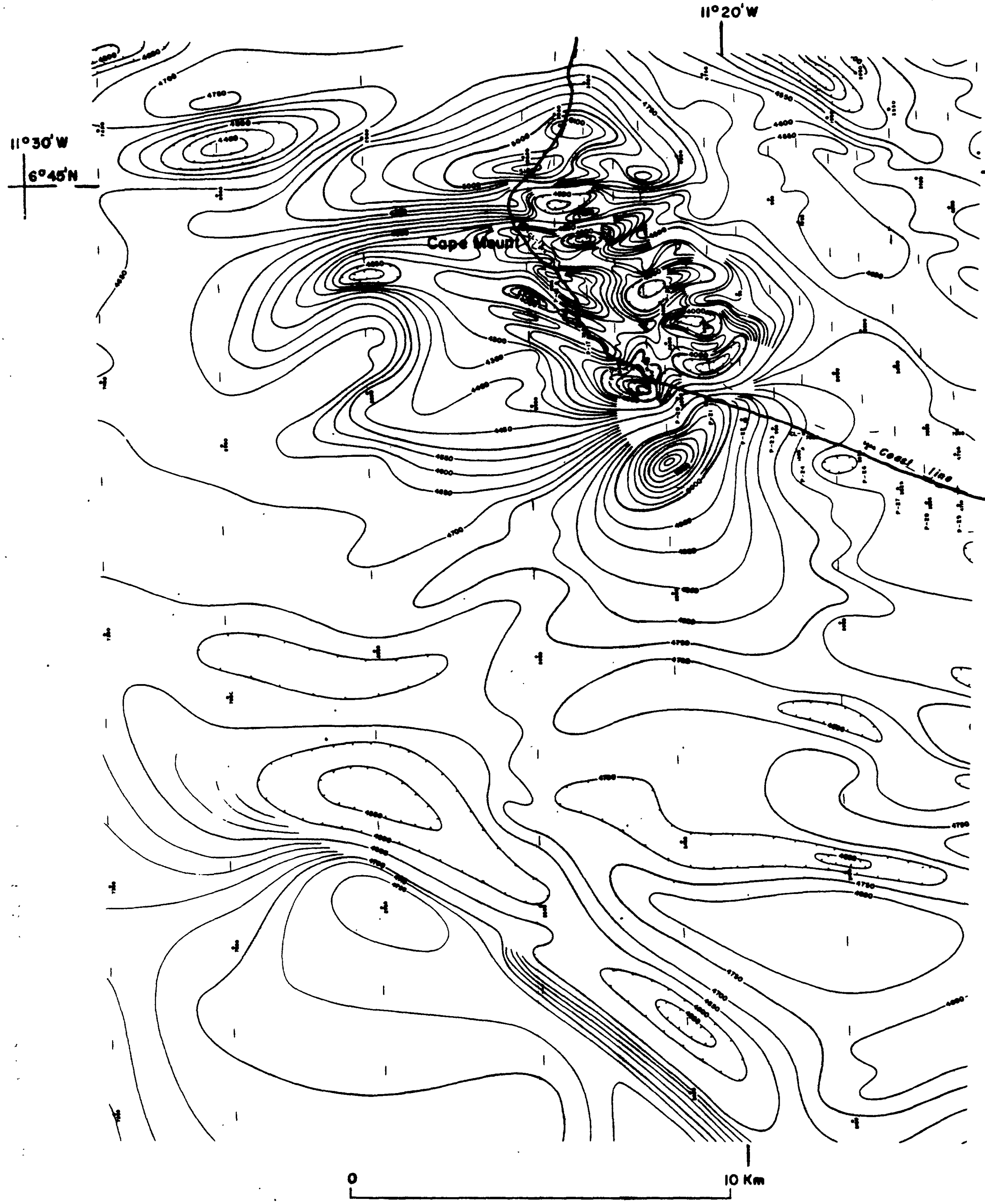

Figure 5.- Aeromagnetic map of the Cape Mount area. Note wider flight line spacing offshore. The high-amplitude anomaly is caused by a gabbro-norite complex. Note deepening of magnetic basement offshore. Contour interval 10 and 50 gammas.

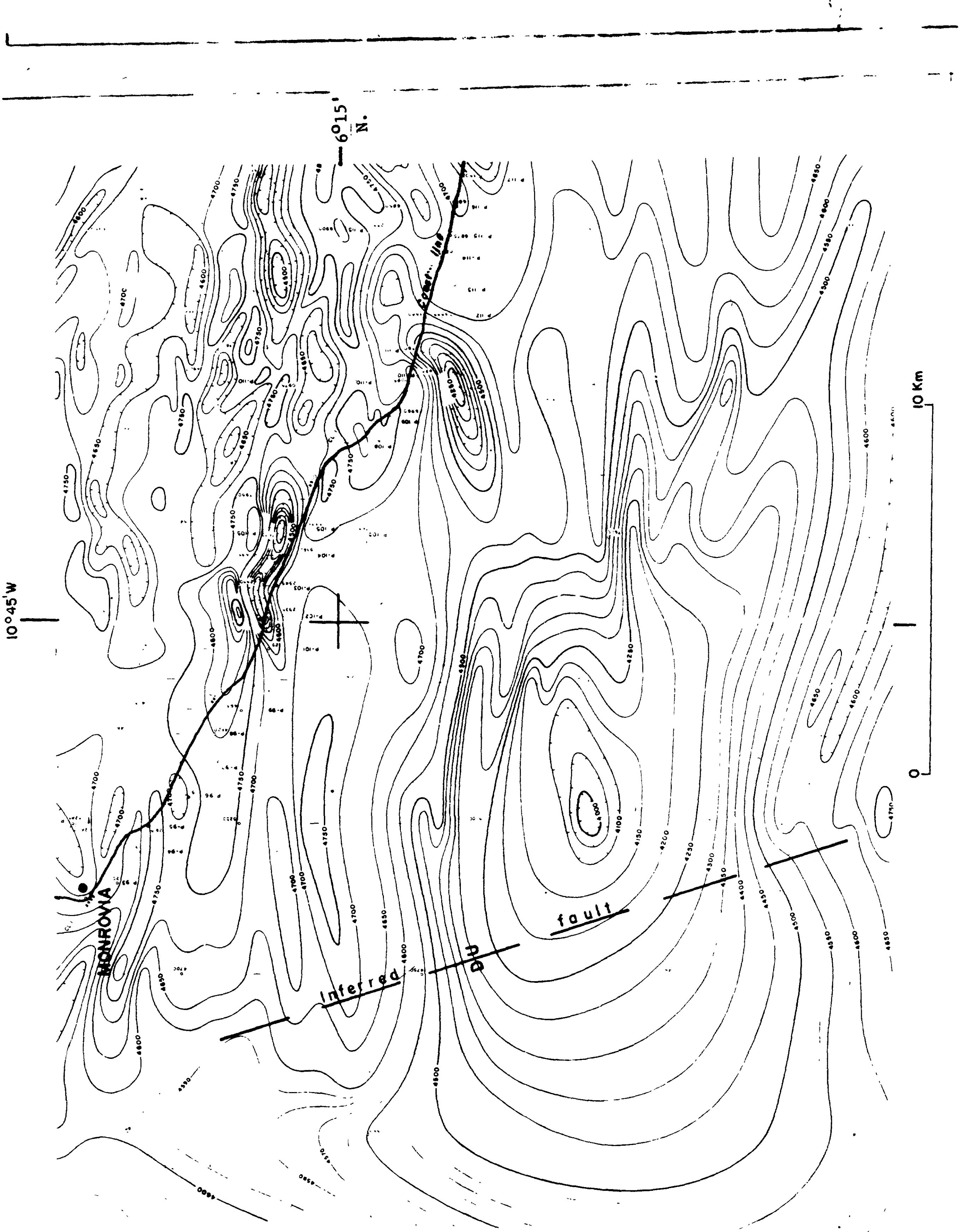

Figure 6.--Aeromagnetic map of the Monrovia area. Note deepening of magnetic basement offshore. Most of the high-amplitude anomalies are due to diabase intrusions; those with linear northwest trends indicate dikes. An inferred fault trends north-northwest. Contour interval mostly 50 gammas.

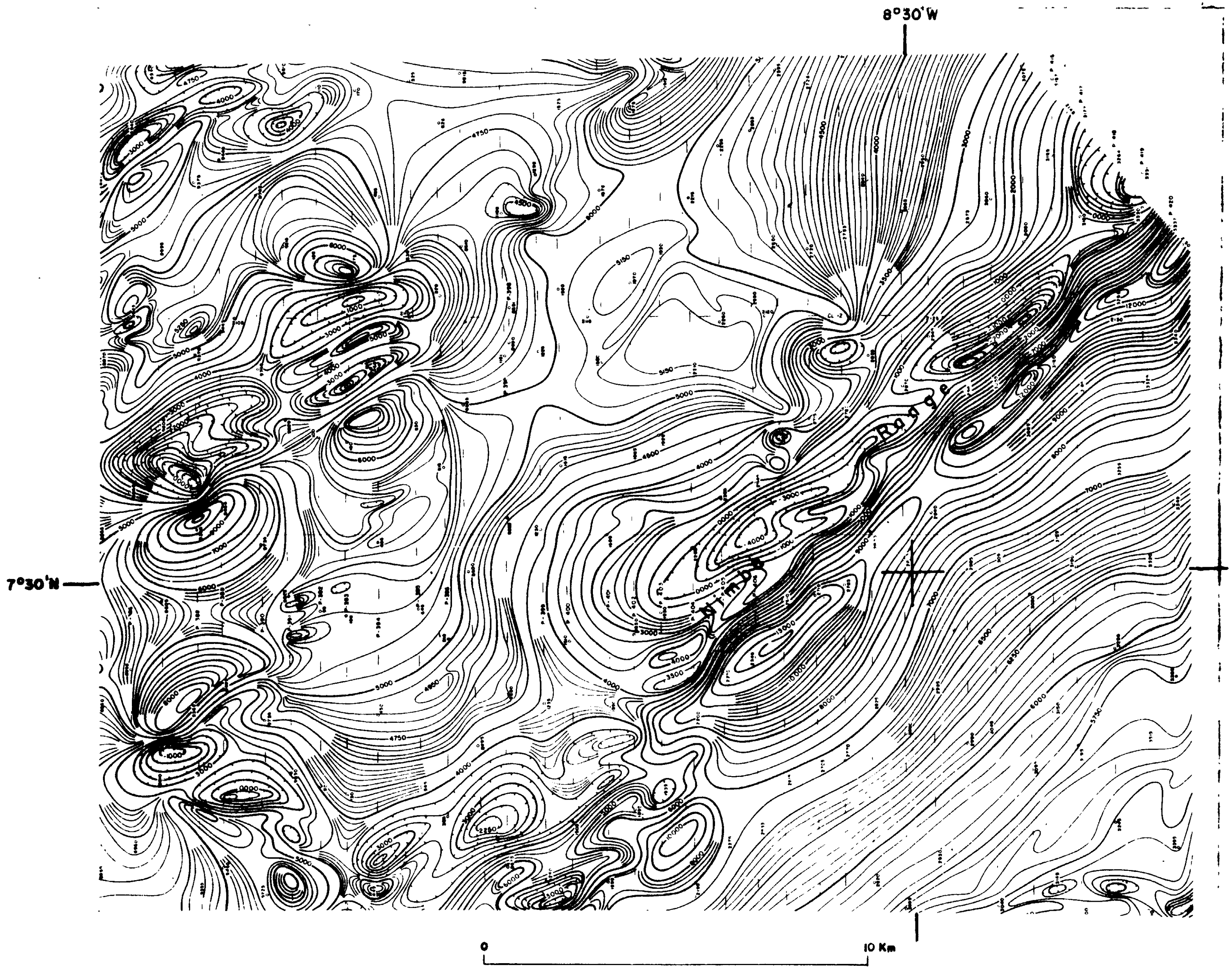

Figure 7.- Aeromagnetic map of the Nimba Range area. The high-amplitude anomalies are caused by iron-formation. Note variable contour intervals.

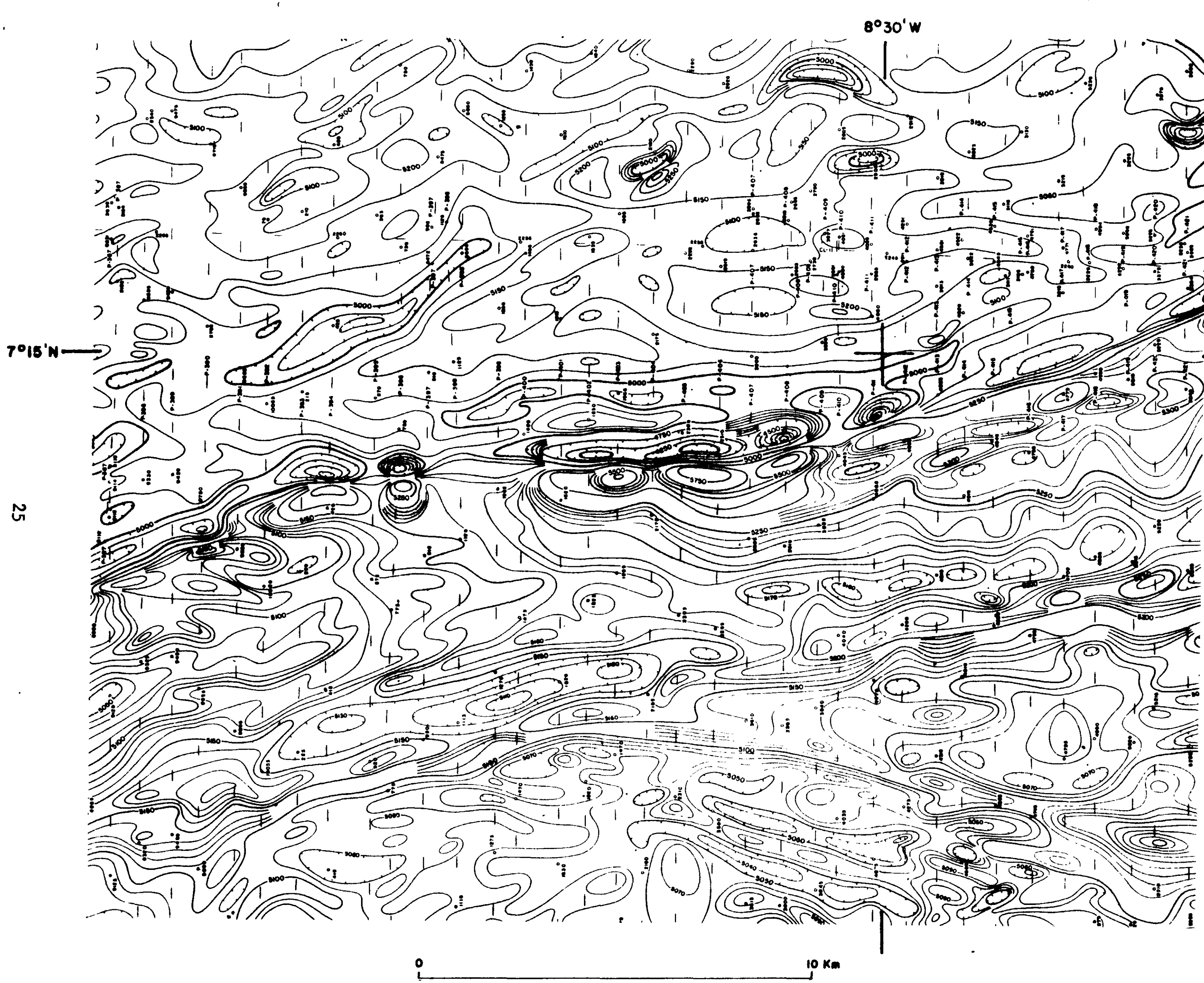

Figure 8.- Aeromagnetic map of the 7°15', 8°30'W region. The prominent linear anomaly is interpreted as a structural feature (fault?) associated with metasedimentary rocks that include some iron-formation. Note 50-gamma contour interval in north and 10-gamma interval in south.

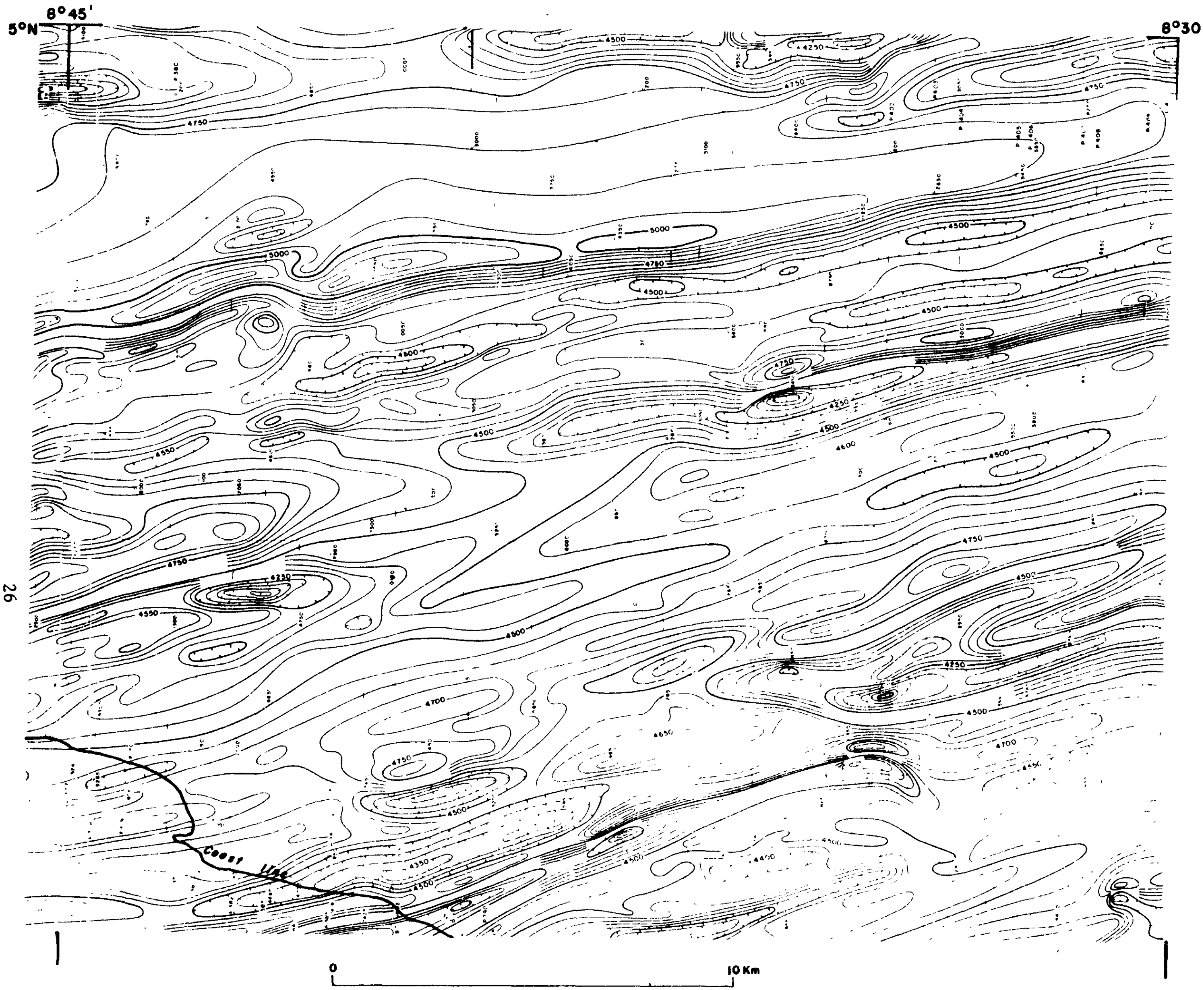

Figure 9.- Aeromagnetic map of part of the Eburnean age province illustrating linear anomalies characteristic of isoclinal folds (and faults ?) in paragneiss. The prominent linear anomaly in the northern part is suggested as a possible fault in plate 1. Iron-formation is probably associated with the highest-amplitude anomalies.

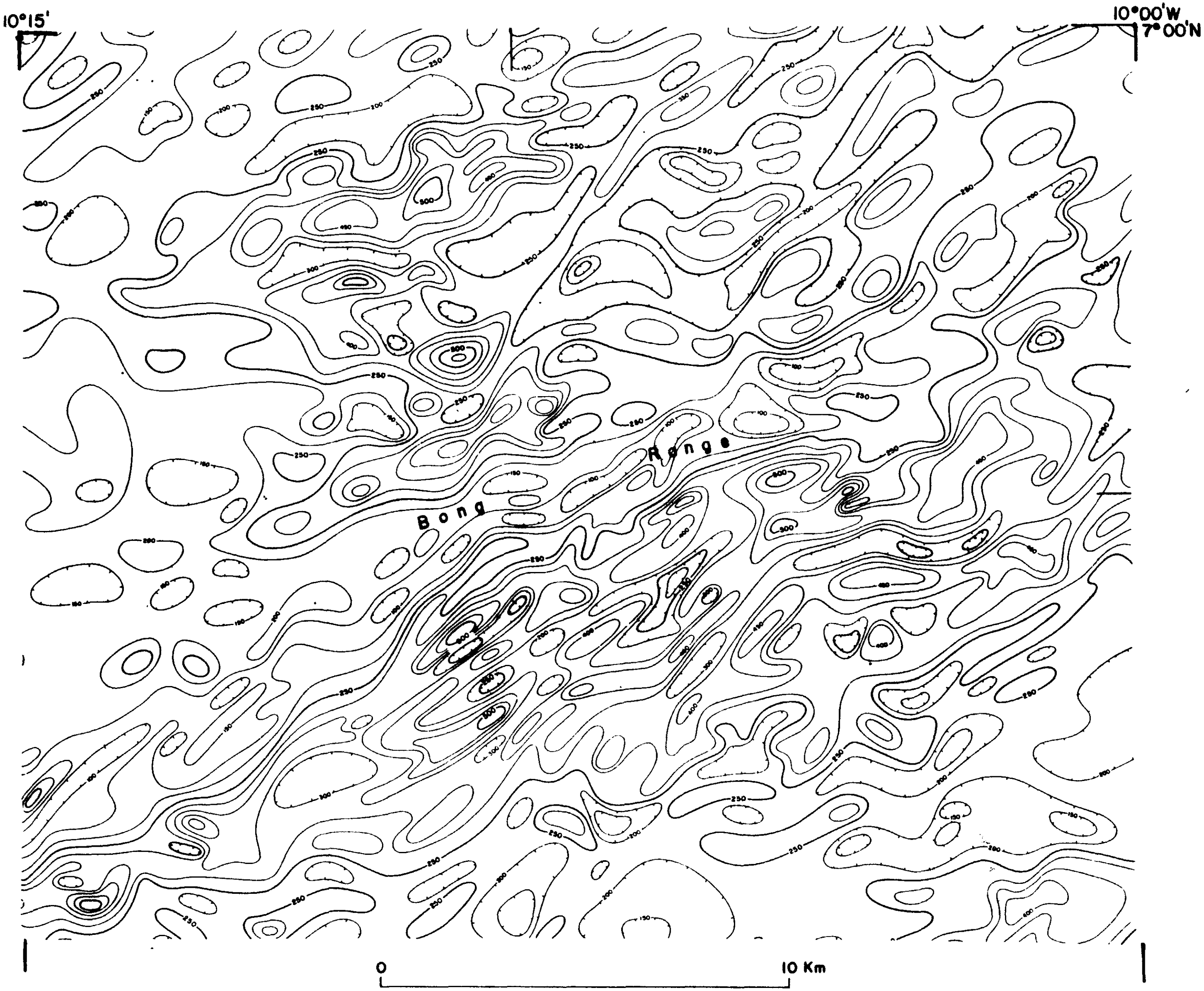

Figure 10.- Total-count gamma radiation map of the Bong Range region (same area as figure 4). Contour interval 50 cps. Note coincidence of low background (<150 cps) radiation level associated with iron-formation having high-amplitude magnetic anomalies as shown in figure 4. The effect of diabase dikes is apparent here although radiation level is low in some of the areas crossed by the associated magnetic anomalies. The northeast-trending lineation of rocks is reflected in the trend of the radiation contours.

Figure 11. Total-count gamma radiation map of the Monrovia area, same area shown in figure 6. The coastline coincides with the 25 cps contour. Contour interval is 25 cps. Comparison with geologic map of White (1969) shows correlation of diabase sills with levels from 100-200 cps. Alluvial deposits vary widely from mostly < 100 cps to 375 and 250 cps anomalies probably associated with "black sand" containing monazite. The sinuous line of 125-250 cps anomalies perpendicular to the coast in the north coincides with clay deposits mapped (Blade, 1969, 1970) along the St. Paul River.

Because of the ... is studied ... in detail at ...000,0... amplitudes of all of the ... on p... essentially ...

... magnetic ... The amplitudes shown here were ... to trough and are shown ... regard to sign, although the positive and negative portions of ... all the high- ... the very

Although we cannot identify the sources of all these anomalies, several generalizations can be made. Essentially all anomalies having amplitudes greater than 2000 gammas are due to iron-formation, which in Liberia is mainly magnetite-itabirite(White and Leo, 1969)(see figs. 4 and 7), hematite itabirite being uncommon(White, written commun., 1970). Much of the ore that is mined is hematite or martite formed by oxidation and leaching of magnetite itabirite. As no magnetite anomaly would result from hematite-martite, the large anomalies over mining areas evidently are not caused by the ore, but by the underlying magnetite itabirite, which must extend to considerable depths. Drilling at Nimba and elsewhere has shown that the ore bodies are small in relation to the enclosing itabirite(White, written commun., 1970). At the one mine(Bomi Hills) where the ore is predominantly magnetite (as high as 70 percent Fe), our 1968 magnetic data show no decrease in amplitude compared with unpublished data obtained in 1953, although the bulk of the ore was removed during the interval 1953-1968; this also illustrates that the anomalies are not caused by ore bodies. The highest amplitude anomalies are 18,000 gammas in the Nimba Range(fig. 7); 18,000 gammas in the Bea Mountains; 12,000 gammas in the Wologisi Range; 12,000 gammas about 25 km northeast of Gahnpa; and 9,000 gammas in the Putu Range. The locations of the Mano River, Bomi Hills, Bong, and Nimba iron mines are shown in plate 2.

Many of the 1000-2000-gamma anomalies are over iron-formation, but others are possibly associated with mafic or ultramafic intrusions. One of these, over an ultramafic(?) body near Juazohn, also has an associated 30-mgal positive gravity anomaly(fig. 16). Preliminary investigations of the feature indicate the presence of anomalous amounts of nickel and cobalt in laterite (H. Gruijs, W. H. Muller Co., oral commun., 1969). Other high-amplitude anomalies similar to that over the composite gabbro and norite pluton near Robertsport(fig. 5)(White and Leo, 1969) are probably caused by mafic intrusions.

The relatively high amplitude(1000 gammas or less), strongly linear anomalies in the Eburnean age province(fig. 9) are probably the result of isoclinally folded paragneiss layers, including amphibolite and iron-formation, as such rocks and structures have been identified along the coastline in this area(R. W. White, written commun., 1969; S. Rosenblum, written commun., 1969). In Ivory Coast, manganese has been found along trends and in association with these magnetic anomalies in the area east of Harper(Bagarre and Tagini, 1965). Some of the anomalies should be investigated as potential targets for mineral exploration.

<u>Residual magnetic map.</u>--The residual magnetic map(pl. 3) shows a number of anomalies not apparent in plate 2; these and other features can best be interpreted by comparison with plates 1 and 2. We attach no geologic significance to the regional 400-gamma level observed throughout the map. The most striking features are the several hundred gamma, 20-80 km wide, northeast-trending anomalies that cross the entire country. Profile A-A'(fig. 12)(location indicated on pls. 3 and 6) crosses one of the anomalies and shows a good correlation of a residual magnetic anomaly with a 25-mgal gravity anomaly.

These broad anomalies in Liberia are continuous with similar anomalies in western Ivory Coast and Sierra Leone(Strangway and Vogt, 1970), as indicated by surveys in these countries adjacent to the Liberian borders. Similar anomalies exist over Precambrian basement rocks in Guyana and Surinam and are used by Strangway and Vogt(1970) to place constraints on predrift continental reconstructions. These authors also show profiles in eastern Ivory Coast and conclude that the linear anomalies shown in plate 3 do not continue across the entire country.

The major break in the Eburnean age province trending northeast from the Greenville area is visible in plate 3 but is less striking than in plate 2. Another boundary farther east shows several hundred gammas relief and suggests a major geologic discontinuity.

The broad northeast-trending anomalies, which are so apparent in plate 3 in the Liberian age province, also exist in the Eburnean province, but are obscured by superimposed linear shorter wavelength anomalies parallel to them.

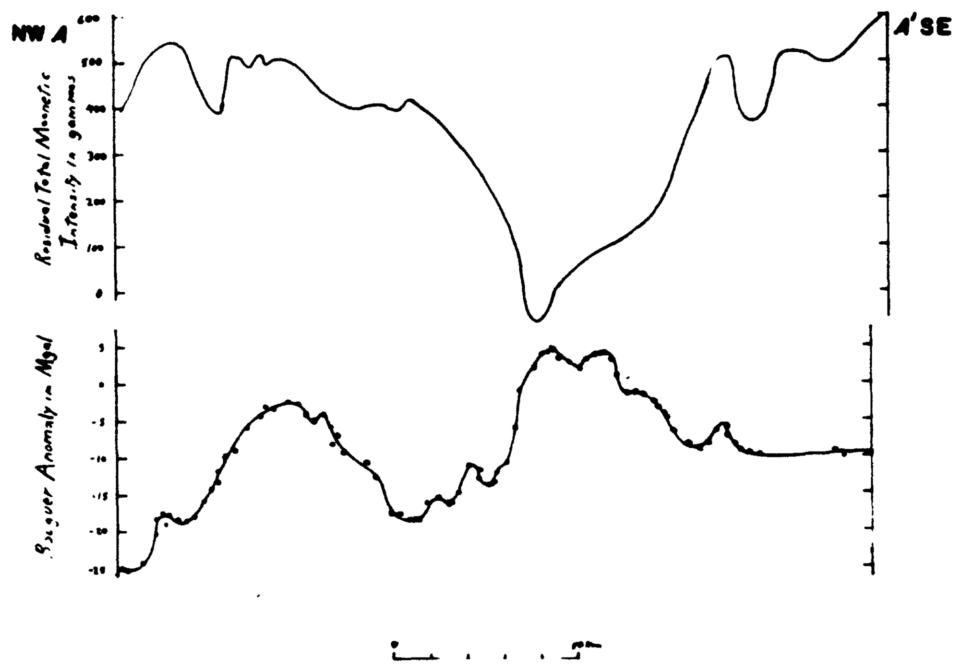

Figure 12.- Gravity and residual magnetic profiles along section A-A', plates 3 and 5. See figure 13.

Comparison of plate 3 with plates 1 and 2 and the geologic map of White and Leo(1969) shows the coincidence of near-surface and residual magnetic and geologic trend directions in the Liberian age province. Therefore, we can infer that the origin of the anomaly bands dates back at least to the Liberian age thermotectonic activity ca. 2700 m.y. ago. Subsequent tectonic activity in the Eburnean province has only modified their general character. A number of the broad anomalies are coincident with linear short-wavelength anomalies on plate 2, suggesting that the sources(or edges of sources) of the broad features approach the surface in these areas. The gravity and magnetic profiles in figure 2 and 13 illustrate this. The masses of rock having the magnetization contrasts that cause the broad anomaly bands must be of substantial vertical extent to produce the amplitudes observed as discussed below. In some of the wider anomalies, such as that shown in figure 12, the thickness of the anomaly-producing bodies must be a significant part of the crust above the Curie isotherm as discussed below(see fig. 13).

Strangway and Vogt's(1970) results in South America, as compared with data published by Hurley and others(1967), show that the anomaly bands occur primarily over rocks equivalent to the Eburnean age(of Africa), although one date of 2700 $\pm$ 300 m.y.(corresponding to the Liberian age thermotectonic activity in West Africa) falls in the area of the anomaly bands in Guyana. Thus, comparisons of these various data show that these anomaly bands are associated with tectonic activity in some of the oldest rocks known in the predrift continental nucleus which later separated into Africa and South America.

The origin of these long-wavelength northeast-trending anomalies is unknown. Behrendt and Wotorson(1969b), Behrendt and others(1968) and Zietz and others(1969) correlated similar anomalies over Precambrian terrane in the Colorado Rocky Mountains with shear zones. On this basis we suggest the possibility of a similar correlation in Liberia. Small shear zones are common in the gneiss of the Liberian age province and have trends parallel to the regional foliation(White and Leo, 1969).

Geologic maps of central Liberia(Offerberg and Tremaine, 1961) show large mapped areas of augen gneiss and "slur gneisses." Possibly there is a correlation between these geologic features and the broad negative anomalies. This is apparent in the Gbanka quadrangle(Behrendt and Wotorson, 1971e). Further geologic mapping may help test this explanation of the broad anomalies.

Profile A-A'(fig. 12 and 13) crosses the broadest and one of the highest amplitude broad anomalies in the Zorzor and Bopolu quadrangles. Whether any shear zone is associated with rocks in this area, and whether the anomaly illustrated in figure 12 is of similar origin to the others shown on plate 3 are unknown. The data suggest that this anomaly(fig. 12) may be different from others. Comparison of plates 3 and 6 shows a negative correlation between residual magnetism and the Bouguer anomaly in the area of figure 12, and positive correlations with two or three anomalies in central and eastern Liberia.

The broad anomaly bands(pl. 3) in the Eburnean province continue over the shallow magnetic basement of the continental shelf to the edge of the magnetic survey. The northeast-trending anomaly bands are obscured to some extent by northwest-trending anomalies northwest of Greenville over the continental shelf; these are probably caused by diabase intrusions or basaltic flows buried beneath sedimentary rocks. Previously(Behrendt and Wotorson, 1969a) we showed that the anomalies associated with the diabase intrusions continue out beneath the continental slope to merge with the typical broad rough magnetic pattern associated with sea floor spreading and extrusion of basaltic flows during reversals of the magnetic field subsequent to the separation of the continents.

Plate 3 also shows a number of short-wavelength anomalies which can be easily correlated with near-surface geologic sources; these anomalies are also visible in plate 2. The mafic intrusions at Cape Mount and near Juazohn are examples, as are the broad anomalies over the iron-formation extensively exposed in the Nimba and Wologisi ranges. In general, however, we caution against using the residual magnetic map to study short-wavelength anomalies, considering the coarse one-minute(1.8 km) grid interval used in digitization, and the generalization and smoothing used in the contouring of plate 3. Plate 2 and the larger scale magnetic maps(for example, figs. 4-9)(Behrendt and Wotorson, 1971a-q; Wotorson and Behrendt, 1971a-c) should be used for examination of detailed anomalies.

The Pan-African thermotectonic event(ca. 550 m.y.) did not obliterate the northeast trends of the broad anomaly bands, although it altered the northeast-trending foliation observed in the surface geology, and the short-wavelength magnetic anomaly patterns illustrated in plates 1 and 2. The diabase dike zone 90 km inland is not apparent on the residual map(pl. 3), but there are suggestions of a westward curving of the anomaly bands within, and southwest of the dike zone. This curving is continuous onto the continental shelf across the 176-192 m.y. old coastal dike zone. Therefore we conclude that the Pan-African age thermotectonic activity "imprinted" previously existing Liberian age rocks and did not generate new crust.

Because most of the basement rocks in the Pan-African province are granulite facies(but include some amphibolite facies) metamorphic rocks, the temperature associated with the Pan African event must have been above the Curie isotherm. As it would be unlikely that remanent magnetization produced ca. 550 m.y. ago would produce anomalies similar to remanent magnetism acquired ca. 2700 m.y. ago, we conclude that the source of the long wavelength anomalies, having Liberian age trends, is not remanent magnetization. Therefore these anomalies must be the result of induced magnetization and must reflect variations in bulk magnetite concentration in the upper kilometers of the crust. Possibly detailed sampling and analyses of magnetite concentration in areas of positive and negative residual anomalies might aid in the understanding of their origin.

We have computed three theoretical, two-dimensional models to help explain the residual magnetic and gravitational effect associated with one of these long wavelength anomalies. Figure 13 illustrates calculated and observed anomalies along profile AA'(pls. 3, 6; fig. 12). The theoretical bodies range from 10 to 30 km in thickness, with susceptibility contrast from 0.0043 to 0.0026 emu, and density contrast from 0.05 to 0.024 g/cm^3, respectively.

These models represent the limits within which the geologic origin of this anomaly probably lies. The base of the thickest body(fig. 13 c) must approach or exceed the Curie isotherm depth, and although appearing to give the best magnetic fit, is somewhat unreasonable geologically. The calculated Bouguer anomaly for model c has a flatter gradient than the observed, suggesting that the model is too thick. Even the thinnest model(a) is quite thick from geologic considerations but represents about the limit for the magnetic models. A body thinner than those shown would have even more anomalous edge effects. The magnetic susceptivility, while high for all the models, would be almost unreasonable for anything thinner than a. The density contrasts are low and reasonable for all models(compare table 1).

Lindsley and others(1966) show the relationship between magnetic susceptibility and magnetite content. Based on their graph, the susceptibilities in the computed models suggest a magnetite content between 0.5 and 1 percent. This seems quite high for metamorphic rocks, but the susceptibilities are within the range reported by Lindsley and others(1966).

The anomaly that we selected to fit has the highest amplitude of the broad anomalies in Liberia(it also has a good gravity traverse across it). The other long wavelength magnetic anomalies could be fitted to similar bodies, having smaller dimensions and lower magnetizati ns, that would be more easily explained geologically. Therefore, we conclude from the simple models in figure 13 that the longwavelength magnetic anomalies can be accounted for by variations in magnetization(probably induced) of the metamorphic rocks extending to considerable depths in the crust.

Aeroradioactivity survey

The total-count gamma radiation data flown at a mean terrain clearance of 150 m, were automatically corrected for altitude variations, and have been adjusted to a level of 220 m. The east-west control lines allowed reduction to a common datum. Cosmic radiation background was removed by extending the flight lines over the Atlantic Ocean and assuming zero radiation level over the water. Three thallium-activated sodium iodide crystals, 12 cm in diameter and 5 cm thick, were used. The original data were contoured at intervals of 25 and 50 cps referred to 180 cps per μr/hr. The data were compiled and reduced at the same scales as the aeromagnetic survey. Figures 10 and 11 show examples at about 1:125,000 scale. The contour maps were generalized as shown in plate 4 to permit presentation at 1:1,000,000 scale. The occasional, several flight-line-wide radiation level changes shown in the 1:250,000 scale maps(Behrendt and Wotorson, 1971i-q; Wotorson and Behrendt, 1971c) were probably the result of rain suppression of gamma radiation, and have been subjectively smoothed out in the 1:1,000,000-scale map shown in plate 4. Plate 4 and the large-scale radiometric maps(for example, figs. 10 and 11) illustrate many changes in radiation level which we interpret as caused by geologic contacts between contrasting rock units. Some of these are indicated in plate 5.

Discussion

In general, the higher the radioactivity background the more felsic the terrane(see fig. 14). Mafic granulite-facies rocks and unmetamorphosed sedimentary rocks in the coastal areas generally have low amplitudes($<$100 cps). Granite and granitic gneiss, which comprise the bulk of the mapped bedrock in the country(see fig. 2) have a high and quite variable radioactivity background. We interpret this to be the result of great variation in potassium feldspar and biotite in granitic rocks in Liberia. Sam Rosenblum(written commun., 1970) and G. W. Leo(written commun., 1968) gave an average of 20-30 percent and range from 0-60 percent for potassium feldspar and an average of 10-15 percent and a range of 0-30 percent for biotite. Biotite would commonly contain concentrations of Th and U, as well as K. Although abundances of K, Th, and U in Liberian rocks are not known, available analyses of K_2O from bedrock samples do show a general straight-line relationship to tota-count gamma radiation below 500 cps(fig. 14).

The correlation coefficient r = 0.81 indicates a significant correlation, as a correlation coefficient of r = 0.47 is required at the 1 percent significance level for a sample this size. As we would expect a general correlation between mostly nonradioactive K and the radioactive elements Th and U.(Clark and others, 1966), the correlation in figure 14 is not surprising, but it is encouraging that this survey, flown over thick forest and deeply weathered rock with very few outcrops, reflects bedrock properties. Consideration of figure 14 suggests that the high-amplitude anomalies shown on plate 4 indicate anomalously high amounts of Th and U, as improbably high K_2O concentrations would be required to explain the anomalies on the basis of potassium alone.

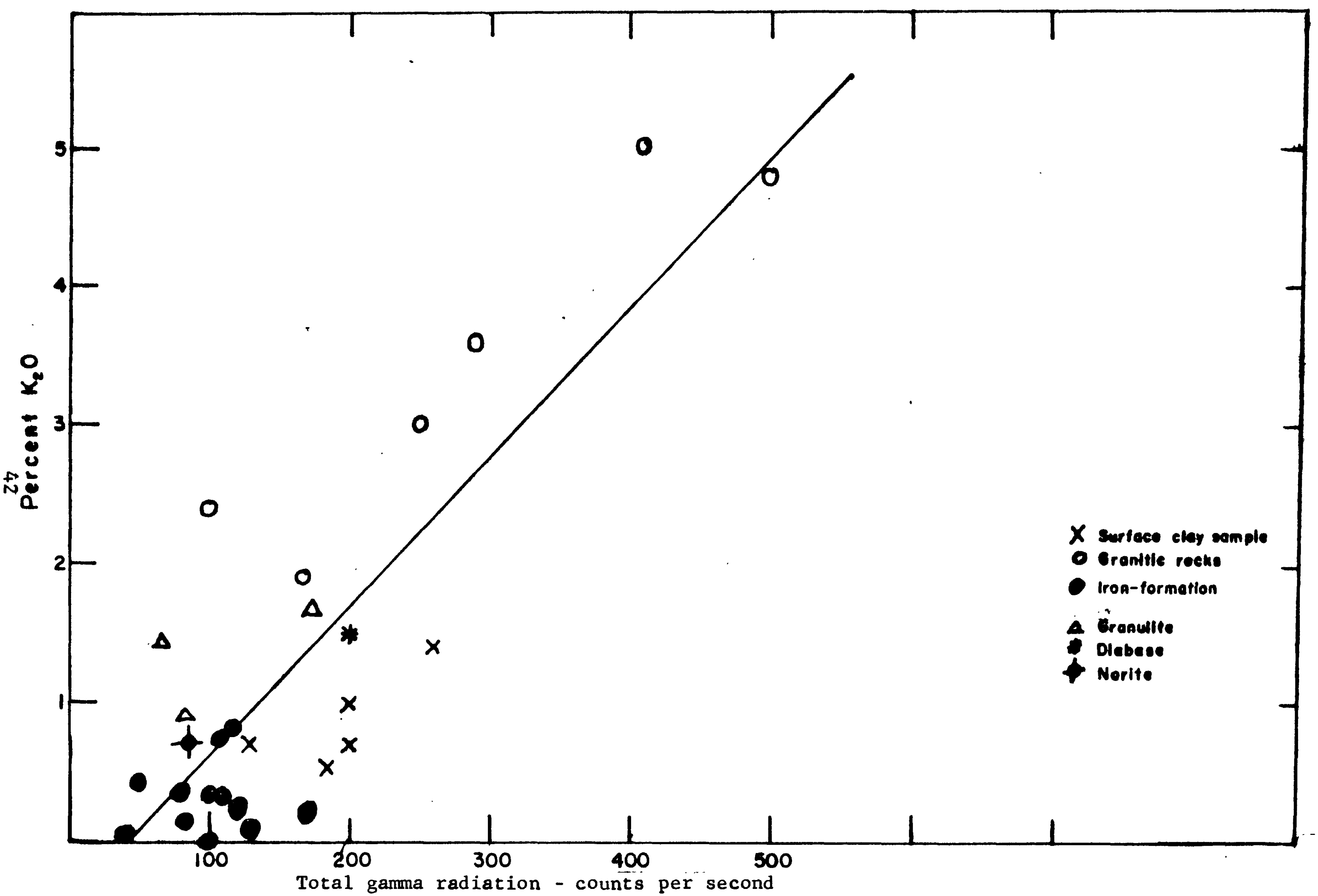

Figure 14. Content of K_2O for several rock types and surface clay samples from Liberia compared with radioactivity data. The least squares regression line has the equation: percent $K_2O = -0.45 + 0.0108\ R$ where R is total gamma count. The standard deviation is $\pm$ 0.79 percent K_2O; correlation coefficient in is 0.81.

Figure 14 illustrates the general relation of several rock types to radiation level. This graph should be considered in using the radiactivity data(pl. 4) for geologic mapping. Granite and granitic gneiss are not distinguishable radiometrically and have a high variability in K and in radiation level, ranging from 2-5 percent K_2O, and 100-500 cps, respectively. Comparison of plate 4 with White and Leo's(1969) geologic map shows that most of the variation on the radioactivity map is within areas of granitic rock. Various units within these terranes can in places be mapped at reconnaissance scale on the basis of the radioactivity data(pl. 5). Plates 4 and 5 and the large-scale maps can be of assistance, if carefully compared with field geology. In general, all the areas shown as above 250 cps on plate 4 are granitic terrane, as well as most between 100 and 250 cps(see also fig. 2).

The radioactivity map shows a good contrast between the granitic terrane, the more mafic terrane, and the metasedimentary rocks. The iron-formation and other metasedimentary rocks show an obvious contrast with the granitic rocks, and their general trends are apparent(compare pls. 1, 4, and 5; figs. 4 and 11). The contact between the granulite belt in the coastal area and the granitic gneiss is evident, and is indicated as contact A in plate 5. The break trending northeast from Greenville within the Eburnean age province, interpreted as the west edge of the paragneisses (pls. 1, 2 and 3) also is readily apparent in plate 4.

The radioactivity data, even at the small scale shown here, show positive anomalies above 100 cps over the thin diabase sills mapped by White (1969) and White and Leo(1969)(fig. 11) whereas the sills have little or no magnetic effect. For example, much of the area above 100 cps, within the low background radiation level over the indicated sedimentary rocks in plate 1, is diabase(see fig. 11). Diabase dikes in several places(pl. 4), show negative anomalies where they cut high-radiation-level terrane. Clay deposits mapped along the St. Paul River(Blade, 1970) and along the Farmington River(R. W. White, written commun, 1970) also show moderately high radiation levels(see fig. 11); obviously additional information is required to make effective use of the radioactivity data for geologic mapping in specific areas.

Plate 5, which shows geologic contacts inferred from radioactivity data, is an example of one type of geologic interpretation that can be made from the radioactivity maps (compare pl. 4). Hypothetical interpretations of this kind must be evaluated in light of geologic mapping and in comparison with the magnetic maps. For additional discussion of the radiometric data, we refer the reader to the individual reports on the various quadrangles(Behrendt and Wotorson, 1971, i-q; Wotorson and Behrendt, 1971c).

The central area of Liberia, which contains most of the high amplitude anomalies, exhibits the highest background radiation levels. Plate 4 shows that in this area the background averages are at least two to three times higher than they are in adjacent areas. The geologic map(White and Leo, 1969) indicates nothing to explain this difference; the terrane is generally granitic gneiss over most of the interior of the country west of 9^{o}W (the eastern limit of the geologic map). A significantly higher heat flow in the high-radiation-level area than that in the low area might be expected; the U. S. Geological Survey began a program of heat-flow measurements in Liberia in 1970.

The east-west linear anomaly about 80 km long, located just south of 7^{o}N between $10^{o}15'$ and $11^{o}15'$W (pls. 4 and 5) is of interest. Samples of laminated paragneiss and laterite containing unusual amounts of monazite and zircon(S. Rosenblum, written commun., 1970) were collected from the areas of the east-trending linear anomaly about 80 km long, located just south of 7^{o}N between $10^{o}15'$ and $11^{o}15'$W (pls. 4 and 5). The 250- to 375-cps anomalies in the northwest coastal area(pl. 4, fig. 11) are known to be associated with beach deposits of black sand containing concentrations of monazite and zircon(S. Rosenblum, S. Srivastava, written commun., 1970). The ultimate source of these and other radioactive minerals probably is in the higher-background regions of the interior; the minerals are transported by rivers from the source areas and concentrated by wave action. Such concentrations may be of economic significance and therefore are worthy of further exploration. Detailed work on specific magnetic and radiometric anomalies should be guided by the use of the larger scale maps(1:40,000 and 1:250,000).

Gravity survey

We have made a gravity survey comprising approximately 1300 stations in the easily accessible areas of Liberia, as the basis for compilation of free-air and Bouguer anomaly maps. The data points are along roads having level lines and photogrammetrically determined elevations, along the coast and tide-water rivers, and along some roads where altimeters were used for elevation control. Approximately 80 percent of the stations have elevations accurate to within ± 2 m; the rest are probably accurate to within ± 5 m(this corresponds to ± 0.4 and ± 1.0 mgal, Bouguer anomaly error, respectively). Positions were obtained from modern 1:40,000-scale planimetric maps that were available in preliminary form for the entire western area, and from 1:125,000 planimetric maps in the eastern area; consequently position errors are believed negligible. A base station net was established and tied to the North American gravity base network. Terrain corrections could not be made owing to the lack of topographic maps, but all should be less than 1 mgal in this relatively flat region, as none of the data reported here were observed on the high ridges underlain by iron formation and associated rocks. Thus, the errors are well within the contour intervals shown. Additional offshore gravity data(Fig. 15, pl. 5) were available from the USCGS Discoverer 1968 cruise(H. Myers, written commun., 1969). The offshore area was not contoured, owing to the lack of adequate control in this area of steep regional gradient associated with the continental margin. A density of 2.67 g/cm^3 was used throughout in the Bouguer reduction. A map at 1:250,000 scale shows the Bouguer anomaly data for the Monrovia quadrangle (Behrendt and Wotorson, 1971).

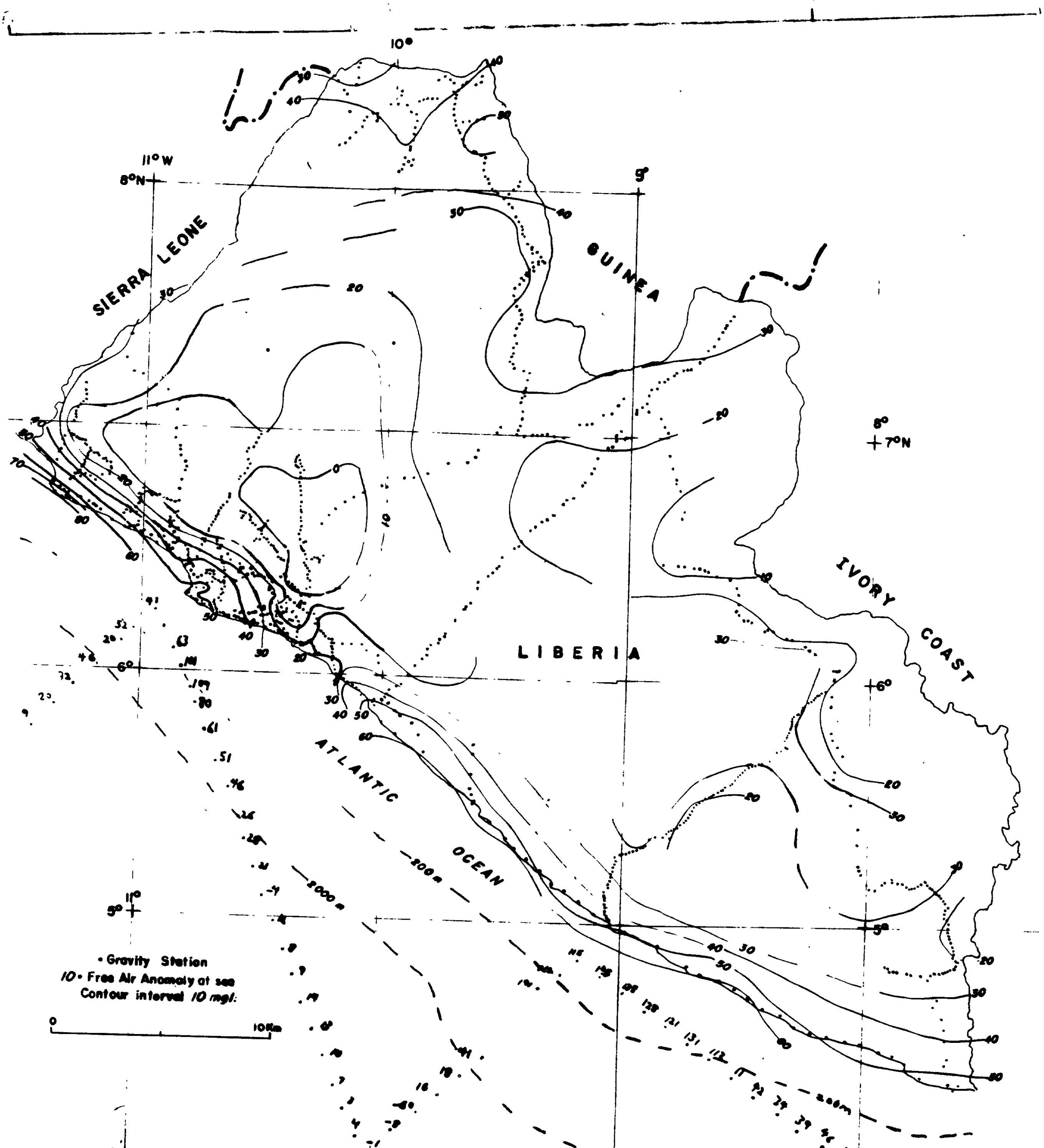

Figure 15.- Free air anomaly map of Liberia. Offshore data is from USCGS <u>Discoverer</u> 1968 cruise.

Discussion

Bouguer anomaly map.--The most apparent feature in the Bouguer anomaly map(pl. 6) is the 40-50 mgal positive anomaly along the coast from Sierra Leone to Ivory Coast. This feature has a gradient of 3-4 mgal/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 margin. In the western part of Liberia this coastal anomaly is positive over terrane of granulite facies metamorphic rocks, mapped by White and Leo(1969), but negative over quartzo-feldspathic gneiss. S. Rosenblum(written commun., 1969) measured average densities of about 3.0 g/cm^3 for granulite and 2.7 g/cm^3 for granite gneiss(table 1). Hurley and others(1971) are uncertain of the age of the granulite as samples have been dated as ca. 2600 and ca. 550 m.y.(pl. 1). Probably the granulites were deep in the crust and were uplifted prior to the time of deposition of the Paleozoic(?) sedimentary rocks. A computed model of the area inland from Monrovia(Behrendt and Wotorson, 1969a) suggests that about 2 km of relative displacement of the granulite and granite gneiss would be required to explain the residual anomaly, assuming a density contrast of 0.3 g/cm^3. Figure 16 suggests that the zone of uplifted granulite may exist offshore beneath the continental shelf in the Greenville area.

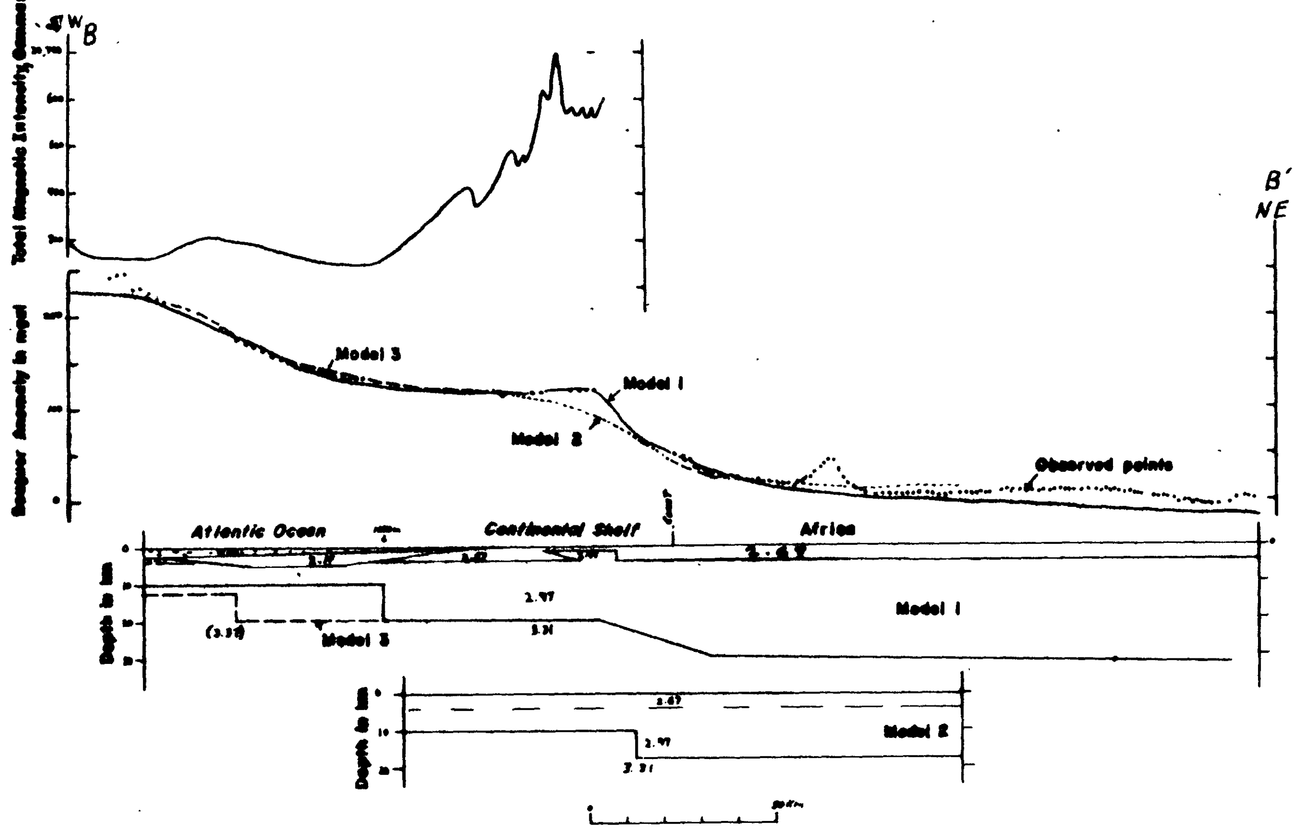

Figure 16. Suggested crustal section fitted to Bouguer anomaly data along profile B-B' on plate 6. A density of 2.67 g/cm^3 was used in the Bouguer reduction for all data. Theoretical Bouguer anomaly curves for computed models are indicated. Densities in models are indicated in g/cm^3. The density (3.37) refers only to model 3. The magnetic profile is from USCGS <u>Discoverer</u> data along the track where gravity observations were made, supplemented with some nearby data from R/V <u>Trident</u>.

Table 1.--Density of rock samples from Liberia.

Determinations by Sam Rosenblum, U. S. Geological Survey

Rock Type	Number of samples	Density range (g/cm^3)	Average density (g/cm^3)
Granite	10	2.52 - 2.67	2.62
Pegmatite 1/	2	2.54 - 2.59	2.57
Aplite 1/	2	2.55 - 2.69	2.62
Gneiss 2/	11	2.62 - 2.79	2.68
Quartzite 3/	10	2.63 - 2.84	2.70
Granitic gneiss 4/	7	2.65 - 2.75	2.70
Migmatite	3	2.66 - 2.97	2.79
Ultramafic rock 5/	7	2.86 - 3.16	2.98
Diabase 6/	6	2.87 - 3.08	2.97
Gabbro	4	2.91 - 2.98	2.94
Amphibolite 7/	15	2.93 - 3.27	3.08
Granulite 8/	4	3.00 - 3.15	3.07
Iron silicate rock 9/	4	3.36 - 3.59	3.47
Itabirite	4	3.53 - 4.66	4.12

1/ Pegmatite and aplite are local intrusives in granite gneiss, perhaps "sweated out."

2/ Undifferentiated metasedimentary gneiss, generally laminated.

3/ Abundant almandite-sillimanite-iron ore locally.

4/ The major rock type in Liberia.

5/ Partly to mostly altered to serpentine and amphibole minerals with relict olivine and pyroxene. Highest value, 3.16, is for a pyroxenite.

6/ Locally granophyric near coast.

7/ Locally rich in almandite and some pyroxene.

8/ Generally has almandite and(retrograde) hornblende; pyroxenes are salite and bronzite.

9/ Generally contains quartz and grunerite-almandite-pyroxene-magnetite-pyrite.

A negative Bouguer anomaly is superimposed on the above-mentioned coastal positive anomaly roughly over the Cretaceous sedimentary rocks just north of Marshall(Behrendt and Wotorson, 1969a); a second negative anomaly to the southeast also overlies Cretaceous sedimentary rocks(p. 6). This indicates that the Cretaceous rocks within the onshore fault-bounded basins are of low density and of substantial thickness. By contrast, the possible gravity effect of the thin Paleozoic(?) sedimentary rocks(White, 1969) is masked by basement gradients. The negative anomalies over these Cretaceous basins are complexly distorted, not only by the positive coastal anomaly, but by another negative basement anomaly which interrupts the coastal anomaly in the area of the sedimentary rocks. This makes quantitative interpretation difficult. The complexity is indicated by the position of the 25-mgal contour east of Bassa Point where it is over Precambrian granitic basement rocks rather than granulite. Along the entire Liberian coast the only major break in this positive coastal cnomaly exists over and adjacent to the only downfaulted basins onshore on the Liberian coast. If the hypothesis suggested for the coastal positive anomaly is correct, this negative basement anomaly would represent an area of the basement that was not uplifted, and from which the lighter basement rocks were not eroded. Plate 6 suggests an average amplitude of -15 to -20 mgal, which corresponds to the effect of a slab 1.1 - 1.6 km thick of granitic rock contrasted with granulite for an assumed density contrast of 0.3 g/cm^3(table 1).

Crustal structure.--The Bouguer anomaly profile across section B-B' (fig. 16) from ocean to continent near Greenville and continuing inland (pl. 6) can be compared with theoretical models 1(preferred), 2, and 3. The marine gravity and magnetic data are from USCGS Discoverer(H. Myers, written commun., 1969) and some magnetic data from R/V Trident(R. McMasters, written commun., 1970). A density of 2.67 g/cm^3 was used for the Bouguer anomalies at sea as well as on land. Although there are gaps in the gravity data, the general increase seaward from continental to oceanic crust can be observed. Sheridan and others(1969) show a seismic section across the continental margin of Sierra Leone a few hundred kilometers to the northwest. If the oceanic crust is similar off Liberia, one might expect mantle-velocity rocks at depths of about 10-12 km beneath the deep ocean. The increase in crustal thickness toward the continent might possibly be the cause of the steep gradient at the left end of the profile in figure 16. Model 3 in figure 16, computed to fit this gradient at the southwest end, requires a steep contact. Such a contact might have been caused by the rifting apart of Africa and South and North America, but should not be found this far seaward.

Bullard and others(1965) showed the fit of the continents around the Atlantic prior to drifting. Figure 3 shows the construction at about the 1000 m (500 fathom) depth contour where the fit is best. In figure 16 this contour is about 45 km toward the continent from the step shown in model 3. The fit of Bullard and others(1965) is good in southeastern Liberia and would have been better if the data showing the location of the 200 and 2000 m isobaths(pl. 1) had been available to them. Our magnetic interpretation and unpublished seismic data show that the continental shelf has little or no sedimentary cover in the area of profile B-B'; therefore the crustal model was computed for that area rather than the Monrovia area. In contrast, the Teledyne sparker profile shown by Behrendt and Wotorson(1969b), indicates that there are several kilometers of sedimentary rocks on the continental slope in this area of Liberia. The USNS Kane seismic profiles(Lowrie and Escowitz, 1969) also show sedimentary rocks on the continental slope there. The magnetic profile in figure 16 supports this interpretation.

On the basis of these considerations and information from unpublished seismic data that show velocities as low as 2 km/sec in some of the basins on the continental shelf, we suggest model 1(fig. 16) as a reasonable crustal section across the continental margin of Africa in the region of Liberia.

The coastal anomaly can be seen near the center of the profile B-B' (fig. 16). Based on the two calculated models shown, we believe that a source at a relatively shallow depth in the crust is required to explain this anomaly. Model 2 shows the effect of a 7.5 km vertical step at the crust-mantle boundary at the unreasonably shallow depth of 10 to 17.5 km. Even this extreme model cannot explain the graident of the anomaly, and a shallow source within the crust such as shown in model 1 is required. As mentioned previously, we correlated(Behrendt and Wotorson, 1969a) the coastal anomaly with the mafic granulite zone mapped by White and Leo(1969) in the Monrovia area. Their map shows only granite gneiss near Greenville, but we suggest that dense rocks, possibly granulite or amphibolite, are uplifted to a shallow depth beneath the continental shelf. We do not imply that the shape of the anomalous mass used in model 1 is geologically realistic, but rather that some mass in this location is necessary to explain the observed data. The suggested crustal thickening on the continent side of model 1 is uncertain at best. A greater density contrast, which one might expect at the crust-mantle boundary, would result in an even thinner continental crust relative to the 10-12 km likely for the oceanic crustal thickness. The high mean-crustal-density suggested by the model is consistent with known surface densities(table 1). The gravity datum of the computed models was arbitrarily chosen to fit the observed data.

The 35-mgal positive anomaly inland from the coast in figure 16, which did not fit with the models, is caused by a mass of ultramafic intrusive rock that has an associated magnetic anomaly. No measured densities are available but the amplitude suggests thicknesses of the intrusive mass of 2.8 and 1.7 km for density contrasts of 0.3 and 0.5 g/cm^3 respectively. Probably the actual density contrast is within this range.

Free-air anomaly map.--The most apparent feature in the free-air anomaly map of Liberia(fig. 15) is the coastal anomaly that also appears in the Bouguer anomaly map. The broad low over granite gneiss centered about 6°30'N, 10°15'W. noted in the Bouguer anomaly map also is the only area having values less than zero mgal. The overall free-air gravity is high, and suggests a lack of isostatic compensation. Figure 17 illustrates the free-air anomalies compared with elevation for 530 stations approximately evenly distributed throughout the country(many of the stations in the Monrovia region were omitted). Although the scatter is large, the high free-air anomaly is obvious. The correlation with elevation is most apparent above 300 m elevation, but a regression line was not computed to fit the free-air anomalies.

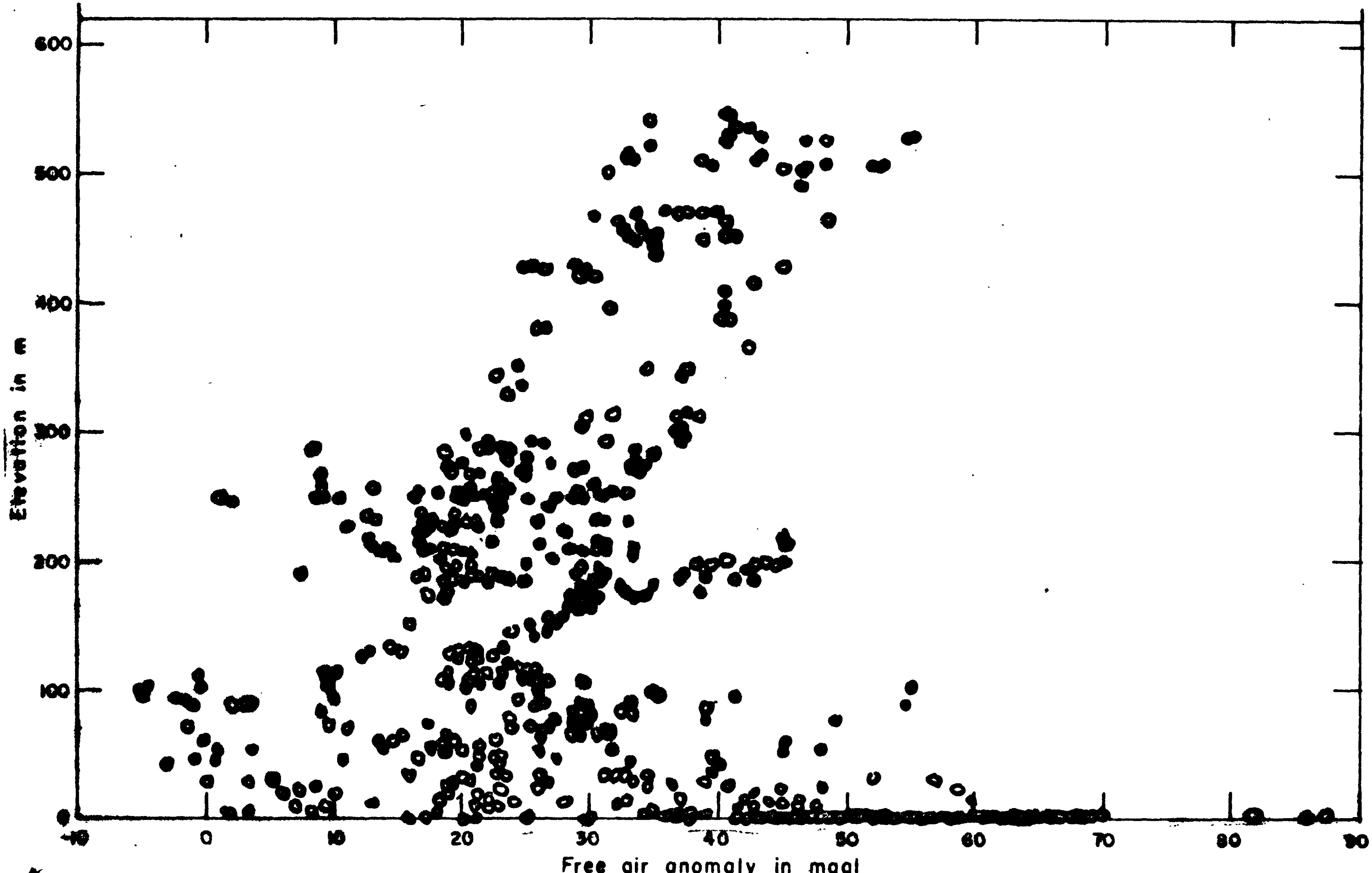

Figure 17.- Comparison of free air anomaly with elevation. Note effect of coastal anomaly and general increase in other data with elevation.

We calculated a mean free-air anomaly over Liberia by estimating average values over 15-minute squares based on the contours of Figure 14 in areas covered by data. Using these values we computed mean values for one-degree squares. The calculated mean for the entire country is + 26 mgal. As the coastal anomaly biases this value, the area over the steep gradient was omitted in figure 15; the resultant mean is + 22 mgal. The mean free-air anomaly over an area of the size and relatively low topographic relief of Liberia should be a good approximation of the isostatic anomaly. If this premise is acceptable, then the mean of + 22 mgal would be equivalent to the effect of an uncompensated slab of granitic material of density 2.67, averaging 200 m thickness over the entire country. Comparison of this value with figure 1 shows that this is close to the regional elevation of Liberia. This implies that the uplift resulting in the relatively high average elevation of Liberia is not compensated, at least over the region of Liberia. Surface densities for West Africa, computed from satellite observations, show anomalously high values over the region of Liberia and nearby areas (Koch, 1970), supporting our interpretation.

Bouguer anomalies compared with elevation.--Figure 18 compares the Bouguer anomalies for the same 530 stations with the elevations. Here the correlation with elevation is more evident than it is for free-air anomalies. The computed regression line has the equation $\Delta G_B = 18.0 - 0.075$ E. The calculated standard deviation of $\pm$ 13.9 mgal, which is an indication of the amplitude of local geologic anomalies, is a reasonable value for most of Liberia, as can be seen in plate 6. In calculation, all Bouguer values greater than 40 mgal were ommitted to avoid bias from the coastal anomaly. The correlation coefficient of the regression line in figure 18 is 0.60, which is greater than 0.12, the value required for significance at the 1 percent significance level. Mabey (1966) compared elevation with Bouguer anomalies in Nevada and determined a slope of -72 mgal/km which compares well with the value -75 mgal/km observed over Liberia. The zero elevation intercept in Nevada is -54 mgal compared with our value in Liberia of + 18 mgal, which may be another indication of the presence of a positive isostatic anomaly. Mabey (1966) also compared regional elevation over varying radii out to distances of 128 km. Unfortunately, this calculation cannot be made in Liberia at this time because the lack of adequate topographic maps. Figure 18 does suggest that we could predict regional Bouguer anomalies within an error of about 14 mgal, on the basis of elevation in areas inland from the coast.

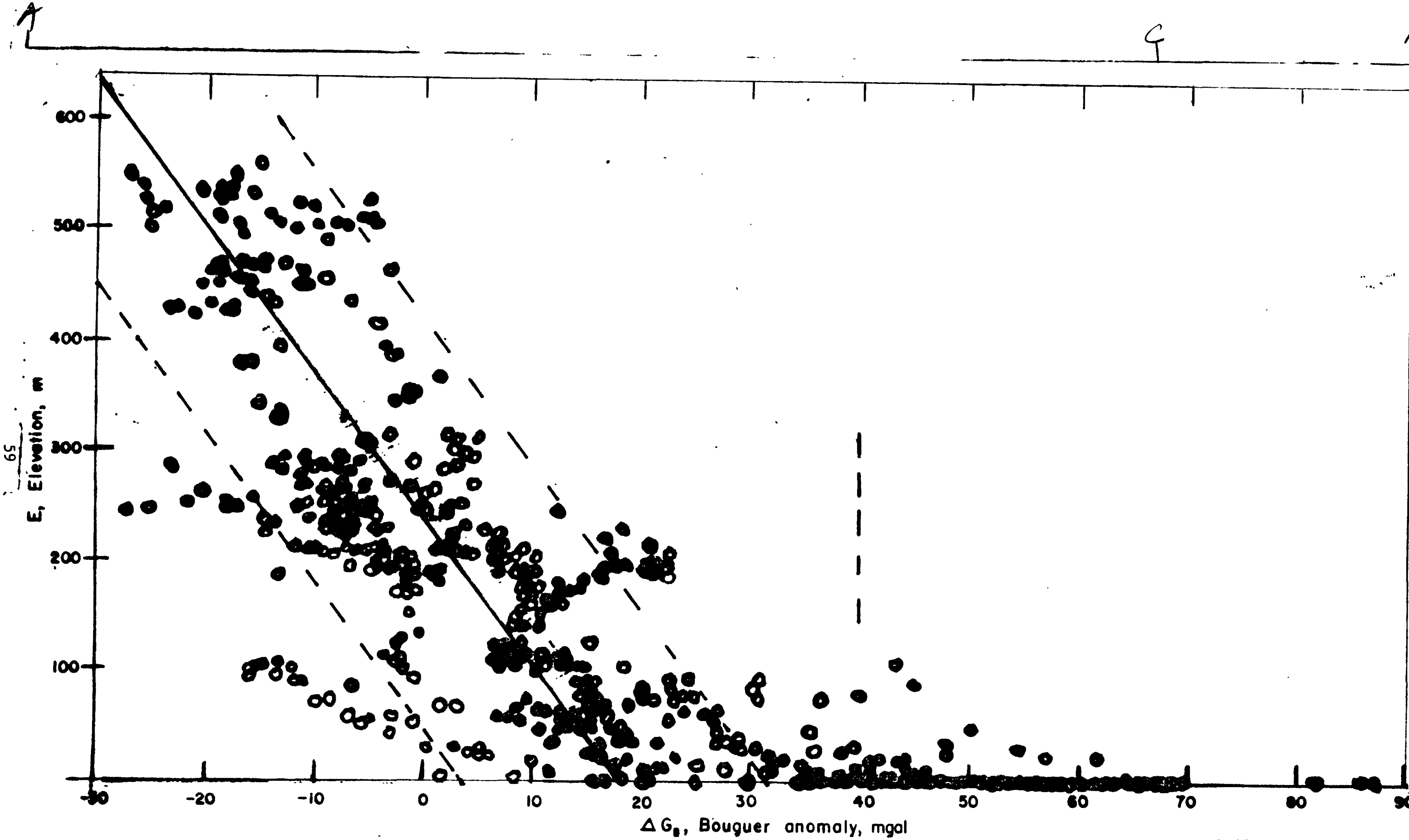

Figure 18. Comparison of Bouguer anomaly with elevation. The correlation coefficient is 0.60 which is greater than 0.12 required at the 1 percent level of significance for a sample this size. Values of ΔG_B above 40 mgal were omitted in the regression calculation.

Compilation of tectonic map

We used the geophysical data and available geologic information to compile a tectonic map of Liberia(pl. 1). Examination of the magnetic, radioactivity, and gravity data, in comparison with the geologic map of White and Leo(1969) and the radiometric age determinations of Hurley and others(1971), made it apparent that some regional generalizations were possible and desirable. Although the geologic information is sparse and would be difficult or impossible to obtain even if the area were more accessible, the total coverage of magnetic and radioactivity data for Liberia allows extrapolation of the known geology into unknown areas. The data shown in plate 1 were compiled at 1:125,000 scale, with the exception of the trends of shortwavelength magnetic anomalies inferred to be associated with foliation directions, which were compiled at 1:500,000 scale.

The features shown on plate 1 reflect variations in physical and chemical properties of rocks large enough to be detected by the geophysical surveys. This means, in the case of the aeromagnetic data, which were the major source of the information shown in plate 1, that the structures indicated must have substantial vertical and horizontal extent. Because of these conditions, some features were not observed, for example, the thin diabase sills mapped by White(1969) in the Monrovia area(fig. 11). Another limitation is the finite line spacing(0.8 km on shore, 4 km offshore)(figs. 5 and 6). The variable magnetic contour interval used in different areas made recognition of similar features possible in some areas that could not be observed in others(figs. 4 and 8). The contour interval is related directly to the geologic noise level; for example, it is easy to follow the diabase dikes through granite gneiss terrane but difficult or impossible to observe them where they cross the linear high-amplitude anomalies associated with the isoclinally folded metasedimentary rocks in the Eburnean age province. We urge the reader to keep these limitations in mind in using the map. They should be distinguished from the limitations of our interpretation and speculation.

Foliation

The shortwavelength magnetic anomaly trend directions on plate 1 were compiled from magnetic data only, although many linear trends are observed in the radiometric data. Because of the possible surface effects on the gamma ray data, the three-dimensional picture presented on the magnetic map (pl. 2) better represents the rock foliation as inferred from the magnetic grain. The foliation symbols were drawn on the basis of axes of elongate closed anomalies or along gradients of the many long linear anomalies. The anomalies associated with the diabase dikes were specifically excluded in compilation of foliation directions and are discussed separately. This exclusion probably has introduced a bias against foliation parallel to the dike zone.

Structural trends

The magnetic lineations shown in plate 1 could indicate structural elements such as limbs or axes of folds, faults, or steep contacts between rock bodies or contrasting magnetic properties. In most cases it is difficult or impossible to distinguish between the alternatives without additional geologic information(for example, figs. 8 and 9). Anomaly amplitudes of about 1000 gammas or more are probably due to iron-formation, as we have discovered in comparing the known iron-formation with the anomalies (for example, figs. 4 and 7).

The direction and location of the structural trends indicated in plate 1 conform to the magnetic contours and may be different from surface geology. This could be due to any of several reasons; the most likely are: 1) the magnetic field is the integrated effect, observed at 150 m altitude, of the structure extending to an appreciable depth beneath the surface; 2) the contours in the extremely high amplitude anomalies were difficult to draw when features only one or two flight lines wide were considered and the gradients were very steep(for example, fig. 7); and 3) effect of topography on the magnetic data.

Iron-formation in some places is not indicated as such, because lower amplitude anomalies make it difficult to distinguish from other magnetite-containing metasedimentary rocks(for example, fig. 9). In many places the magnetite in iron-formation is too sparse to produce high-amplitude anomalies. Nevertheless, all the known major iron-ore concentrations in Liberia have high-amplitude magnetic anomalies caused by associated magnetite iron-formation; we are reasonably certain that our interpretation has not missed any sizable, previously unknown deposits.

Diabase dikes

A separate symbol was used on plate 1 for linear anomalies that are associated with the magnetic diabase dikes because of the relative ease in distinguishing these bodies on the magnetic map(for example, figs. 4 and pl. 2), and their importance to'an understanding of the tectonic history of Liberia. Most of the anomalies are negative and vary in amplitude from tens to a few hundred gammas. We have previously pointed out(Behrendt and Wotorson, 1970c), on the basis of comparison of observed and computed anomalies that many or most known dikes correlated with magnetic anomalies were

too narrow where measured to account for the observed and computed anomalies, that many or most of the known dikes correlated with magnetic anomalies were too narrow where measured to account for the observed anomaly widths; it is also likely that many dikes that crop out and could be seen in the field are too thin to produce an observable or contourable magnetic anomaly. We have examined many of the observed magnetic profiles over known outcrops, and can correlate the outcrops with low-amplitude anomalies to the data resolution limit of a few gammas. Probably the dikes shown on the aeromagnetic map could be thicker at depth, which is geologically unlikely; more probably, the magnetic anomalies are caused by several narrow dikes in a zone that approximates a thick dike when observed at a survey height of 150 m. If so, possibly only one of the several dikes actually crops out. If this is true for most of the magnetic dikes shown in plate 1, then a number of these either do not crop out at all or do so only along a part of the indicated length.

The diabase dikes indicated over the continental shelf probably are beneath the Cretaceous or younger sedimentary rocks that are present in the basins, and the dikes are the sources of many of the anomalies(for example, figs. 5 and 6) used to calculate the depth to magnetic basement.

Faults

Faults are difficult or impossibly to distinguish on the basis of magnetic data from the synclinal folds known to be commonly associated with the metasedimentary rocks in the Eburnean age province(fig. 9). Many of the linear structures(as opposed to the suggested faults) mapped on plate 1 are probably faults, but we cannot make the distinction. In some places these lineations are indicated as possible faults, and in a few places as probable faults, where geologic evidence indicates faults in the vicinity. Other faults are inferred from apparent offsets in trends which suggest strike-slip movement.

Block faults are inferred in the pattern indicated along the coastal area and continental shelf(figs. 5 and 6). Here the existence of near-vertical faults was interpreted on the basis of displacements in the magnetic basement. In some places these inferred faults can be correlated with known faults that extend onshore, where they displace Cretaceous sedimentary rocks. In other places faults are indicated in seismic reflection record sections that cross the basins(Behrendt and Wotorson, 1970c). The seismic data lead us to believe that the block faults on the continental shelf are more complex than shown on plate 1, and the probable faults indicated might be considered as fault zones. This may be true of most or all of the possible faults shown on the tectonic map.

Age province boundaries

The boundary separating the Liberian and Pan-African age provinces on plate 1 was drawn from examination of the structural grain as indicated by the magnetic data and the known trends within the provinces. The dates published by Hurley and others(1971, 1967) and Bagarre and Tagini(1965) are shown on plate 1. The boundary between the Liberian and Eburnean provinces is probably 50 to 60 km west of the geologic boundary shown on plate 1 as trending eastward from Greenville. The latter boundary is indicated on the basis of the pronounced break in the magnetic data(pl. 2), whereas no such break exists at the age boundary which can only be provisionally located (pl. 1) on the basis of the radiometric age data shown (pl. 4).

Discussion

The structural patterns characteristic of the Liberian, Eburnean, and Pan-African thermotectonic events are apparent on plate 1. Within the provinces many structural lineations of probable syntectonic origin are parallel to the general trends. Other tectonic lineations of a different age have a crosscutting relation to the general trends.

Throughout the map are features shown as possible faults that trend north-northeast. None of these has been positively identified as a fault, but the general similarity of trend suggests that the trends of the magnetic anomaly patterns on which these are based are caused by tectonic activity younger than the Eburnean event of ca. 2000 m.y. ago. None of these possible faults shows any offset where it crosses the inland dike zone. Probably the north-northeast-trending linear structures are also older than the dikes in the Voinjama area. However, interpretation of these north-northeast trends are highly speculative, and they may not be faults.

Most, but not all the dikes associated with positive anomalies trend east, and cut across the Liberian age lineations in the Voinjama area. Although no determinations have been made, the positive anomalies probably indicate reversed magnetization, whereas the dikes associated with negative anomalies have normal magnetization. Some dikes in the Voinjama area have negative anomalies similar to those located closer to the coast, and of these some are weakly metamorphosed(R.W. White, written commun., 1970), whereas others are not. These relations suggest different ages of intrusion.

The major dike zone about 90 km inland is a striking feature of plates 1 and 2. This zone, which is parallel to the coast, may indicate the tensional fracturing that was a precursor to rifting(fig. 3). Right-lateral shear in this dike zone is indicated by curves and more easterly trends in linear anomalies. As has been mentioned previously, basement-rock foliation parallel to the dikes has been observed in outcrop in southeastern Liberia. The residual magnetic and Bouguer anomaly maps(pl. 3 and 6) show no effect of this dike zone. The coastal dike zone, dated at 176 and 192 m.y., extends beneath the continental shelf about as far as Greenville. The dikes shown on plate 1 in the area of the basement contours, particularly offshore, are at various depths, as indicated by the contours and do not necessarily crop out at the land surface or sea bottom. This is in contrast to the other dikes indicated on plate 1, which are at or near the land surface.

A mafic granulite belt or amphibolite may be present at a relatively shallow depth(see p.52 -54 and pl. 6) in the area of the continental shelf southwest of 5° N, 9° W. Plates 1 and 2 show a change in magnetic character that is suggestive of a fault terminating the isoclinal fold belt offshore in this area. This is the area of the postulated uplifted block of dense rock shown in the figure 16 model. If the granulite is present at a shallow depth in this area, it may not extend much farther to the southeast, as suggested by the seaward extension of the boundary of the Pan-African age zone. This zone roughly correlates with the granulite belt in western Liberia.

SUMMARY

The following sequence of tectonic events are indicated by the combined geophysical and geological information now available for Liberia:

1. Thermotectonic activity during the Liberian age period ca. 2700 m.y. ago caused folding, faulting, and shearing of granitic and metasedimentary rocks with a resultant northeasterly structural trend. Probably considerable amounts of synkinematic granitic rocks were produced by partial anatexis of metasediments during this activity, and all rocks were strongly metamorphosed. Granulites were probably first formed, and ultramafic rocks in the Liberian province may date from this time(R. W. White, written commun., 1970). Long wavelength, northeast-trending magnetic anomalies originated.

2. Thermotectonic activity during the Eburnean age (ca. 2000 m.y. ago) in eastern Liberia, caused isoclinal folding, some faulting, and metamorphism in a region chiefly underlain by sedimentary rocks, and partial anatexis of those rocks to migmatite. Older crystalline rocks (in the northwest part of the Eburnean province were remetamorphosed. Long-wavelength magnetic anomalies of Liberian age were modified but not obliterated by this activity. Some crosscutting granitic intrusives were emplaced (R. W. White, written commun., 1970).
3. Tectonic activity of unknown age caused north-northeast-trending faults(?) throughout Liberia.
4. East-northeast to east-trending dikes were intruded in northern Liberia during a period of reversed magnetic field. The ages of these dikes are uncertain; they might have formed after events described in paragraphs 5, 6, or 7, or later. Some of the dikes were weakly metamorphosed at a later time. Some of the dikes in this area were possibly intruded at a different time during a normal field polarization.
5. Pan-African age (ca. 550 m.y.) thermotectonic activity in the coastal area of western Liberia, resulted in change from the Liberian-age northeast trend of some small-scale magnetic lineations associated with foliation to a northwest direction. Long-wavelength residual magnetic anomalies were largely unaffected, but there is some suggestion of shearing in a northwest direction (this event could be associated with intrusion described in paragraph 8). Remetamorphism, partly to granulite, anatexis, and emplacement of granitic rocks occured.

6. Granulite facies rocks of relict Liberian age(?) and/or of Pan-African age in the coastal area of the Pan-African age province were uplifted and exposed. A positive gravity anomaly is associated with the granulite belt but there is no obvious long-wavelength magnetic anomaly. The part of the coastal area covered by later sedimentation (events 7 and 10) was apparently not uplifted.
7. Deposition of Paleozoic(?) sandstone presently observed in coastal area from Monrovia to about 70 km southeast.
8. Intrusion of diabase dikes in a zone about 90 km inland, across the entire country parallel to the coast took place during a period of normal magnetization in present field direction. Possible shearing of basement rocks in the dike zone is suggested by magnetic data and sparse field geologic evidence, but no large horizontal offsets are known. No noticeable long-wavelength magnetic or gravity anomalies are associated with the dike zone. This dike zone probably is of the same age at the coastal zone.

Intrusion of diabase dike zone in coastal area and continental shelf, with associated sills, intruded at dates of 176-192 m.y., cutting Paleozoic(?) sandstone during period of normal magnetization in present field direction. Some basalt was extruded at this time. This dike zone apparently does not extend far east of Greenville. Possibly it is associated with rifting and the opening of the North Atlantic and was a precursor to the separation of North America from Africa. Six dikes in this zone have reversed polarization of magnetization(S. Gromme, written commun., 1969), suggesting a different time of emplacement of some.

Kimberlite dikes of unknown age were emplaced.

9. Uplift resulted in exposure of diabase dikes, enclosing crystalline rocks, and Paleozoic(?) sandstone.

10. Seafloor spreading started in the area off Liberia northwest of Greenville (North Atlantic).

11. Deposition of Lower Cretaceous sedimentary rocks in coastal area and on continental shelf accompanied by subsidence, block faulting along west-northwest and northwest trends, and active sea floor spreading.

12. Rifting apart of Africa and South American occurred; sea floor spreading commenced in the area of the Gulf of Guinea, about 140 m.y. ago. Probably the Liberian continental shelf southeast of Greenville was involved with this activity.

13. Tertiary(?) sedimentary rocks were deposited on the continental shelf and slope.

14. Continued sea floor spreading was accompanied by extrusion (and intrusion) of basaltic rocks on the sea floor.

15. Liberia was uplifted to present mean elevation of about 200 m, apparently associated with an isostatic anomaly equivalent to the uplifted mass.

In summary the geophysical surveys have contributed valuable information to the geologic mapping program in Liberia. They have been found to be particularly useful in the interpretation of geologic features that are impossible to observe in inaccessible areas or even in accessible surface exposures. Large-scale aeromagnetic and radioactivity maps should also prove useful in unraveling geologic problems that will come to light in future field mapping. Similarly, future geologic mapping will furnish a better base for interpreting the geophysical data.

The data presented here illustrate the more general case of the usefulness of geophysical studies in humid tropical areas. Although at the planning stage there was no doubt about the potential usefulness of the aeromagnetic survey, the radioactivity results were not as predictable. We believe we have demonstrated that radioactive elements at the surface of the residual soil overlying a thick weathered zone reflect their proportional content in the underlying bedrock. On the basis of present results we recommend the use of gamma-ray spectral surveys for future work, where costs and objectives justify this approach. Conversely, we would not hesitate to use total-count gamma surveys in conjunction with aeromagnetic surveys for reconnaissance geologic mapping programs similar to that in Liberia, if the cost were significantly lower.

Although the gravity coverage is sparse, the results presented here do illustrate the usefulness of this approach, not only for obvious problems such as the study of the Cretaceous sedimentary rocks, but for problems related to crystalline bedrock, such as the transition between the granulite and granitic gneiss or the mafic plutons. Gravity surveys in inaccessible tropical areas such as Liberia are much more expensive for broad areal coverage than the airborne programs, particularly considering the problems of elevation control.

Other airborne geophysical techniques, such as electromagnetic surveys, might prove useful in mineral exploration in selected areas based on the magnetic survey but probably are too expensive at present for routine geologic mapping, on a reconnaissance scale, of a large area.

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__________, 1971n, Total count gamma radiation map of the Buchanan quadrangle; U. S. Geol. Survey open-file rept.(IR) LI-62E, scale 1:250,000; Liberian Geol. Survey Memo. Rept. 62E, scale 1:250,000.

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