A DETAILED GRAVITY SURVEY OF THE MIDDLE BENUE, NIGERIA

BY

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ABSTRACT

The results of a gravity survey carried out in the Middle Benue and discussed in this work, indicate the existence of a rift of normal width (about 40 km), buried under Cretaceous cover. This rift is axially located between the axial ridge of the trough end the northern boundary of the trough. The gravity low (about - 37 to - 15 mgals) which occur between the axial ridge and the southern boundary of the trough has also been ascribed to another rift. The interpretations further suggest the existence of buried, deeply - rooted (about 7 km) intermediate and localised volcanic intrusions, whose tops are located at about 200 to 500 m below the ground surface, just beyond the present margins of the trough and along the axial ridge of the trough respectively. The above facts suggest that the Benue trough did not only originate through rifting but that it may presently consist of two parallel rifts which are separated by an axial ridge.

Furthermore, the gravity data suggests that the Middle benue can be divided into five structural regions which includes a previously unknown (geologically and/or geophysically) region. Within the four regions which

contain known structures, the trends and locations of the structures were confirmed by the gravity data. However, features such as the trend of the Giza syncline between Radarko and Obi and the location of the axis of the Keana anticline in the project area, as deduced from the residual gravity map, did not agree with those on the geological map. The new structures revealed by the gravity data include a broad anticline about 30 km south' of the River Benue, which is axially placed within the trough as the Keana anticline about 30 to 40 km north of the river, and a normal fault which separates the two axial anticlines. The new structural region deduced from the gravity data is characterised by low gravity (values - 20 to 36 mgals)and it is a southeast trending zone which might be a zone in which subsidence is accompanied with block faulting. Finally, the results of the work also suggest possible reasons for the geological peculiarities of the trough such as the abnormal width of the trough, the folding of the sediments in the trough and the apparent lack of surface, indications of rifting at the margins of the trough.

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CHAPTER I

INTRODUCTION

1.1 Background and Aims of the present survey

The author became aware of the gravity survey of the Benue trough by Cratchley and Jones (1965) as a result of a graduate seminar he gave in 1973 on a geophysical work in Nigeria, while studying in the Colorado School of Mines, Golden, U.S.A. From the work of Cratchley and Jones and other publications on the Benue Trough, the author realised that the issue of the origin of the trough had not been resolved. Several theories have been proposed by different authors to explain the origin of the trough. Among the popular theories are:

(a) the rift origin (King, 1950)

(b) a geosyncline with folding involving the basement (Lees, 1952)

(c) a combination of a rift valley and a geosyncline (Cratchley and Jones, 1965)

(d) a spreading ridge (Burke et al, 1970)

(e) a subduction zone (Grant, 1971) and

(f) a zone with an "on and off" Cretaceous hotspot (Olade, 1975)

Some of these theories tend to contradict rather than complement each other.

Also, these theories failed to explain some peculiar properties of the trough pointed out by Wright (1968, 1970). These peculiar properties are:

(a) The fact that the width of the trough is about 130 to 145 kms. This is two to three times wider than that of a normal rift valley which is usually about 50 ± 15 kms (Holmes, 1964).

(b) The fact that the sediments within the trough are folded with their axes parallel to the axis of the trough.

In an attempt to resolve some of the problems above, raised by previous workers, the author decided to carry out a detailed gravity survey of a portion of the trough. The Middle Benue was chosen because of its relatively easy accessibility. The aims of the survey thus included,

(i) to attempt to throw more light on the controversy of the origin of the Benue Trough,

(ii) to attempt to explain why the Benue Trough is considerably wider than most rift valleys in other parts of the world and

(iii) to contribute to the general knowledge of the structural geology of the Middle Benue.

1.2 Previous Geophysical Work in the Project Area

The major geophysical work carried out in the project area prior to the present survey was the gravity work of Cratchley and Jones (1965) carried out over the whole of the Benue Trough which includes the present project area. This survey was primarily carried out to determine whether or not the trough originated through rifting. Even though the survey partially confirmed the rift theory, the limitations of the survey were the large station interval (5km) used and the gross inadequacy of roads in the entire area during the time of survey.

Between 1965 and 1976, there was no published geophysical work of any type in the project area. Ajakaiye and Ajayi (1977) carried out a detailed gravity survey of the salt springs area of the former Lafia Division, for the Nigerian Mining Corporation, purely to explore for rock salt deposit(s). Akubue (1977) carried out a resistivity and a gravity survey of the Obi coal-fields. Because of the restricted nature of the survey, the results could not contribute to the knowledge of the regional structures in the area.

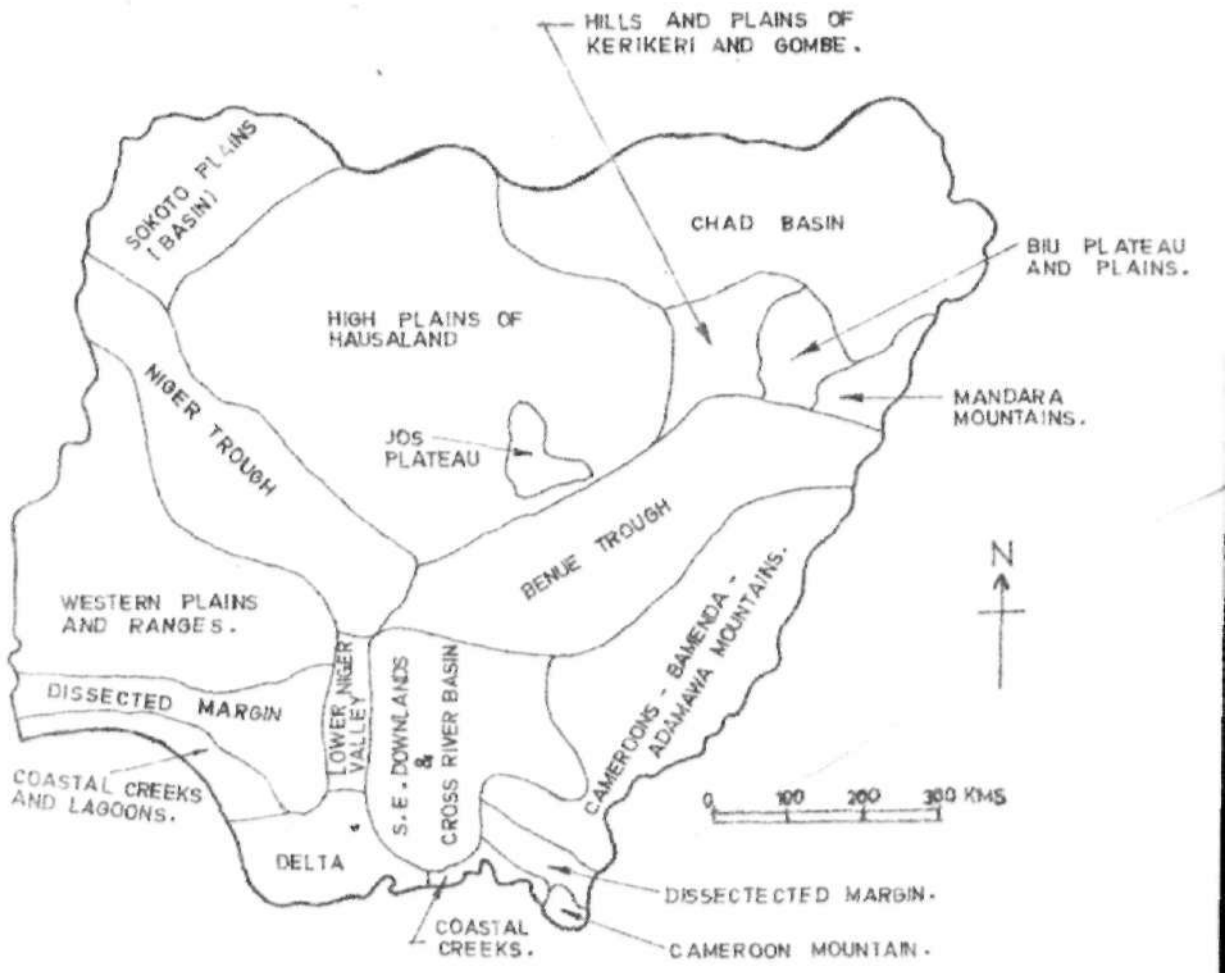
Umego (1978) carried out a detailed gravity survey around the salt pond in Ribi following the recommendations of Ajakaiye and Ajayi (1977). The primary aim of Umego's survey was, therefore, related to the origin of the salt in the brine water of the pond and not the regional structures in the Middle Benue

In view of the foregoing, only the survey of Cratchley and Jones (1965) yielded information on the regional structure of the Middle Benue out of all the geophysical surveys carried out in the area prior to the present survey.

1-3: General Description of the Project Area

1.3.1 : Location of the Benue Trough and the Project Area

The Benue Trough, a physiographic unit sandwitched between the Northern (Hausa) Highlands and the Jos Plateau to the northwest and the Cameroons-Bamenda-Adamawa Mountains to the southeast (fig 1-1), occupies the eastern section of Central Nigeria. The trough is about 130 to 200kms wide, about 500kms long and is approximately oriented in the southwest-northeast direction. The major physical feature in the area is the River Benue after which the trough is named.



NOTE :-

(1) boundaries are not fixed.
(2) some units can be subdivided.
(3) unit names are arbitrary.

(AFTER BUCHANAN & PUGH, 1969)

FIG.1.-1 : THE PHYSIOGRAPHIC (Topographic) UNITS OF NIGERIA.

The trough has been broadly divided by Cratchley and Jones (1965) into three regions, namely the Lower (Southwest), Middle and Upper (Northeast) Benue.

The project area, for the present survey, lies within the Middle Benue (fig. 1-2). It is bounded in the West by longitude $8^{o}30'E$ and in the east by longitude $9^{o}30'E$. Latitudes $7^{o}15'N$ and $9^{o}N$ form the southern and northern boudaries respectively. The project area approximately covers 22,000 square kilometres.

1.3.2 : The Relief, Climate and People of the Project Area.

The relief, both within the project area and the entire Benue Trough, is generally low. Along the River Benue, elevations are usually in the range of 60 to 70m. Towards the northern and southern boundaries of the trough, the elevations are as high as 250m. In between these two extremes, elevations increase gradually in form of rolling hills with elevation increasing towards the trough boundaries. Beyond the boundaries elevations increase rapidly towards the highlands (fig 1-3). All the rivers in the project area drain into the River Benue (fig 1-3).

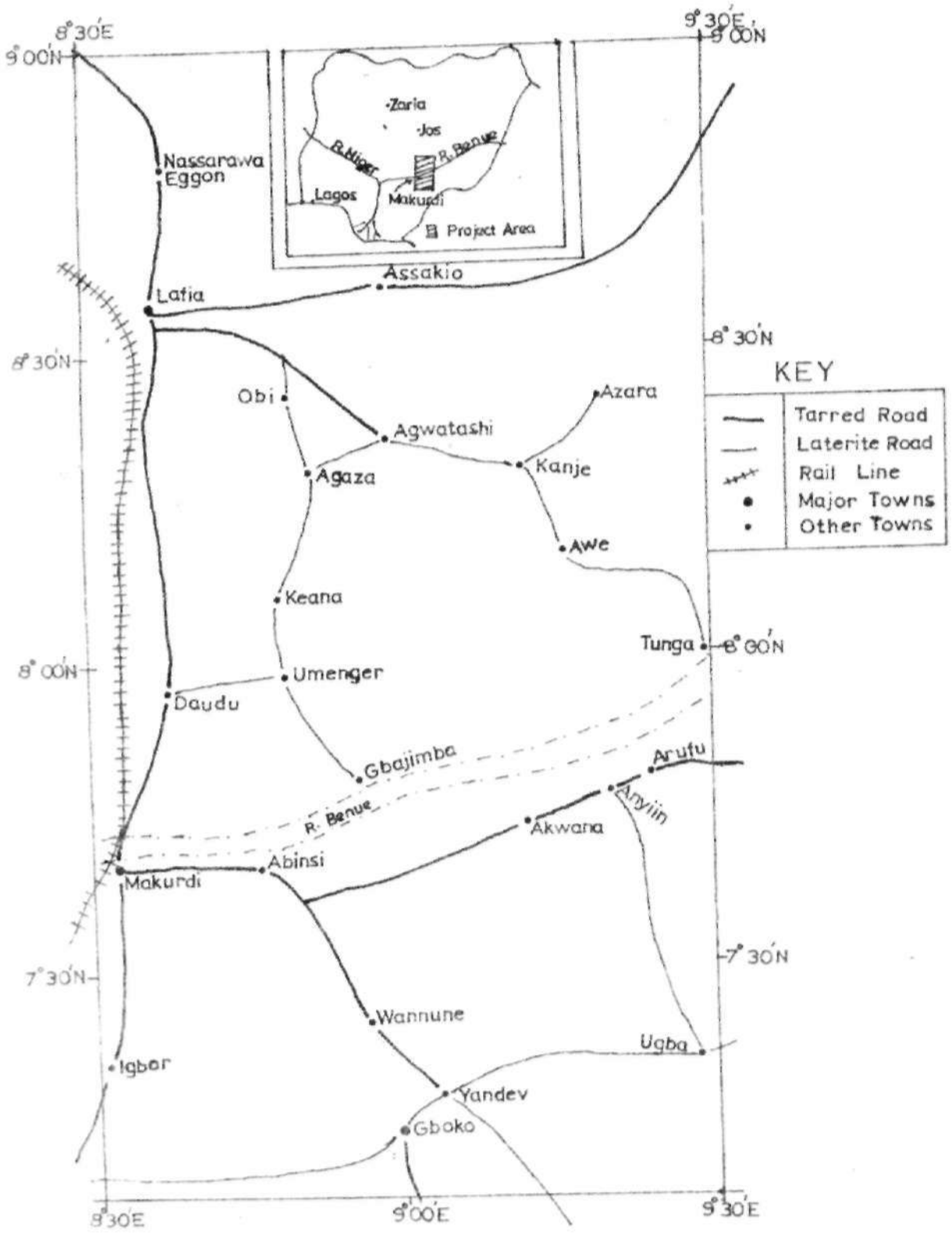


Fig. 1-2: Location Map of Project Area

The vegetation in the entire Benue Trough is mainly the "parkland savannah" or the "transitional woodland" type (Buchanan and Pugh, 1969; Udo, 1970). Because the area has a mean annual rainfall of about 1?5cm spread over six to eight months, the region is a transitional belt between the rain forest region to the south and the pure savannah (grassland) to the north. Similar to all parts of the Guinea savannah, the project areas has two distinct seasons - the wet and dry seasons. The wet season is approximately from Mid-March to Mid-November while the dry season occurs in the remaining months. Maximum temperatures in the area are up to about 33°C and 25°C during the dry and wet seasons respectively. It is pertinent to mention here that roads which are waterlogged and therefore unmotorable during the wet season become dry and motorable during the dry season. This fact coupled with the scanty rainfall in the dry season, makes the season the most ideal period to carry out any field work in the area.

The project area is largely in the Tivland which is spread over parts of the Benue, Plateau and Gongola States.

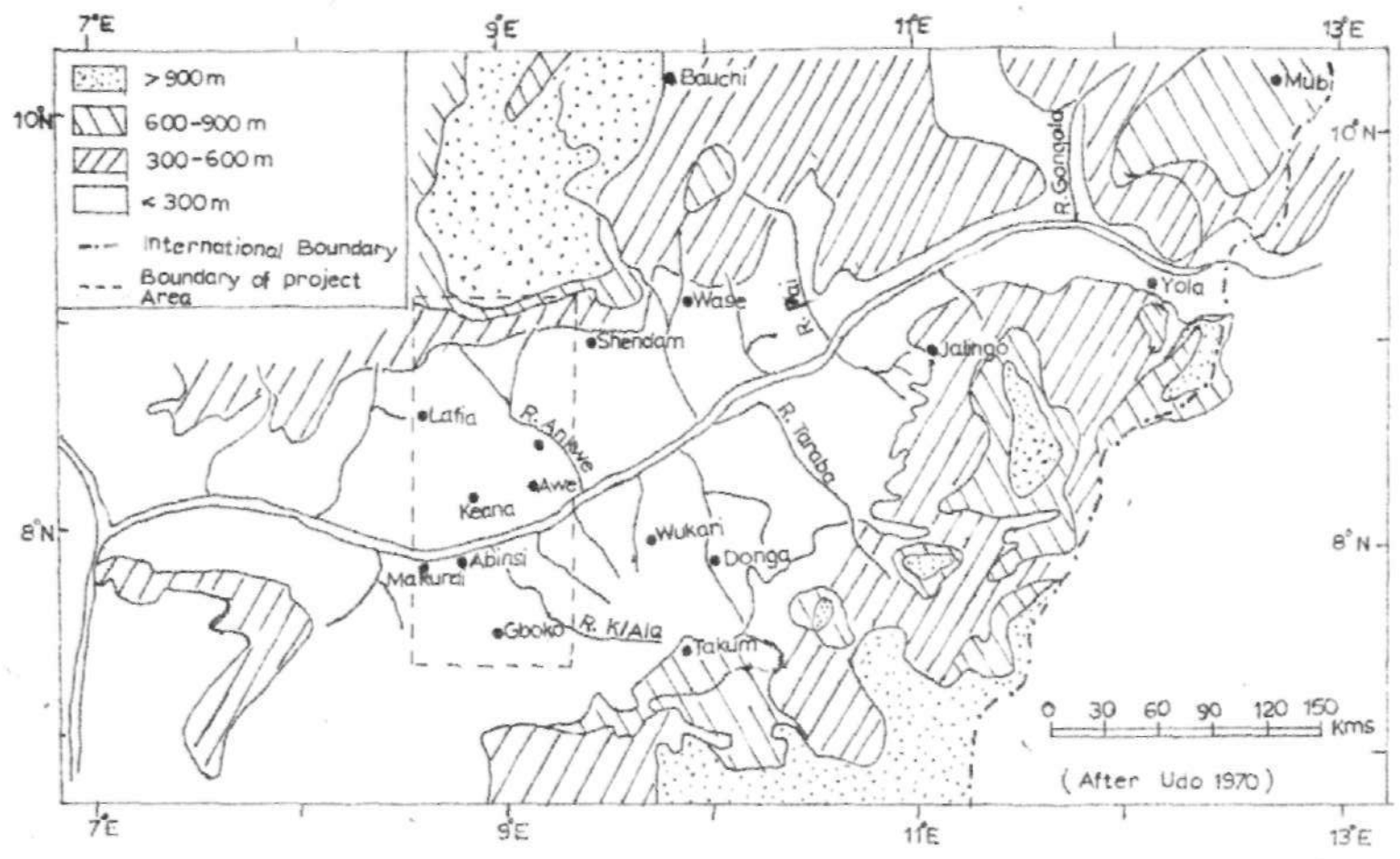


Fig. 1-3: Relief and Drainage of the Benue Trough (Valley)

About 50 to 60% of the project area is occupied by the Tiv. Other ethnic groups found in the area are the Aragos, the Hausas and the Jukuns. The major occupation of the people is farming. Because of the fertility of the soils in the area coupled with the farming ability of the people, the area is a major food producing part of the country. In places where salt springs exist, some of the women are involved in refining salt from the brine obtained from the springs.

1.4 : The Field Work

The field work involved six field trips, between December 1975 and October 1978, carried out either to collect new data or to repeat measurements suspected to be in error. In all, 60 base stations and 1400 detail stations were established in the area using a Worden gravimeter. The gravity stations were established at 1km interval on all motorable roads and tracts in the area. There were no benchmarks at most of the gravity stations established. The elevations of such stations were determined from the readings of two Wiernan and Tiernan altimeters. In addition, rock samples were collected during the field trips for density analysis.

CHAPTER II

THE GEOLOGY OF THE MIDDLE BENUE

2.1 : General Geology of the Benue Trough

Geologically, the Benue Trough coincides with the physiographic region of the same name discussed in section 1-3 and shown in fig 1-1 The trough is filled with sediments of up to 5,500 m in thickness (Carter et al, 1963) and is about 110 m.y. old (Wright, 1970) Even though all the previous workers in the area do not agree on the mechanics of the origin of the trough, most of them have thought it to be a rift valley. As earlier mentioned, the sediments within the trough are folded with their axes of fold parallel or sub-parallel to the axis (length) of the trough. The folds are usually less than 30^{o} (Burke et al, 1963; Offodile, 1976). Volcanic and igneous extrusives and intrustives of Cretaceous to Tertiary age are found within the sedimentary units. These volcanic activities were approximately centred along the axis of the trough. The age of the sediments range from Middle-Late Albian to Maestritchian (Offodile, 1976).

As earlier mentioned in section 1.1, there are certain geological occurences in the trough which are thought to be peculiar to the trough as a rift valley. Listed below are the two peculiarities:

(i) the excessive width of the trough. According to Wright (1968, 1970), the width of the Benue Trough is about two to three times that of a normal rift.

(ii) the folding of the sediments it contains.

Further to (ii) above, Burke et al (1970) asserted that the Benue trough is the only rift valley in the world which has a fold axis parallel to its length.

The project area is assumed to possess the peculiarities and features of the Benue Trough so far discussed because it occupies the middle part of the trough.

2.2 : The Geological Map of the Project Area

The Benue valley (trough) is yet to be completely mapped in detail, geologically. At the time of the survey of Cratchley and Jones in 1965, the north-east and south-west portions of the trough had been adequately mapped.

On the basis of the piecemeal information obtained from various sources, published and unpublished, these authors produced tentative stratigraphic columns for the three divisions of the entire Middle Benue - namely the Lower, Middle and Upper Benue. Since then the situation had not improved significantly. Burke et al (1970) did some detailed geologic mapping in the north-east part of the valley. Recently, several geologists have embarked upon the process of mapping the Middle Benue in connection with the exploration for minerals by various gevernment agencies such as the Nigerian Steel Development Authority (NSDA) and the Nigerian Mining Corporation (NMC). Most of these exploration activities are concentrated north of the River Benue in an area which represents, and also overlaps, about one-third of the author's project area. In 1976, Offodile published a detailed geological map of the Lafia sheet, bounded by longitudes $8^{o}30'$ and $9^{o}0'E$ and by latitudes $8^{o}0'$ and $8^{o}30'N$, and a reconnaissance map of the adjacent 'kiri sheet, bounded by longitudes $9^{o}0'$ and $9^{o}30'E$ and by latitudes $8^{o}0'$ and $8^{o}30'N$. The two maps together, cover the area of active exploration mentioned above.

The Geology Dept. of this University is presently actively engaged in field work in the area below the River Benue and they have published a geological map of the Makurdi sheet, bounded by longitudes $8^{o}30'$ and $9^{o}0'$ E and latitudes $8^{o}0'$ and $8^{o}30'$N, which is directly below the Lafia sheet.

As a result of the above facts, the only geological map presently available and which covers the entire project area, is that tentatively produced by Cratchley and Jones (1965). This map is not ideal for a detailed geophysical work of the type now being discussed. Fig.2-1, the geological map of the project area, was compiled by the author on the basis of the information obtained from Cratchley and Jones (1965), the Geological Map of Nigeria (G.S.N., 1974), Offodile (1976) and Kogbe et al (1978).

2.3 : The Stratigraphy of the Sedimentary Units in the Project Area.

Six different formations have been identified in the Middle Benue by the previous workers. Some of the formations have been grouped together by certain authors (Simpson, 19[illegible] Reyment, 1965; Cratchley and Jones, 1965).

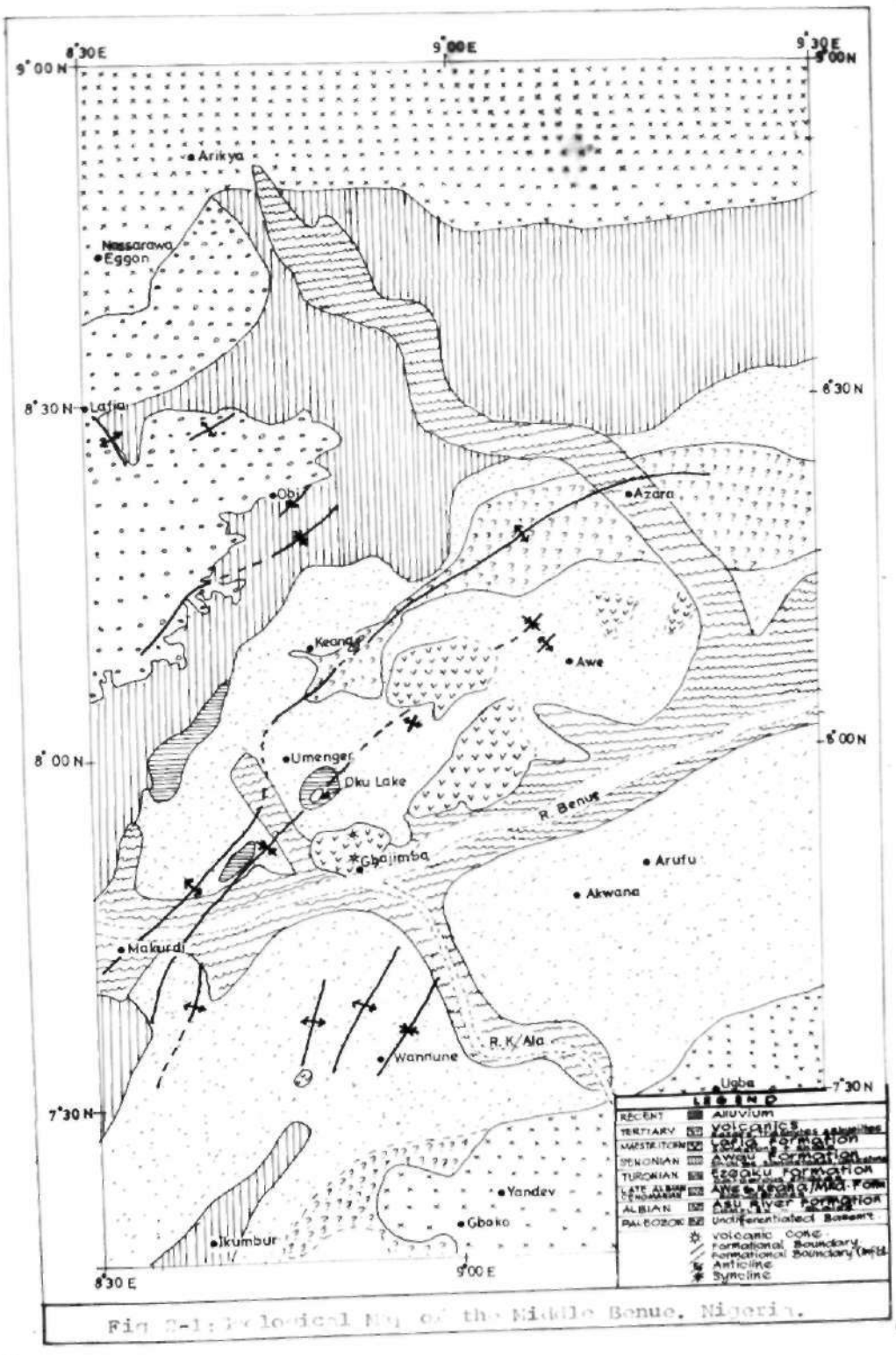


Fig 2-1: Geological Map of the Middle Benue, Nigeria.

The names used in this report are those derived by Offodile (1976) for the formations encountered in the Lafia-Awe area, which the present author considered to be representative of the Middle Benue. The stratigraphic column for the project area is shown in table 2-1. The various formations which exist in the area together with their corresponding lithologies and approximate thicknesses are as described below.

2.3.1 : The Asu River Formation

The Asu River formation is the oldest sedimentary deposit in Nigeria. It is Albian in age and, therefore, rests uncomformably on the crystalline basement which is of Paleozoic age (Cratchley and Jones, 1965; Oyawoye, 1970). It consists mainly of dark shales of marine origin and is thought to have been formed during the transgression of the ocean water immediately after the rifting of the trough. Towards its base, it consists of micaceous siltstones, mudstones and clays of varying colours. Where the formation is in contact with the igneous extrusives, the mudstones have been locally baked.

Age		Formation thickness	Description
PALEOCENE		volcanics	mainly basalts trachytes and ryholites.
DANIAN			
MAESTRITCHIAN	Late	LAFIA (50 - 1000m)	red ferruginised sandstones, loose sands, flaggy mudstones and clays. Environment of deposition - Continental.
	Early		
SENONIAN	campanian	AWGU (700 - 1500m)	black shales sandstones, and limestones, has local seams of coal which grades to limestone towards the South. Environment of deposition - shallow sea.
	santonian		
	coniacian		
		HIATUS	
TURONIAN	Late	EZEAKU	Calcerous shales and micaceous fine to medium grained friable sandstones, occasional beds of limestone. Environment of deposition - shallow marine.
	Early		
CENOMANIAN	Late	KEANA (1500 m)	massive heavily current bedded fine to very coarse grained sandstones at times conglomeratic. Indurated, gritty and arkosic. Deltaic environment of deposition. Lateral equivalent of Muri (Bima) and Makurdi formations.
	Early		
ALBIAN	Late	AWE (1000m)	medium to fine grained sandstone interbedded with shales and clays, fine grained towards base. Environment of deposition transitional between marine and continental.
	Early	ASU RIVER (3000m)	olive - green to dark - grey pinkish micaceous siltstones, fissile shales, mudstones and clays. Forms axis of Keana anticline and baked where in contact with extrusives. Environment of deposition - marine.
PALEOZOIC ?		BASEMENT	Undifferentiated.

(Compiled from Cratchley & Jones, 1965; Wright, 1975; and Offodile, 1976.)

Table 2-1: The stratigraphy of the Middle Benue.

3000m has been suggested as the maximum thickness of the formation in the area (Offodile, 1976). This formation froms the core of the Keana Anticline.

2.3.2. : The Awe Formation

This is a formation of whitish sandstones, thought to be transitional beds formed between marine and fluviate conditions (Offodile 1976). The grains of the sandstones vary from medium to coarse. In some locations, the sandstones are calcerous but towards the base of this formation, they are fine-grained and current-bedded. At Awe, the thickness of the formation is about 1000 m (Offodile, 1976). The Awe formation was formed during the Late Albian regression and is thought to be connected with the uplift in the south west section of the trough (Cratchley and Jones, 1965). Salt springs issue from this formation in the project area (Beltaro and Bojarski, 1971; Offodile, 1976). The name of this formation was proposed by Offodile (1976) as other workers before him simply referred to it as "passage beds", even though they recognised it as a distinct mappable unit.

2.3.3 : The Keana Formation

The formation is of fluviate origin and is thought to be of Turonian age (Reyment, 1965). It consists of fine to coarse grained massive sandstones which are locally conglomeratic and in places, heavily current-bedded. Also, they are usually indurated, gritty, arkosic and form very competent beds (Offodile, 1976). Cratchley and Jones (1965) thought it to be a lateral equivalent of the Muri (Bima) sandstones to the north-east (Upper Benue) because of similar regressive movements found in them. Offodile (1976) and Kogbe et al (1978) also thought it to be the lateral equivalent of the Makurdi formation south-west even though the Makurdi formation is slightly older (fig 2-1). The estimated thickness of the formation in the project area is about 1500 m (Offodile, 1976).

2.3.4 : The Ezeaku Formation

This formation contains mainly carbonaceous shales but fine to medium grained friable sandstones also occur within the formation. The formation occassionally contains limestone beds and is very rich in fossils (fauna).

The environment of deposition was thought to be a shallow quiet lagoonal type of coastal water during a Late Cenomanian transgression (Offodile, 1976). In the Makurdi area, paleonthological evidence show that the age of the formation is Turonian (Kogbe et al, 1978).

2 3 5 : The Awgu Formation

This formation comprises of black shales, sandstones and limestones. There are seams of coal appearing locally towards the northern part of the formation. Various thicknesses ranging from 700m to 1500m have been assigned to the formation by different workers (Reyment, 1965; Esso, 1967) but in the project area its thickness is thought not to exceed 700m (Offodile, 1976). The environment of deposition was a shallow sea, which was more swampy towards the north due to a transgression during the Coniacian.

2.3.6 : The Lafia Formation

This formation is the thinnest and youngest in the project area. It was deposited in Late Campanian to Early Maestrichtian (Offodile, 1976; Ajibade, 1977). The formations occurs in the north-west corner of the project area-see fig. 2-1.

Offodile (1976) estimated its thickness around Lafia to be about 50 m. He also proposed that the formation wedges out in that area. The formation consists of coarse ferruginised sandstones, loose sands, mudstones and clays. Its environment of deposition was continental and was brought about by the diversion of the trans-saharan seaway to the Middle Benue (Offodile, 1976).

2.3.7 :Summary

Previous workers have worked out the stratigraphy of the Middle Benue as consisting of six formations of Cretaceous age. They are the Asu River formation (or complex) which mainly consists of Albian shales, the Awe and Keana formations which consist of mainly Late Albian and Turonian sandstones respectively. Others are the Ezeaku and Awgu formations which are primarily shales of Cenomanian and Coniacian age respectively. The sixth formation, which is the thinnest and youngest in the area, is the Lafia formation. It mainly consists of ferrigenous sandstones of Late Campanian to Early Maestrichtian ages.

2.4 : Structures in the Project Area.

The major structures found in the area are folds, faults, current-beddings and cross-beddings. According to Offodile (1976), the last group of structures is common in both the Lafia and Keana (Makurdi) formations. From the statistical analysis of current bedding data collected in the Keana formation, on either side of the main structural feature in the area, the Keana Anticline, Offodile (1976) found that a major water current direction existed on either side of the anticline parallel to the anticline. This he attributed to the environment of deposition. Discussed below are two other types of structures which exist in the area.

2.4.1.: Folds

As mentioned in section 2.2, one of the peculiarities of the Benue Trough is the folding of the sediments it contains in a direction parallel to the axis of the trough. This implies that the axis of fold trend NE-SW, except that of the Lafia Anticline which trends NW-SE (fig. 2-1). In the project area, the folds are in the form of gently folded anticlinorium and/or synclinorium.

Serial No.	Name of Fold	Trend	Type
1	Lafia Anticline	NW-SE	small
2	Agyaragu Anticline	NE-SW	minor
3	Giza Syncline	"	major
4	Obi Anticline	"	minor
5	Keana Anticline	"	major
6	Tokura Syncline	"	small
7	Awe Anticline	"	"
8	Makurdi Anticline	"	minor (part of Keana Anticline?)
9	Makurdi Syncline	"	minor
10	Wannune "	"	"

(Compiled from Cratchley and Jones, 1965; Offodile, 1976); Kogbe et al, 1978)

Note: Small < minor < major

Table 2-2 : Known Folds in the Project Area and their characteristics

However, the Lafia fold has been dated by Offodile (1976) as Maestrichtian. These facts suggest the possibility of two episodes of folding within the Middle Benue - i.e. a major folding episode in the Santonian and a relatively minor one in the Maestrichtian.

2.4.2 : Faults

Because the whole Benue Trough has not yet been geologically mapped in detail, most of the faults known to exist in the area were infered, by previous workers, mainly from aerial photographs. For example, Burke et al (1970) identified some large scale thrust faulting in the Upper Benue from air photographs.

The only major fault in the project area, identified from ground mapping, is about 10 km long and occurs south of Giza (Offodile, 1976). The fault trends NE-SW parallel to the axis of the nearby fold. Generally, faults in the area are parallel to the axes of fold. Hence they are thought to be strike faults (Offodile, 1976).

There are two types, and possible stages, of faulting (Reyment, 1952 Offodile, 1976) in the project area.

The first type generally trends NE-SW and are associated with the lead-zinc mineralization while the second type generally trends NE-SE and are infilled with barytes. According to Offodile (1976), bed displacements in the Middle Benue are not obvious since there are virtually no slickensidings.

2.5 : The Basement and Volcanic Rocks

The basement rocks form the northern and southern boundaries of the entire Benue Trough. These rocks form part of the undifferentiated basement complex of Nigeria (Oyawoye, 1970; GSN map, 1974) which belongs to the Pan-African orogeny (Oyawoye, 1977). Gneisses and migmatites are the major components in the northern basement and other minor fomations are rhyolites which are localized as dykes in the Younger granites, quartzites, dolerites and quartz veins (Oyawoye, 1977).

The volcanics exist in the form of intrusives and/or extrustives. The intrusives are closely associated with anticlinal structures (Cratchley and Jones, 1965; Wright, 1975a) and are more abundant in the Albian sediments (Wright, 1975a).

Also, the anticlines seem to have provided the centres for the Cretaceous volcanic activities in the area (Offodile, 1976). Intrusives encountered in the Lafia formation, within the project area, are mainly sills, domes and dykes (Offodile, 1976). In the Upper Benue the volcanics are mainly in form of plugs, hills and plateaux (Cratchley and Jones, 1965). The main rock types of the volcanics are diorites and gabbros with their hyperbasal equivalents (Wright, 1975a). In the Awe area, the extrusives are vessicular basalt which are present in highly laterized zones (Offodile, 1976). On the other hand, olivine basalts, tholeitic dolerites, vessicular and amygdaloidal basalts have been mapped in the Gbajimba area (Kogbe et al, 1978). The laterization is thought to be confined to areas underlain by basalt (Farrington, 1952) but no laterite capped basalts have yet been mapped (Offodile, 1976; Kogbe et al, 1978).

2.6 : Origin of the Benue Valley

The origin of the Benue Valley is still a very controversial subject. Previous workers have tried to explain the origin of the valley using different geologic tools. For example, King (1950) using geomorphology, first proposed the rift hypothesis for the valley.

Later, Carter et al 1963), Kennedy (1965), Cratchley and Jones (1965), Stonely (1966), Dessauvagie (1969), Wright (1968), Whiteman (1970) arrived at their conclusions using stratigraphic, structural and geophysical (seismic, gravity and magnetics, at various times) data. Also, Burke et al(1970) and Offodile (1976) arrived at their own conclusions using photogeology and ground mapping. Most of the authors listed above agree, without any concrete evidences, that the trough is a rift valley. However, they do not all agree on the mechanics of rifting in relation to the peculiarities of the trough. Consequently, different reasons have been advanced to explain the mechanics of the rifting of the valley. It is the consensus of the latest (i.e. after 1968) workers that the rifting of the valley was linked with the separation of the South American and African continents and the subsequent opening up of the South Atlantic. The various schools of thought on the origin of the trough, to which the previous workers belong are summarized below:

2.6.1 : A Rift Valley

By projecting the South Atlantic and the Cape San Rouge rifts to coincide with the present Niger and Benue Valleys respectively, King (1950) Postulated the Benue Valley to be a rift valley.

This idea was supported by Kennedy (1965) who was of the opinion that the Benue Trough is a tensional rift of the Red Sea. Later, Wright (1968, 1970) shared the same idea but ascribed the rifting to the "tearing apart" of South America from Africa or vice versa. He also explained the folding of the sediments to be due to an "elastic rebound" of the African continent as a result of the loss of South America.

2.6.2. : A Geosyncline With Folding Involving the Basement

The idea that the trough was a type of geosyncline was first proposed by Lees (1952) on the basis of the great thickness of the sediments within the trough coupled with the fact that there were no marginal faults in the trough. Stonely (1966) supported the idea by stating that "the Benue Trough evolved rapidly as a miniature geosyncline," based on the tremendous thickness of the Cretaceous sediments within the trough.

2.6.3. : A Spreading Ridge or A Subduction Zone Due to a Triple Point Junction

(i) A short-lived spreading Ridge or Subduction Zone

Burke et al (1970), using magnetic data, proposed the existence of an RRR (ridge-ridge-ridge) triple junction somewhere beneath the present day Niger Delta.

To these authors, the medial zone of high gravity (Bouguer Anomaly) values identified by Cratchley and Jones (1965), in the trough, corresponds to the zone of the short-lived ridge. Later Burke and Dewey (1974) using the RRR idea thought that the zone of high gravity values could be a subduction zone created by the accretion of the two African plates - i.e. the West African and Congo cratons, respectively to the north and south of the trough. The authors attributed the folding of the sediments to the differential motion (speed and direction) in the two African plates.

(ii) A Zone of lithosphere spreading (also short-lived)

Grant (1971) proposed this idea and suggested that the triple point junction beneath the Niger Delta was an RRF (ridge-ridge-fault) instead of an RRR junction discussed in (i) above. In his model, the oceanic transform faults of the Gulf of Guinea form the fault arm of the triple junction. The African and South American continents were thought to have moved apart along the faults (Romanche' and St. Paul's) for about 20 m.y. before they finally separated.

The strain in the African plate due to the prolonged movement of the two continents along the fault was thought to be responsible for the local volcanism in the trough and in Northern Brazil. Like in (i) above, the medial zone of high gravity values correspond to the zone of lithosphere spreading.

2.6.4 : A Combination of a Rift Valley and a Geosyncline (i.e. 2.6.1. and 2.6.2 above).

The authors in this school of thought are of the opinion that the origin of the Benue valley could be explained by combining the rift and geosyncline theories. For example, Cratchley and Jones (1965) using the geologic and gravity data at their disposal, explained the medial zone of high gravity values in terms of a combination of crustal thinning and shallow basement (which might have been involved in the folding). These authors also stated that the fact that there were no surface evidence of marginal faults in the trough did not preclude the possibility of the trough being a rift valley. The faults could be buried deep in the sediments and hence masked from the surface.

Offodile (1976) was of the opinion that the marginal zones of low gravity values could be explained in terms of the rifting of the trough while the medial zone of high gravity values could be due to the flexuring of the sediments and the basement.

2.6.5. : A zone with a periodic "on-and-off" Hot spot

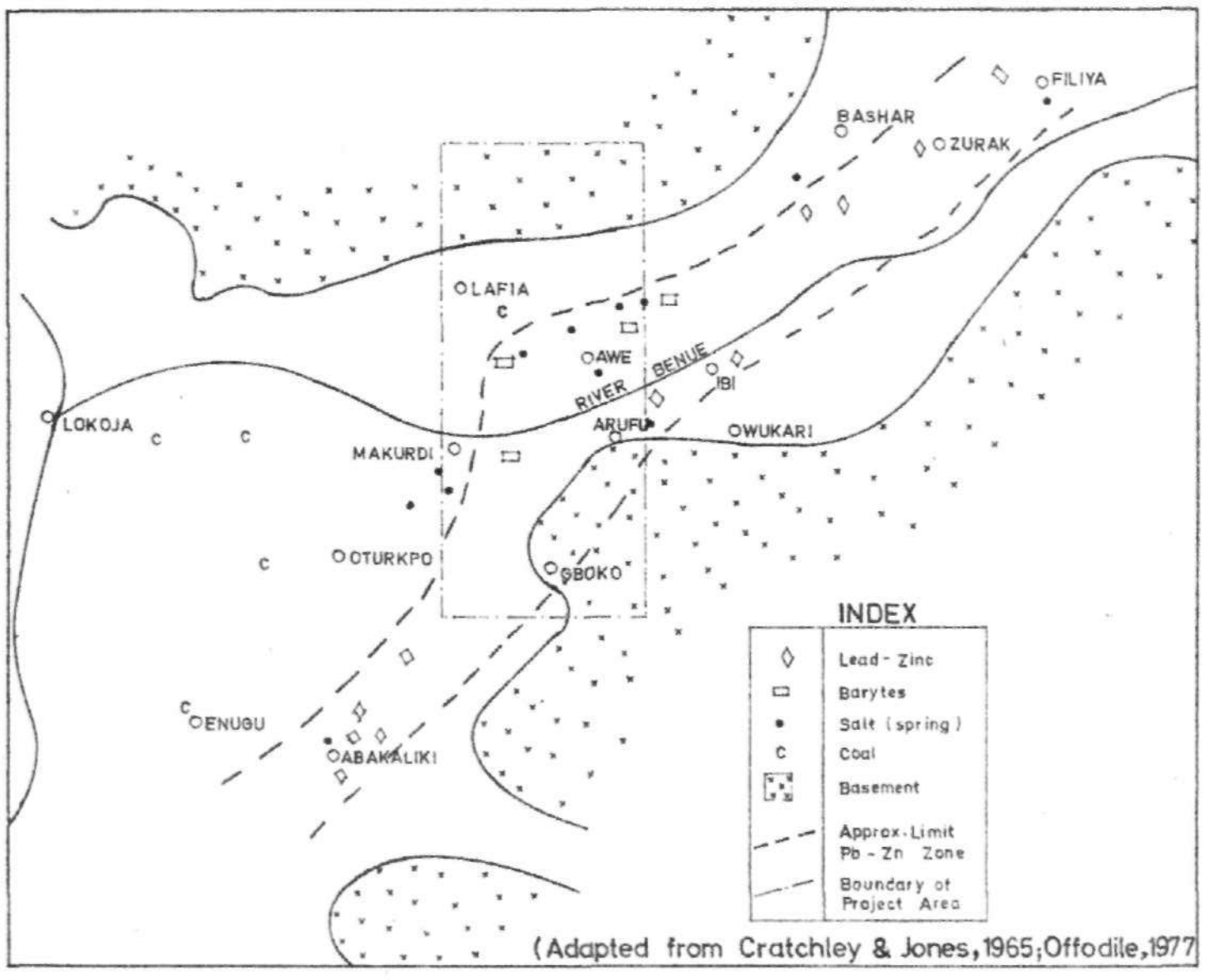
This model was proposed by Olade (1975) in an attempt to explain the origin of the trough without employing certain plate tectonic concepts, such as accreting margins and colliding plates, which, according to him, could not be supported by surface geologic evidences. The model assumed the existence of a Cretaceous hot-spot beneath the present day Niger Delta. The upwelling of the mantle plume, created a hotspot which resulted in the doming and rifting of the Benue area and the formation of a rift-rift-rift triple junction, with the Benue trough as one arm. The Benue rift failed to develop into an ocean basin and thus became filled with sediments, as a result of the stresses associated with the opening up of the South Atlantic. In this model, the subcrustal contraction caused by the temporary cessation of the mantle upwelling resulted into the compressive folding of the Albian sediments in the trough.

2.7 : The Economic Geology of the Project Area.

The minerals found in the Benue Trough and their distributions are shown in fig. 2-2. The commercial minerals known to exist in the project area are lead, zinc, salt, coal, barytes, limestone and fine quality (high grade) crystalline rocks for rock aggregates useful in road construction and other civil engineering purposes. A short discussion on each of the important minerals is given below.

2.7.1 : Lead and Zinc

These minerals are found in a narrow belt which almost runs through the entire length of the Benue Trough. This belt corresponds to the medial zone of high gravity values discussed above. The minerals are thought to be emplaced towards the end of the period of the basic to intermediate igneous activity in the trough (Grant, 1971). In the project area, these minerals are found in the northeast-southwest trending faults in Arufu, Kanje, Adudu and Abuni. Mining of the minerals by the inhabitants started many centuries before modern methods of pospecting and mining commenced in Arufu as early as 1885 and 1925 respectively (Farrington, 1952).



FIG·2-2 : MINERALS OF THE BENUE TROUGH.

The Nigerian production of lead, zinc and associated minerals between 1925 and 1949, excepting the period between 1938 and 1946 when the mining of the ores was considered uneconomic, came from Arufu area (Farrington, 1952) There has been no known recorded production in the area since 1949.

2.7.2 : Barytes

Barytes are generally found associated with lead and zinc in the Benue Trough. They generally occur as siliceous infills of the second system of faulting found in the area which trend northwest-southeast. In the project area, major occurences of barytes exist in Aloshi, Keana, Azara, Chiata and the area between Akiri and Muse. The deposits vary in size and purity. In Chiata, for example, the deposit is almost pure (93-94%), the vein is about 1 m thick and about 500 m long while in Aloshi the deposit is largely mixed with quartzites and not signifant (Offodile, 1976). There has been no major production (exploitation) of the mineral in the area but there is currently an intensive exploration programme being carried out by the Nigerian Mining Corporation (NMC).

2.7.3 : Salt

Occurences of salt in the Benue Trough are in form of non-thermal salt springs which are mostly found near the axes of anticlines. The temperature of the springs have been found to be between 28° - 35°C (Beltaro and Bojarski, 1971). In the project area, such springs exist in Keana, Assakio, Ribi, Azara, Akiri, Awe, Arufu, Akwana and Maigbo (Igbor). Systematic studies of the brines in the area have shown that the salinity of the spring water increases towards the Keana anticline, the concentration decreased with depth in Keana between 10 to 40 m but remained constant in Igbor between 30 to 60 m (Offodile, 1975). Local salt refining in the area, by evaporation, dates back to the sixteenth century when some of the settlements were founded. For example, the discovery of salt springs near Keana about 1581 to 1594 led to the founding of the town (Adefuye, 1977). The salt industry has since then been a great factor in the economic, social and political lives of the people.

Past feasibility surveys have noted the low salinity of the brines in the area (Phoenix and Kiser, 1966; Beltaro and Bojarski, 1971). This fact could make the industrial recovery of the salt from the brines uneconomical but current

annual estimates of salt recovered by traditional method in Keana, for example, could be up to 5,900 tonnes (Adefuye, 1977). Presently, the Nigerian Mining Corporation is actively engaged in prospecting for rock salt deposit(s) or salt domes in the northern half of the project area.

2.7.4 : Limestone

Limestone is fairly well distributed in the project area. North of the River Benue, limestone deposits occur in Agwatashi, Jangerigeri, Tokura, Chiata, Hagha, Awe and Noko. South of the river, there are deposits north of Yandev and in Akwana which may likely serve as the raw material for the nearly completed Benue Cement factory in Yandev Generally the deposits occur in the Awgu and Ezeaku formations (Offodile, 1976).

2.7.5 : Coal

High grade coal has also been discovered in the project area. It occurs in the Obi-Agwatashi area. The extent and mode of extraction of the coal are currently being explored by the Nigerian Steel Development Authority. It is hoped that coal from these deposits will provide the coking coal for the integrated Iron and Steel Complex planned for Ajaokuta, Kwara State. Sub-bituminous coal also exists in the area (Offodile, 1976).

CHAPTER III

THE GRAVITY SURVEY

3.1 Initial Studies of the Instruments Used

3.1.1 : The Gravimeter

A Worden gravimeter, number 135, belonging to the Physics Department of this University was used for obtaining the gravity data. It has a scale constant of 0.08829 mgals per division The accuracy of the scale factor was approximately checked to be correct (about 2% error) by reading the instrument at the different floors of the three-storey building bousing the Physics Department (A.B.U , Zaria).

Before embarking on any of the field trips, readings of the gravimeter were taken in front of the author's residence (F 139, A.B.U. Senior staff Quarters) for two consecutive days at thirty minutes interval from 0700 hours to 1900 hours, local time. The times of observation were chosen to be representative of those in which the actual field work would be carried out. Figure 3-1 shows typical diurnal base station drift curves of the gravimeter with the corresponding diurnal temperature . curve superposed. The hourly drift of the gravimeter was found to be usually less than 0.06 mgals/hr.

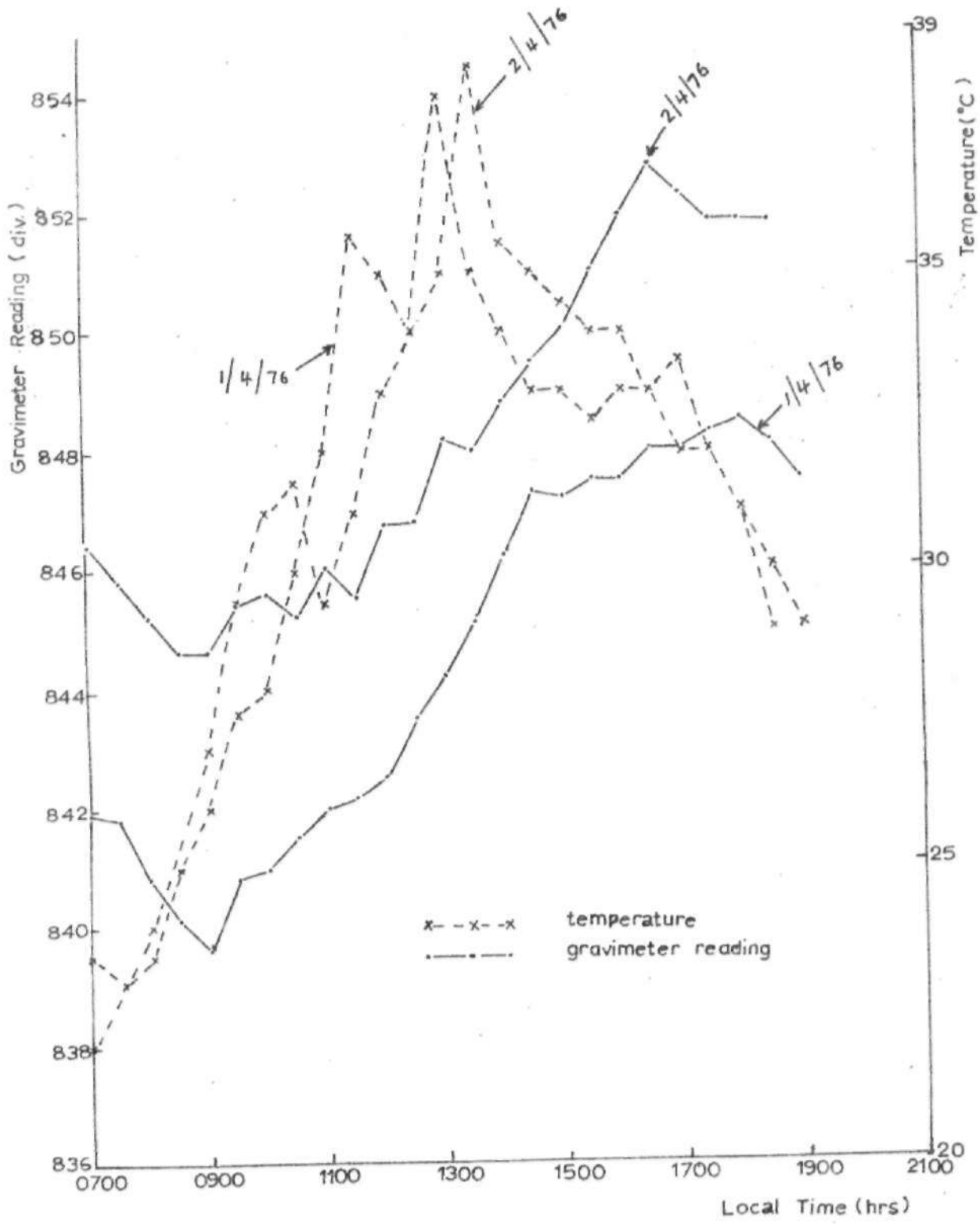


Fig. 3-1: Typical Gravimeter Drift Curve at a Base Station

3.1.2. : The Altimeter

Two Wallace and Tierman Altimeters model FA181, which were labelled 'C' and 'D' by the Physics Department, were used for height determination during the survey. Their drift patterns were observed along with that of the gravimeter. This was achieved by taking the altimeter readings immediately after the gravimeter reading described in section 3.1.1. was taken. The resulting typical drift curves for each altimeter are shown in fig. 3-2. Each drift curve has a minimum and a maximum similar to that of the gravimeter. The maximum drift rate, for each of the altimeters, was found to occur between 0700 and 0800 hrs. The values were -10.17m/hr and -9.18m/hr for altimeters C and D respectively. Their respective minimum drift rates were found to be 0.0m/hr and 0.66m/hr. occuring between 1700 and 1800 hours. Between 1100 and 1430 hrs., the altimeters drifted almost linearly (fig. 3-2) at the rate of 7.40m/hr. In addition, from figs 3-1 and 3-2, it can be seen that the gravimeter and the altimeters do not respond to temperature changes until after about two to four hours.

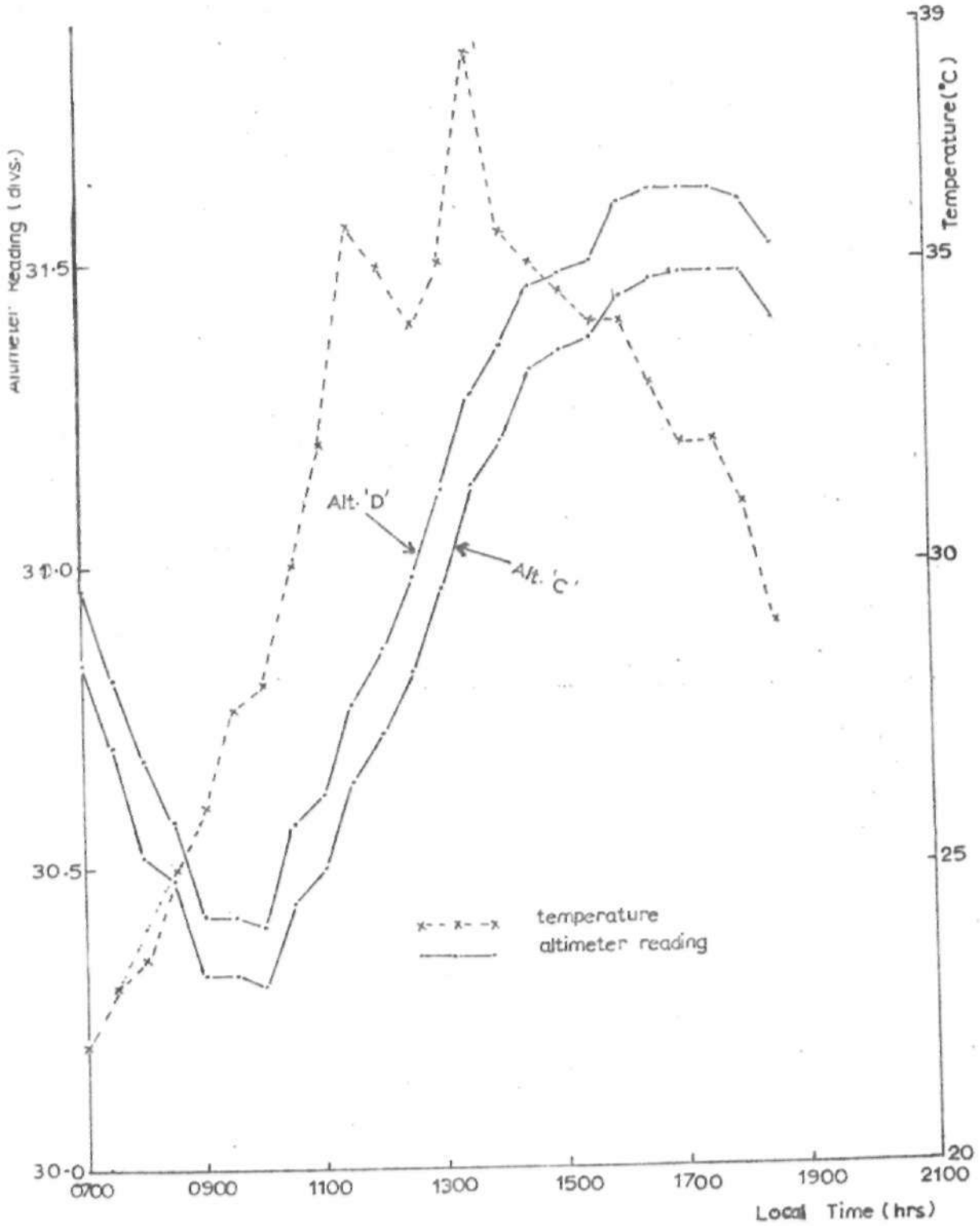


Fig 2.9: Typical Altimeter Drift Curve at a Base Station.

Diurnal pressure changes have been found to be neglible in Nigeria during the dry season except at the beginning and end of the harmattan period (Verheijen and Ajakaiye, 1978). Therefore, the effects of pressure changes were not considered in carrying out the analysis above since the data used for the analysis were collected during the harmattan period.

3 2 : The Field Work

As earlier mentioned in section 1.4, the field work was carried out at various times from 1975 to 1978. The survey involved four major field trips for colledting raw data and which were undertaken in the following periods:- Mid-December 1975 to the first week of January 1976, March 1976, March 1977 and Mid-February to the end of the first week of March 1978. Altogether, the survey involved fourteen weeks of field work. In order to be able to cover the project area within the fourteen weeks, data were collected for about ten to twelve hours a day, seven days a week. Two short field trips were later on undertaken to repeat data suspected to be in error.

3.2.1 : The Gravity Stations

During the survey, sixty base stations were established mainly at road junctions. Others were established near or at easily locatable landmarks such as a village dispensary, court, market, etc. A total of one thousand four hundred (1400) detail stations were also occupied during the survey. Establishing the detail stations involved collecting data at one kilometre interval on all motorable roads and tracts in the project area.

3.2.2 : Transportation Methods Used

The field crew, gravimeter and the other instruments used for the survey were transported mainly by a motor vehicle. Because of the difficult terrain usually encountered on the tertiary roads and foot paths, a requisite criterion of the motor vehicle was its being a four-wheel drive. Another criterion of the vehicle considered vital was its possessing a trip recorder in kilometres and tenths of a kilometer to ensure accurate spacings of the detail stations.

Other modes of transportation used during the survey were the paddle boat, motorised boat, the ferry and the motorcycle. The paddle boat was used on two occasions - once to "loop" between base stations 9037 (Gbajimba) and 9046 established on the opposite banks of the River Benue and to cross the River Katsina Ala during the "looping" between base stations 9048 and 9040 (fig. 3-4). The motorised boat and the ferry were used at Gburuku to cross the River Katsina Ala during the "looping" between base stations 9050 and 9051 and to work on the eastern side of the river respectively. The motorcycle was used in locating the sites (positions) for the detail stations at one kilometre interval on roads inaccessible to the motor vehicle. In such cases, the gravimeter was transported on foot in order to take readings at previously marked-out stations.

3.2.3 : Data Coverage

Bearing in mind the aims of the survey as given in chapter one, the survey was designed to cover the project area adequately in order to reveal both local and regional anomalies of interest. Ideally, such a survey should be

on a regular (uniform) grid. This was, however, not done because such an exercise would not only have been time consuming the cost involved would also have been very prohibitive. The latter factor would have been largely due to the labour cost in cutting the traverses for the grids. Readings were, therefore, taken at one kilometre interval along all the available roads and tracts in the project area.

3.2.4. : Height Measurements

Less than one-tenth of the gravity stations, base and detail, were established on benchmarks. This was due to the extensive road reconstruction exercise going on, on most of the major roads in the project area, during the survey periods. Such roads were originally benchmarked but the benchmarks had been removed by the road contractors. For example, by December 1975 when this work (gravity) was started, the Lafia - Obi-Awe-Tunga road had benchmarks. By March 1977 nearly all the benchmarks along the road had been removed as the road was being reconstructed. It was only on this road that some base and detail stations were established on benchmarks. Some base stations were, also, established on some standard Benchmarks (SBM) which

were unaffected by the road reconstruction exercise. In addition, some stations were established at kilometre indicators (marks) put along the roads being reconstructed by the contractors. For this group of stations, their heights relative to a fixed location on the road, which also formed part of the author's base network for heights, were supplied by the contractors.

Because of the reasons discussed above, the heights of the majority of the gravity stations were determined by means of the two Wiernan and Tiernan altimeters referred to in section 3.1.2. The altimeters were treated exactly in the same way as the gravimeter. That is, all the base stations were "looped" height-wise along with the base-looping of the gravity case. Also, the altimeter readings were taken along with that of the gravimeter at each detail station. Whenever the readings of the altimeters were taken, the readings of a whirling wet-and-dry thermometer were also taken to determine the humidity correction factor for the altimeter readings.

3.2.5 : Behaviour of Instruments under Field Conditions

In order to find out if there were any significant changes in the drift rates of the instruments as dicussed under section 3.1, under field conditions, a day's survey was arranged such that six readings of the instruments, spread over the day, could be taken at a fixed base station. The readings observed at base station 9039 (Yandev) on 12/3/77 are shown in fig. 3-3 The figure shows the approximate diurnal drift pattern of the gravimeter and that of each altimeter. ABCDEF represents the drift pattern of altimeter 'C' while AB'CD'E'F represents that of altimeter 'D'.

By comparing fig. 3-1 with the gravimeter drift in fig 3-3 and fig. 3-2 with the drifts of the altimeters in fig. 3-3, it can be seen that the instruments almost have the same drift pattern at rest and under field conditions. From fig 3-3, the maximum drift rates for the gravimeter and altimeters were found to be -0.09 mgals/hr, compared with 0.06 mgals/hr mentioned in section 3.1.1 and -13.80m/hr, compared with -10.17 and -9.18 m/hr mentioned in section 3.1.2, respectively. These figures show an

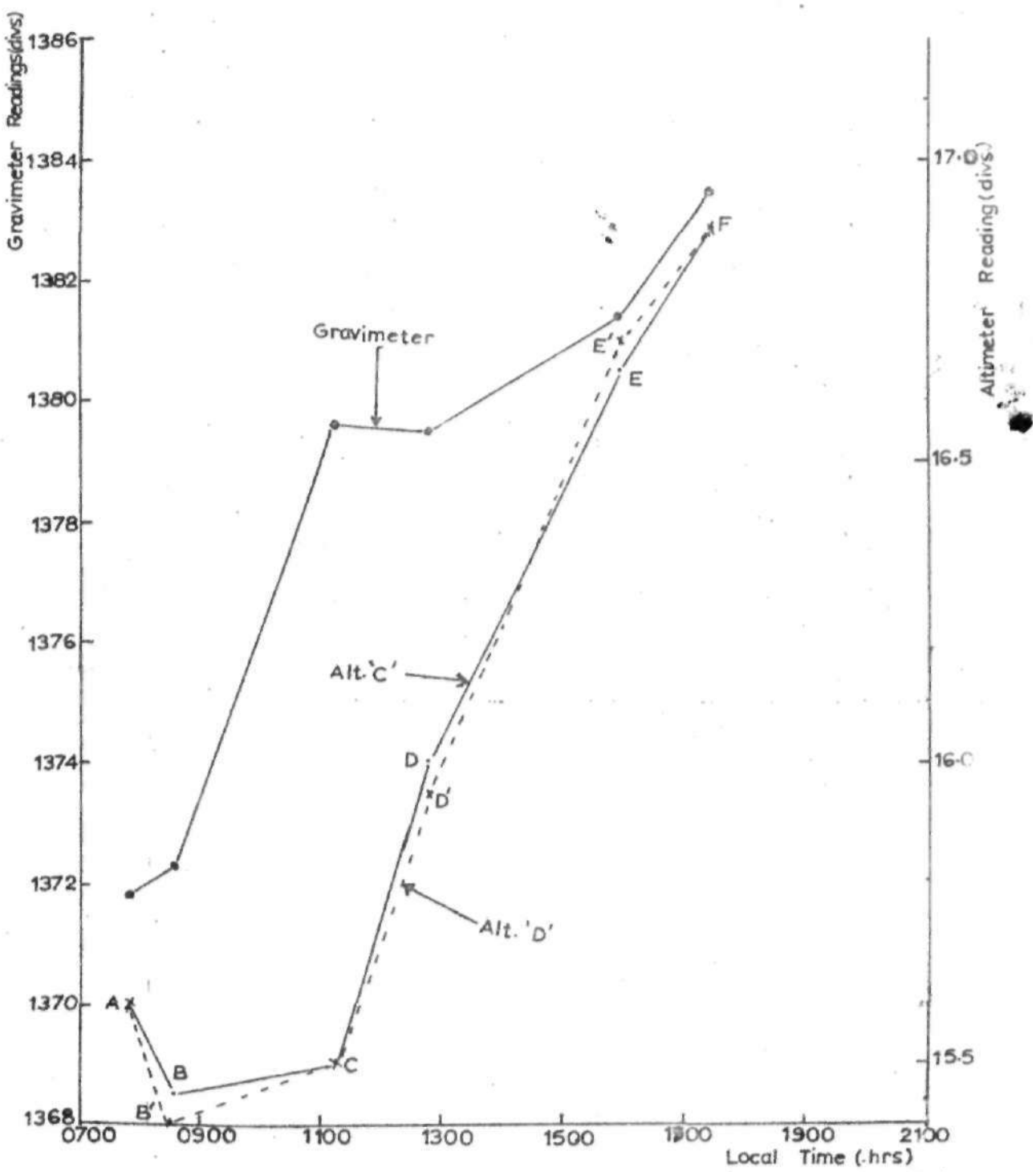


Fig. 3-3: Gravimeter and Altimeter Readings in Yandev (on 12/3/77)

increase of about 50% and 36% in the maximum drift rates of the gravimeter and altimeters over their respective values at rest. The higher drift rates of the instruments under field conditions could be attributed to a combined effect of a longer exposure to heat and the excessive shocks and vibrations to which they were subjected during transportation.

3.2.6 : Field Problems Encountered

During the course of the survey, some field problems were encountered. Some of these problems could be attributed to the fact that the base (topographic) maps used were outdated. Though the maps were produced in 1972, the aerial photographs used in their production were taken in November-December 1964 (as indicated on the maps). As a result, roads indicated as being motorable on the maps were generally found not to be so during the survey. The converse was also found to be true. Also, some disjointed minor roads on the maps were found to be continuous first-class, recently tarred roads. On such roads, the main problem encountered was that of locating on the maps, the positions of the gravity stations along the new extension or diversions made on the old roads.

The mode of settlement of the inhabitants of the project area also contributed to the problems discussed above. The inhabitants of the area are mainly farmers and they settle, especially in the southern half of the project area, around their farms in families. As soon as the land around such a settlement is no longer fertile, the family moves en-masse to another location. If some people stay behind, the village assumes a new name. As a result, some villages shown on the maps are either now non-existent or now bear new names.

Another problem encountered was that due to abrupt termination of some roads by some fairly big rivers on which there were no bridges. At some of these places there were no settlements nearby and also no means of crossing the rivers. Such obstructions did not only slow down the rate of data collection, they also prevented uniform data coverage of the entire project area.

In some areas within the project area, there are no roads. This also contributed to the unevenness of the data distribution (coverage) in the project area. Worse still, there was no topographic map, contoured or uncontoured, for the north-eastern portion of the project area. Hence, the area was not surveyed.

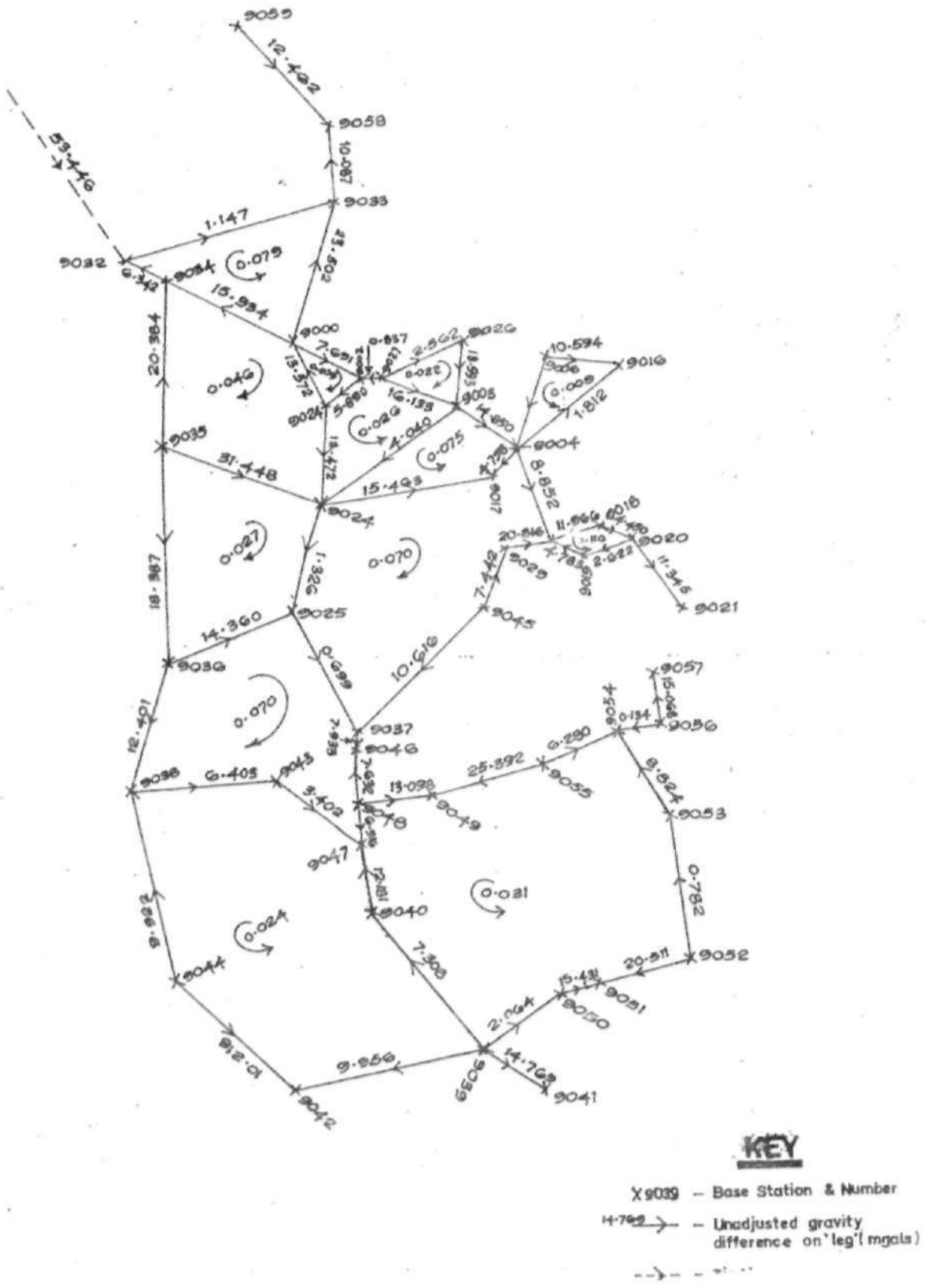
3.3 : The Base Networks

3.3.1 : Gravity

The base stations were established by the "looping" technique either using the ABAB or the ABABCBCD..... method (Nettleton, 1940) The resulting network was made up of thirteen (13) closed loops and three (3) open loops. The biggest open loop approximately in the middle part of the project area could not be closed because of the author's inability to cross the River Benue between base stations 9057 and 9021 in fig. 3-4.

Figure, 3-4 shows the gravity base network of the survey with the respective closure error for each loop. The values of the maximum and minmum closure errors in the network are 0.11 mgals and 0.01mgals respectively. The average absolute value of the closure errors was found to be 0.046 mgals.

To determine the observed gravity difference (Δg) between two base stations A and B on a 'leg' given by line AB, the repeat reading(s) at each base station was corrected for the instrument drift, using a computer program written by the author, assuming a linear drift (change) with time. The resulting Δg was multiplied by the scale constant



KEY

X9039 – Base Station & Number

14.768 → – Unadjusted gravity difference on 'leg' (mgals)

--→-- – ...

(0.08829 mgals/div.) to determine the gravity change between the two base stations in milligals. After repeating this process for each 'leg' in a loop, the closure error was calculated by vectorially adding the Δg's in the loop. The closure errors in the network were then adjusted by means of a least-square technique (Pentz, 1953).

3.3.2. : Heights

As mentioned in section 3.2.4., the altimeters were read at the same locations as the gravimeter. ence, all the steps taken in obtaining the base network for the heights were exactly the same as those outlined in section 3.3.1 to obtain the gravity base network but using the appropriate conversion factor for the altimeters.

Figure 3-5 shows the base network for the heights with the corresponding misclosures. The maximum closure error was found to be 2.23m.

3.4. : Adopted Base Values and Ties to other Surveys

The gravity data were reduced to both the Potsdam and IGSN systems in order to compare the data obtained in the present survey to those obtained in the earlier surveys of

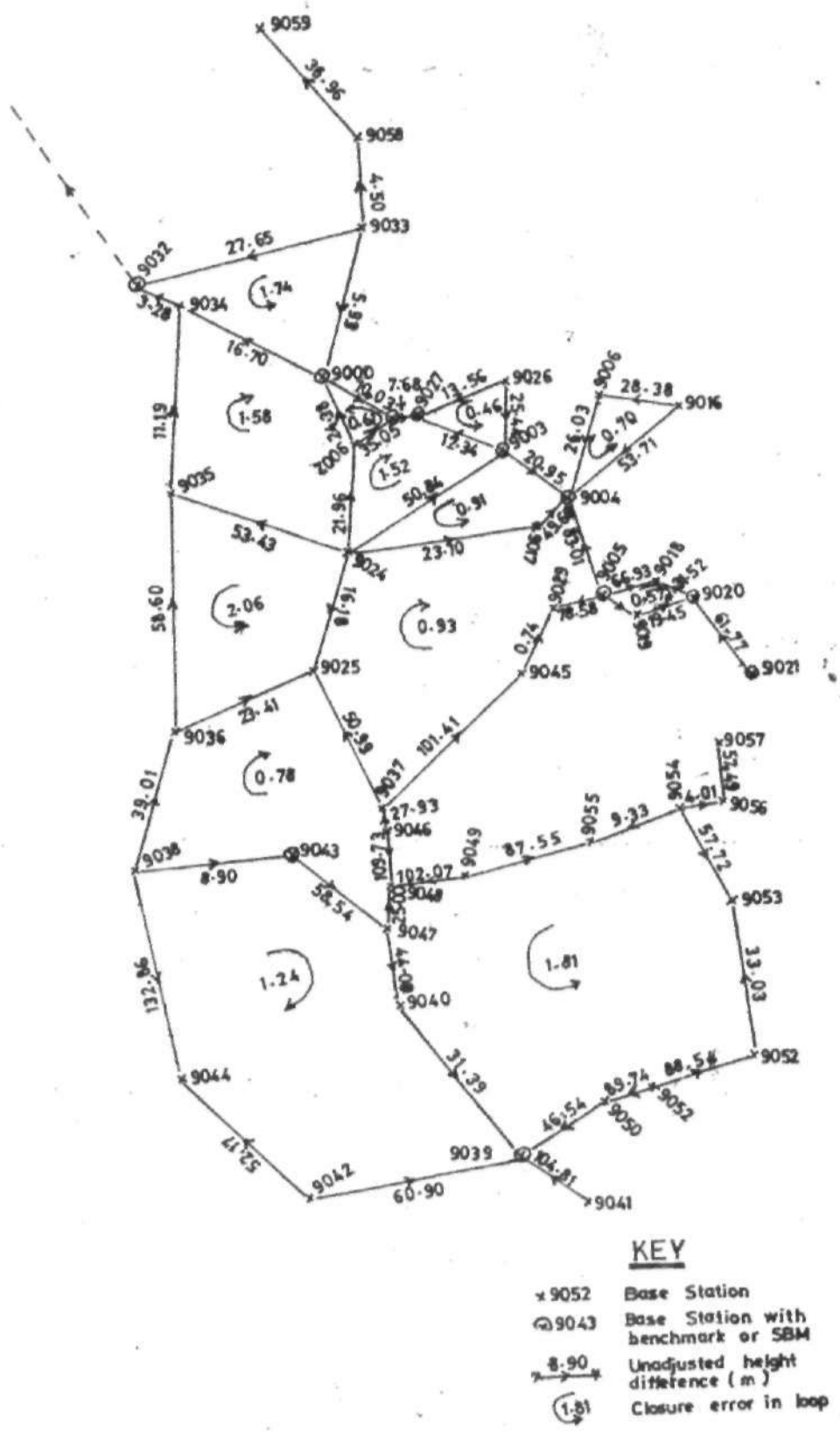


Fig 3-5 : THE BASE NETWORK (HEIGHT)

Cratchley and Jones (1965), Ajakaiye (1970) and the more recent survey of Umego (1978). The survey of Cratchley and Jones was carried out over the entire Benue Valley while that of Ajakaiye was carried out in the Younger Granite Province of Nigeria which is just north of the Benue Valley. In both surveys, the Potsdam system was used. The survey of Umego was carried out in Ribi area, which is within the area of the present survey and was reduced to the IGSN system.

3.4.1 : Reduction to the Potsdam System

In reducing the observed data of the present survey to the Potsdam system the gravity values at all the stations, base or detail, are relative to the value 978045 63 obtained for the base station 9031 near the round-about in Akwanga. This value was obtained by Ajakaiye (1970) in a survey carried out in December 1967 and February 1968. That survey was tied to that of Cratchley and Jones(1965) carried out in 1960 and 1961. The latter survey was in turn tied to the O.R.S.T.O.M. (Duclauex et al, 1954) base in Lagos via a Shell-BP network terminating in

Boju Bga and Oturkpo (Cratchley and Jones, 1965). The survey by Cratchley and Jones was also tied to the O.R.S.T.O.M. Base in N'djamenna (Fort Lamy), Chad Republic, via a Chad Basin network established in 1959 by the British Overseas Geological surveys (Cratchley and Jones, 1965; Ajakaiye, 1970).

The project area of the present survey entirely lies within the area covered by the survey by Cratchley and Jones. As a result, there are twelve towns and villages common to both surveys in which base stations were established in each of two surveys Table 1 of the Appendix shows the comparison between the observed (absolute) gravity values obtained in the 1960/61 survey and in the present survey, for the common base stations. The largest difference in the values of the absolute gravity, at the common stations in the two surveys (2.307 mgals), occurs at Keana. It must be emphasised that the gravimeter readings in those villages and towns might not have been taken at the same points during the two surveys. This is due to the fact that the exact locations of the base stations used in the survey of Cratchley and Jones were not known. However, it is the contention of

the author that the stations in most of the villages/towns in the two surveys may not be too far apart due to the fact that the base stations in the present survey were established at prominent places coupled with the fact that the absolute gravity values determined at those villages/towns in the two surveys, except in Kanje and Keana, are in close agreement.

If the value of the absolute gravity at Akwanga determined by Ajakaiye (1970) were made equal to that determined by Cratchley and Jones (1965) for Akwanga, then the maximum difference in the absolute values listed in table 1 (Appendix) would be 1.937 mgals in Keana rather than the 2.307 mgals mentioned earlier.

3.4.2 : Reduction to the IGSN System

In reducing the data to the IGSN system, the values determined at all the stations were relative to 978092.255 mgals obtained by Umego (1978) in Ribi for the base station 9006 in the present survey, originally established by the author in an earlier survey (Ajakaiye and Ajayi, 1977). The above value was determined, using a Lacoste and Romberg gravimeter, from six single tie measurements between a

first order base of the Nigeria Calibration Line in Jos and the station 9006. The international gravity formula used along with this system was that of 1967.

It is interesting to note that the absolute gravity value at Ribi (9006) and consequently at each station, on the IGSN system was lower than that on the Potsdam system by 14.97 mgals - see tables 1 and 2 of the Appendix. However, the latitude effects at each station, using the gravity formula of 1967, was on the average about 16.68 mgals higher than those obtained using the formula of 1930. The net effect was that the Bouguer anomaly value at each station on the IGSN system was on the average, about 1.7 mgals higher than those obtained using the Potsdam system and the gravity formula of 1930

3.5: Data Processing and Corrections to the Observed Gravity Readings

3.5.1 : Data Processing

The entire data processing was carried out using the University's computer - CDC Cyber 72. Most of the programs used in the data reduction stage were written by the author. The data processing was carried out following the conventional

sequence of reducing raw gravity data. Also, the corrections normally applied to the observed gravity readings were carried out. The detail analysis of the corrections are discussed below.

3.5.2 : Corrections to the Observed Readings

In calculating the Bouguer anomaly at each station, the usual corrections to the observed gravity readings were made using the following formulae:-

(a) Drift Rate : As earlier mentioned in section 3.3.1, the drift rate of the gravimeter (or each altimeter) was assumed to be linear for a two-hour time interval. To determine the drift rate, d, on a traverse in which A and B are base stations, the formula used was

$$d = \frac{\Delta R_{BA} - \Delta g_{BA}}{t_B - t_A} \qquad \text{.....(3-1)}$$

where ΔR_{BA} = the gravimeter (or altimeter) reading at B minus that at A

Δg_{BA} = gravity (or height) difference between bases A and B in instrument units (determined from adjusted base network)

t_B = observation time at base B

and t_A = observation time at base A

(b) Observed Gravity at a Detail Station

The equation used to determine the observed gravity value, g_S, for any detail station, S, on a profile AB above was

$$g_S = g_A + K.\Delta R_{AS} + d\,(t_S - t_A) \qquad \ldots\ldots\ldots(3\text{-}2)$$

where g_A = observed gravity value at base station A

K = instrument constant

ΔR_{AS} = gravimeter reading at S minus that at A

t_S = observation time at detail station S

Note: d and t_A have the same meanings as in (1) above.

(c) Theoretical Gravity or Latitude Effect (at a Station)

As mentioned in section 3.4, the observed gravity data in this survey were reduced to both the Potsdam and IGSN 71 systems.

In calculating the latitude effect, using the Potsdam system, the reference spheroid used was the International Ellipsoid of 1930. Hence the gravity formula

$$g_t = 978049\ (1+0.0052884\ \sin^2\phi - 0.0000059\ \sin^2 2\phi) \qquad \ldots\ldots(3\text{-}3a)$$

For the IGSN 71 system, the International gravity formula of 1967, on which the system is based, was used i.e.

$$g_t = 978031.85\ (1+0.005278895\sin^2\phi + 0.000023462\sin^4\phi) \qquad \ldots\ldots(3\text{-}3b)$$

In both cases,

g_t = theoretical gravity value in milligals and

ϕ = station latitude

(d) Elevation Correction (Factor): This correction is normally computed in two components - the free-air and Bouguer correction

(i) The Free-Air Correction (FC) is due to the fact that the gravity field decreases with increase in elevation. It is given by

$$FC = \frac{dg}{dz}.h \quad \ldots\ldots\ldots(3\text{-}4)$$

where $\frac{dg}{dz}$ = vertical gradient of gravity which is 0.03086 mgal/m and h=station elevation (relative to the sea level)

(ii) The Bouguer Correction (BC) is meant to correct for the attraction due to an infinite slab existing between the station and the sea-level datum (i.e. for a slab of thickness h). For any station of elevation h, the Bouguer correction is given by

$$BC = 2\pi G \rho_m h \quad \ldots\ldots(3\text{-}5)$$

where G = universal gravitational constant

ρ_m = mean crustal density

Usually, the Bouguer correction is 0.04191 ρ_m mgal/m.

(e) Free-Air Anomaly: At any station, S, the free-air anomaly

(FA) is the difference between the observed gravity value (g_s) and the extrapolated theoretical gravity value (g_t) from the reference spheroid with the free-air correction applied. The anomaly is given by

$$FA = g_s - (g_t - FC) \quad \ldots (3\text{-}6)$$

(f) Bouguer Anomaly: The Bouguer anomaly is the free-air anomaly minus the Bouguer correction. Therefore, it is represented as

$$BA = FA - BC \quad \ldots (3\text{-}7)$$

Substituting equations (3-4), (3-5) and (3-6) in (3-7), the anomaly can also be represented as

$$BA = g_s - \left(g_t - \frac{dg}{dz} \cdot h\right) - 2\pi G\rho_m h \quad \ldots\ldots (3\text{-}8)$$

After applying all the corrections discussed above, the resulting Bouguer anomalies reduced to the IGSN 71 system, were plotted by the computer and then manually contoured. The subsequent Bouguer anomaly map for the project area is shown in fig. 3-6.

3.6 : Errors in the Bouguer Anomalies

The computed Bouguer anomaly at each station is usually subject to two major types of error - random and systematic errors. Each of these types of error originates from at least two different sources.

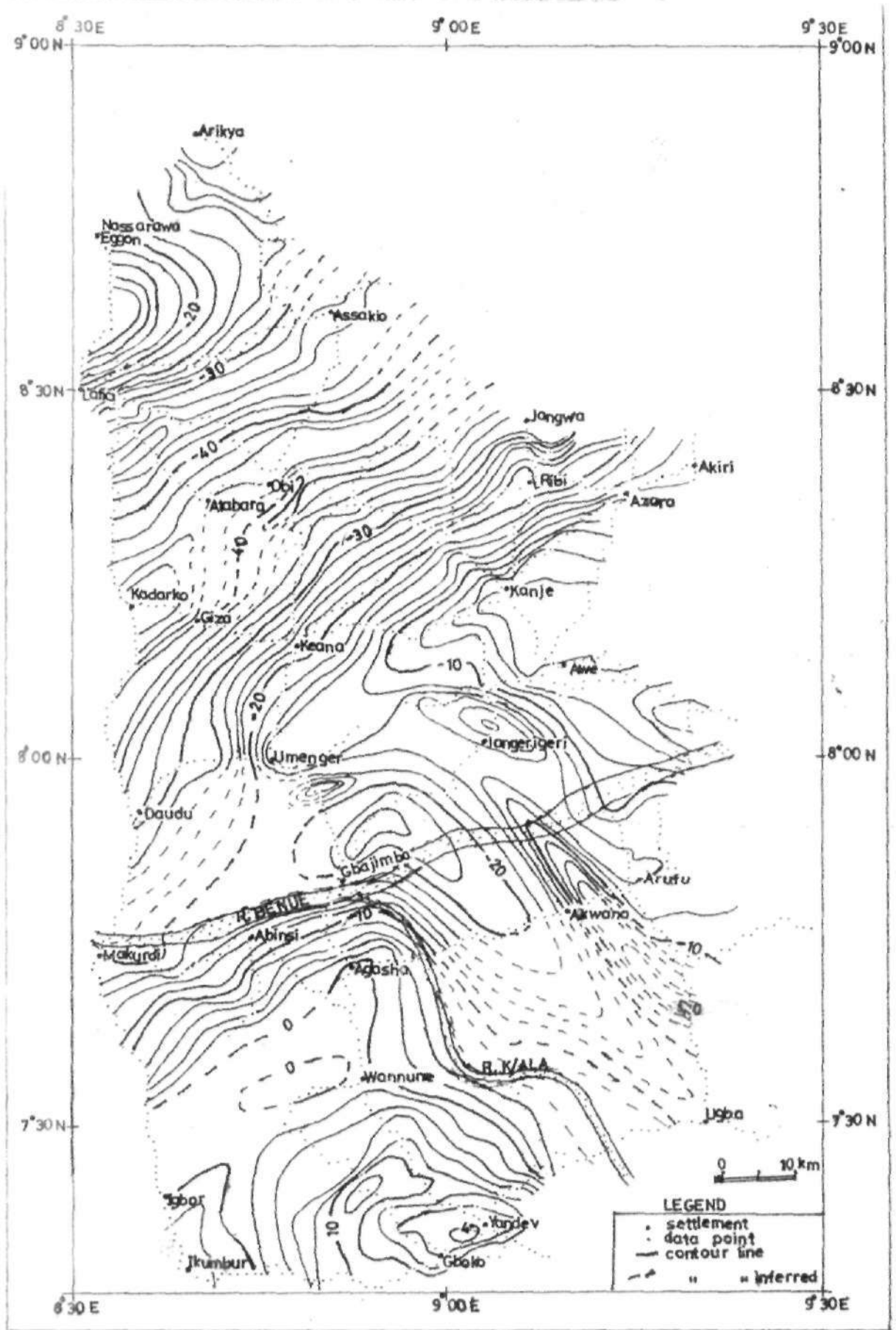


Fig. 3-6: THE BOUGUER ANOMALY MAP OF THE MIDDLE BENUE

3.6.1 : Systematic Error

This type of error is not uniquely defined for a gravity anomaly because it depends on the aspect of the anomaly being investigated (Pick et al, 1973) Irrespective of the aspect of the anomaly under investigation, the two main sources of this type of error are:-

(i) error in the calibration factor of the instrument(s) used

and (ii) error introduced by using a wrong mean crustal density in the Bouguer correction.

In this survey, the maximum gravity difference at any station, relative to the station whose gravity value was adopted as zero, is about 80 mgals. Therefore, if a two percent error in the calibration factor of the gravimeter is assumed as determined in section 3.1.1, the contribution of this type of error to the overall error in the gravity data at such a station would be 1.41 mgals.

The mean crustal density used in the Bouguer correction was 2.67×10^3 kgm^{-3}. That determined from the density analysis of the field samples collected was $2.65 \times 10^3 kgm^{-3}$. There is, therefore, a difference of 0.02×10^3 kgm^{-3} between the assumed

and the actual values of the mean crustal density. The maximum elevation encountered in the survey area was about 240m. Therefore, the maximum error in the Bouguer corrections in the survey area would be 0.22 mgals. Thus the overall systematic error in the survey would amount to about 1.43 mgals.

3.6.2. : Random Errors

These errors are of four main types. They are errors in determining:

(i) the observed gravity, g_s

(ii) the station height, h

(iii) the station latitude, $\emptyset$

and (iv) the terain corrections.

The error in obtaining g_s emanates from the reading error and the error originating from the gravimeter drift. In his work, the maximum error originating from reading the gravimeter, was expected not be greater than 0.029mgals, except where a recording mistake was made. The low value of the anticipated error was due to the fact that only the two or three readings that differed from each other by not more than one vernier unit on the instrument were used out of more than five readings normally taken at each station. The error

arising from the instrument drift originates from the assumption that the gravimeter drifts linearly between readings at two adjacent base stations occupied within two hours and reading errors at base stations. From fig. 3-1 it can be seen that this is not the case, although the error that could be introduced from the non-linearity of the drift pattern are generally small except in the vicinities of the turning points. At such turning points the maximum error that could be introduced by assuming a linear drift could not be more than 0.3 mgals, if the time between observations at the two base stations is not more than two hours.

The greatest source of error in any gravity survey is the station elevation. This is due to the fact that both the Bouguer and free-air corrections approximately add up to 0.2 mgals/m. As mentioned in section 3.24, most of the station elevations for this survey were determined by means of two altimeters. The sources of error in determining station elevation by means of altimeters, as given by Verheijen and Ajakaiye (1978) are:

(i) calibration error

(ii) error due to instrument drift (period of measurement)

(iii) error due to the hysterisis in the coil of the altimeter.

(iv) error due to change in pressure

and (v) reading error

These authors have shown that errors from sources (i), (iii) and (v) amount to about 1.0 to 1.5m. Errors (ii) and (iv) were found to be negligible for short periods of measurement when altimeter readings are taken in the dry season.

Both gravity and altimeter readings were taken at some stations with benchmarks during the survey. The difference between the computed (from altimeter readings) and known heights (from benchmarks) are shown in table 2 of the Appendix. For the eighteen stations tabulated, the mean value of the absolute differences between the two sets of heights was 0.46m, while the largest error was 1.19m. For the stations where benchmarks were not available, the computed heights were compared with the interpolated heights obtained from the topographic (base) maps which were either on scale 1:100,000 or 1:50,000. In most of the stations, the two heights agreed to within 3 m. This agreement was possible because of the fact that the project area is virtually flat coupled with the accurate procedure used in taking the altimeter readings. With a maximum error of 3m, in the value of the station elevations, the corresponding error in the Bouguer anomalies would be about 0.6 mgals, From the results in table 2 (Appendix), this type of error would be much less than 0.6 mgals for most of the stations.

The third component of the random errors is that due to the wrong determination of a stations' geographic latitude, ϕ. Its value is 0.081 $\sin^2 \phi$ per 10 m north-south distance (Parasnis, 1973). The latitudes of the stations were determined by gridding each of the base maps using a transparent graphical overlay. Because of the accurate method used in determining the station latitudes, the main source of this type of error would have to be from the wrong location of stations on the base maps, due to the factors discussed in section 3.2.6. On existing roads shown on the maps, the stations could be located exactly. For some roads which have changed course(s) from those shown on the maps, the possibility existed that some stations on such roads might have been mislocated by up to 0.2 km in the north-south direction. Such a mislocation would introduce an error of 0.17 mgals if the mislocation had occured around the most northern latitude encountered (about 8.83°N, Table 3, Appendix I)

The error introduced in the terrain correction, which is the correction for the attraction due to the excess mass above (or void below) the level of a gravity station,

is determined by the accuracy of the mean height of each compartment and how far away from the point (station) concerned the compartments exte nd to (Pick et al, 1973). No terrain correction was made for this survey simply because the project area is virtually flat (about 70 m to 240 m). It was only in the neighbourboods of Gboko and Arikya, which were respectively in the southern and northern fringe of the project area, that hills were encountered. At such places, the error due to the non-application of this correction may not exceed 1 mgal because the gravity stations were established at least a kilometre away from the foothills.

From the above analysis, the maximum error in the computed Bouguer anomaly at any station in this survey is equal to 1.87 gmals. For most of the stations, the actual error in the Bouguer anomaly is anticipated to be considerably less than 1.87 mgals.

CHAPTER IV

DENSITY DETERMINATION AND ANALYSIS

4.1 : Introduction

The gravity exploration method primarily detects horizontal variations in the densities of rocks buried beneath the ground surface. Therefore, for any meaningful interpretation(s) of the anomalies found in a survey, the best geologically permissible density contrasts must be used to model the body or bodies responsible for the anomalies. In order to have a fair estimate of this ideal density contrast, the densities of the rocks found in the survey area must be accurately determined.

4.2 : Sampling Technique

For this survey, 130 rock samples were collected during the field work. The fact that the geology of the project area is largely hidden under alluvium cover accounted for the limited number of specimens collected. The hand specimens were collected wherever there were outcrops along a traverse and at road cuts where rocks were exposed during the recent reconstruction of roads in the area. Each rock sample was labelled with the number of the station at which or in

whose vicinity it was collected. Samples collected between two gravity stations were labelled with the numbers of the two stations.

4.3 : Density Determination (Method of)

To determine the densities (dry and wet) of the samples, each of the samples was initially weighed dry in air to obtain its dry weight before they were all soaked in water until saturation. The period of soaking varied with the rock types. The crystalline rocks which get saturated quickly were soaked for about 24 to 30 hours while the sedimentary rocks were soaked for about 48 hours. Each rock was weighed in water, at saturation, to obtain its saturated weight. It was later weighed in air, after wiping off the excess water on the sample, to obtain its wet weight. The dry and wet densities for each rock were then calculated using the formulae:

$$\text{dry density } (\rho_{dry}) = \frac{\text{dry weight}}{\text{wet weight-saturated weight}} \quad \ldots\ldots\ldots (4\text{-}1)$$

and

$$\text{wet density } (\rho_{wet}) = \frac{\text{wet weight}}{\text{wet weight-saturated weight}} \quad \ldots\ldots\ldots (4\text{-}2)$$

Generally, the differences obtained between the dry and wet densities for crystalline rocks, except for vessicular basalt, were negligible. For sedimentary rocks, the wet densities were usually found to be about three to five percent higher than the dry densities. These significant differences in the densities of sedimentary rocks is to be expected as sedimentary rocks have more pore spaces than crystalline rocks. For both types of rocks, the average of the dry and wet densities for each rock type was adopted as the density of the sample because it was considered a better approximation of the true density of the sample at depth. The dry and wet densities listed against each rock type in tables 4-1 and 4-2 are the combined average of the dry and wet densities for the rock type respectively. Consequently, the average density against each rock type in the same tables is actually the average of the two average densities for the rock type.

4.4 : Error in (Accuracy of) Density Values

The balance used for weighing the samples has an accuracy of $\pm$ 1×10^{-4} kg (0.1g). Also, the weight of the majority of the samples was in excess of 0.6kg. For such samples, the error

in the determined density values due to the reading error of the balance would, be negligible (about 0.005×10^3 kg m^{-3}) For the samples which weighed about 0.2kg, the error in the determined density value was estimated to be less than $0.015 \times 10^{3} kg_{m}{}^{-3}$.

4.5: Density Analysis

After determining the average density for each rock sample as discussed in section 4.3 above, the densities were grouped according to rock types, and a density histogram was drawn for each rock type. The interval used for each histogram was either 0.02 or 0.05 ($\times 10^3$) kgm^{-3}, depending on the range of densities of the rocks in the group. The details of the histograms are discussed below.

4.5.1 : Sedimentary Rocks

The sedimentary rocks in the area were sandstones, gritstones, shales and gritstones. A summary of the densities of the sedimentary rocks analysed is shown in table 4-1.

(a) Sandstones

They form the majority (97%) of the sedimentary rocks collected in the area. They have been considered, for detail analysis, under two broad groups - namely, ferrigenous

Rock Type	No of Samples	DENSITY ($x10^3 kgm^{-3}$)				STANDARD DEVIATION
		Range	Dry	Wet	Mean	
Ferrigenous sandstones of Lafia formation	15	2.32-2.84	2.50	2.61	2.56	± 0.186
Late Albian-Cenomanian sandstones	36	2.23-2.84	2.37	2.42	2.40	± 0.161
Albian gritstones	4	2.59-2.64	2.52	2.65	2.62	---
Albian siltstones	4	2.55-2.64	2.58	2.62	2.60	---
Laterite	18	2.19-2.70	2.29	2.44	2.37	± 0.140

Table 4-1 : Densities of Sedimentary Rocks and Laterite.

and non-ferrigenous sandstones.

(i) Ferrigenous sandstones:-15 out of the 59 sandstone samples analysed belonged to this category. They were collected in the Lafia formation and, therefore, were of Late Campanian to Early Maestritchtian age. Their densities ranged from 2.32 to 2.85($x10^3$kg m^{-3}) with a mean density of $2.56x10^3$ kgm^{-3} and a standard deviation (r.m.s. error) of $\pm$ $0.186x10^3kgm^{-3}$. The histogram, fig. 4-1 (a), drawn with an interval of $0.05x10^3kgm^{-3}$, seems to indicate the existence of two categories of ferrigenous sandstones. The first group has a mean density of $2.3x10^3kgm^{-3}$ and the other group has a density range of 2.45 to 2.87($x10^3$) kgm^{-3} with a mean density of $2.69x10^3kgm^{-3}$. It is the opinion of the author that the group of ferrigenous sandstones with higher mean density might contain more iron than the group with a lower mean density. This opinion could be supported by the fact that Ojo (1974) obtained a density value of $2.64x10^3kgm^{-3}$ for ferrigenous sandstones with high iron content in the Niger basin which is very close to the value $2.69x10^3kgm^{-3}$ obtained in the present survey.

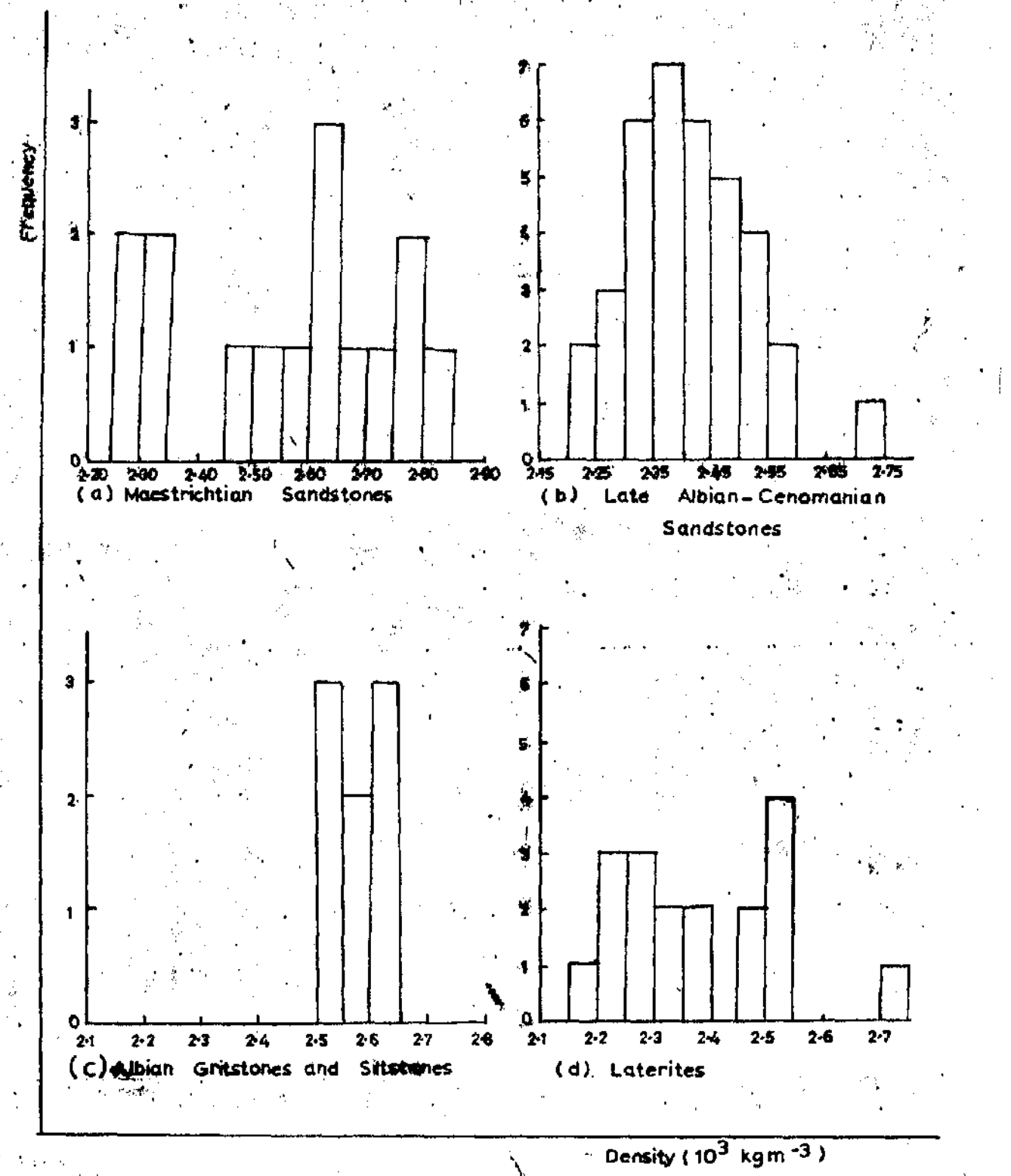


Fig. 4-1: Density Histograms For Sedimentary Rocks and Laterites

(ii) Non-Ferrigenous Sandstones

36 of the samples collected on the field belonged to this group. They were collected from the Awe and Keana/ Makurdi formations. Therefore, their ages range from Late Albian to Cenomanian. Their densities also ranged from 2.2 to 2.75 ($x10^3$) kgm^{-3} with a mean density of 2.40$x10^3 kgm^{-3}$ and a standard deviation of $\pm$ 0.161$x10^3 kgm^{-3}$. The histogram, fig 4-1 (b), shows an almost normal distribution with a mode of 2.41$x10^3 kgm^{-3}$.

(b) Albian Gritstones and Siltstones

Only eight samples, four each, of these rocks were collected. The densities of the samples ranged from 2.50$x10^3$ to 2.64($x10^3$) kgm^{-3}. The histogram for these rocks, shown in fig. 4-1 (c), indicates that the densities are evenly distributed about the mode (2.58$x10^3$ kgm^{-3}) which is also close to the mean density value of 2.61$x10^3 kgm^{-3}$.

4.5.2 : Laterites

18 samples were collected and their densities analysed. The range of densities obtained was 2.17 to 2.70 ($x10^3$) kgm^{-3} and their mean density was 2.37$x10^3 kgm^{-3}$ with a standard deviation of $\pm$ 0.14$x10^3$ kgm^{-3}. The histogram for these samples has two peaks approximately centred at 2.28 and

2.53 ($x10^3$) kgm^{-3} fig. 4-1(d) Even though no chemical analysis of the samples was made, the higher density lateries are assumed to contain more iron than the low density ones similar to the high density ferrigenous sandstones. Also, they could be less weathered than the low density ones.

4.5.3 : Basement Rocks

51 rock samples collected belonged to the basement complex. The samples were made up of granites, quartzites and pegmatites. Their respective density analysis are discussed below.

(a) Granites:

20 specimens mainly coarse-grained granites were collected. Their densities varied from 2.51 to 2.66 ($x10^3$) kgm^{-3}. The mean density obtained was $2.56x10^3 kgm^{-3}$. Though the mean density obtained is much lower than 2.65 and 2.68($x10^3$)kgm^{-3} obtained by Ojo (1974) for biotite granite and granite gneiss, respectively, in the Niger Valley and $2.66x10^3$ kgm^{-3} obtained for the Older granites of the Younger granite province of Nigeria (Ajakaiye, 1970), it is within the published range of densities for granites - e.g. 2.50 to 2.70 ($x10^3$) kgm^{-3}

(Farasnis, 1973) and 2.52 to 2.81 ($x10^3$) kgm^{-3} (Dobrin, 1960). The density histogram for this group of rocks, fig. 4.2 (a) shows a normal distribution with a mode of $2.56x10^3 kgm^{-3}$ Because the granite samples collected for the density analysis were not weathered, the author is of the opinion that the low density value obtained for the samples is due to the nature of the rocks.

(b) Quartzites:

The density analysis was carried out on only 8 samples. Their densities varied from 2.53 to 2.70 ($x10^3$) kgm^{-3} and the mean density was $2.64x10^3$ kgm^{-3} with a standard deviation of + $0.03x10^3 kgm^{-3}$. Even though the density analysis for this rock type involved only a few specimens, the density histogram (fig 4-2(b)) shows a normal distribution of the densities about $2.65 x10^3 kgm^{-3}$. The mean density value obtained from the density analysis ($2.64x10^3 kgm^{-3}$) is within the published range (2.60 to $2.70 x10^3 kgm^{-3}$) for quartzites (Farasnis,1973).

(c) Pegmatites

Only 3 samples were collected. Their densities ranged from 2 54 to 2 64 ($x10^3$) kgm^{-3} with a mean density of $2.59x10^3$ kgm^{-3} Because of the few number of specimens collected, no histogram was drawn for their densities but the mean density obtained is close to the value $2.64x10^3 kgm^{-3}$ obtained by Fairhead (1976) for pegmatites in East Africa.

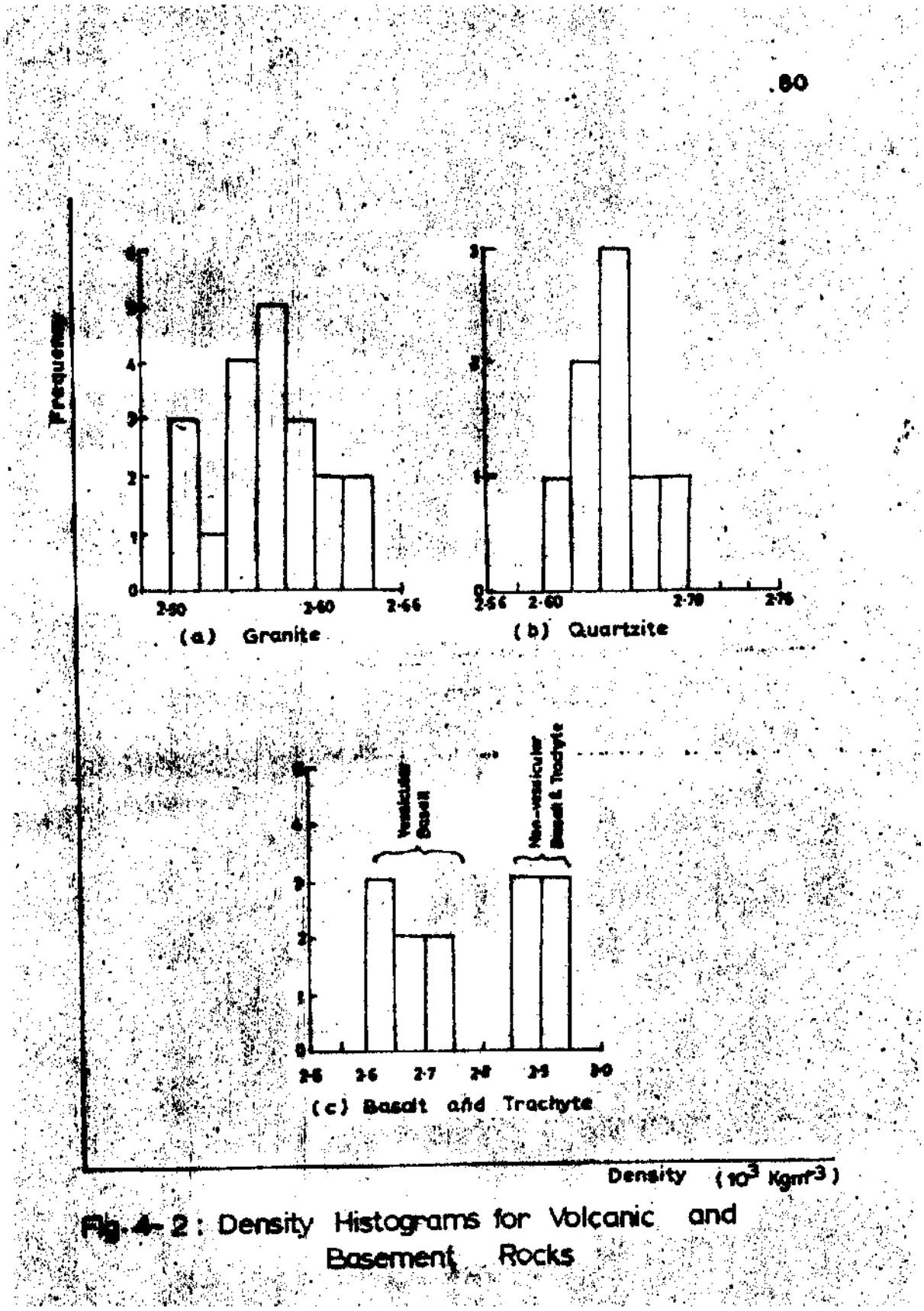


Fig. 4-2 : Density Histograms for Volcanic and Basement Rocks

4.5.4 : Volcanic Rocks

Rocks of this category collected during the survey were basalts, vessicular and non-vessicular olivine types, trachytes and ryhotites. The details of their densities are discussed below.

(a) Basalt

As mentioned in the last paragraph, two types of olivine basalts, vessicular and non-vessicular, were collected for density analysis The densities of each type was therefore treated separately.

(i) Vessicular Basalt

The densities of the specimens collected ranged from 2.62 to 2.70 ($x10^3$) kgm^{-3}. The mean density obtained was $2.66x10^3 kgm^{-3}$ with a standard deviation of $0.066x10^3 kgm^{-3}$. As for the quartzites and pegmatites, no density histogram was drawn for the vessicular basalts because of the small number of specimens analysed. The mean density value obtained in the present survey ($2.66x10^3 kgm^{-3}$) is slightly higher than the value $2.50x10^3 kgm^{-3}$ obtained by LaFehr (1965b) for vessicular basalts in the Southern Cascade Range, U.S.A.

(ii) Non-Vessicular Basalt and Trachyte

Six samples of this class of rocks were collected and their densities varied from 2.86 to 2.93 ($x10^3$)kgm^{-3}. The mean density was found to be $2.90x10^3 kgm^{-3}$ with a standard deviation of $\pm$ $0.027x10^3 kgm^{-3}$. Again, because of the small number of specimens collected for density analysis, the density histogram for the rocks was not drawn. The value of the mean density compares favourably with $2.90x10^3 kgm^{-3}$ obtained by Garland et al (1961) for basalts in Western Canada, 2.92 and 2.97 ($x10^3$) kgm^{-3} obtained by Hill (1963) and Thompson and Talwani (1964) for basalts in the Western and Central parts of the United States of America respectively. The value obtained from the current survey also falls within published values 2.70 to 3.30 ($x10^3 kgm^{-3}$) (Nettleton, 1940; Parasnis, 1973).

When the densities of all the basalts and trachytes were combined, the resulting histogram is shown in fig. 4.2 (a). The mean density then falls to 2.74 $\pm$ 0.13($x10^3$)kgm^{-3}. However, the histogram clearly shows two distinct density distributions. The first distribution has a mode of 2.67 $x10^3 kgm^{-3}$ while the other has a mode of $2.90x10^3 kgm^{-3}$. These two modes represent the mean densities for vessicular

and non-vessicular basalts respectively. Therefore, the mean density obtained here ($2.74x10^3 kgm^{-3}$) may not be useful for interpretation purpose since it does not truely represent the density of either of the two types of basalts in the project area. However, the value compares with $2.74x10^3 kgm^{-3}$ obtained by Pakiser (1964) for basalts in the Cascade Range of the United States of America.

(b) Rhyolites

Six samples of this rock type were collected. Their densities ranged from 2.58 to 2.74 ($x10^3$) kgm^{-3}. The mean density obtained was $2.64x10^3 kgm^{-3}$. The density histogram for this class of rocks was not drawn because of the few specimens collected for the density analysis.

A summary of the densities for basement and volcanic rocks are listed in table 4-2.

4.6 : Adopted Densities Used in the Interpretation of the Gravity Data

Combined density histograms were drawn for each of the major rock types (sedimentary, basement and volcanic rocks) to determine their respective group mean densities.

ROCK TYPE	NO OF SAMPLES	DENSITY ($\times 10^3 kgm^{-3}$)				STANDARD DEVIATION
		RANGE	DRY	WET	MEAN	
Quartzite	8	2.53-2.70	2.62	2.65	2.64	$\pm$ 0.034
Granite	20	2.51-2.66	2.54	2.57	2.56	$\pm$ 0.041
Vesicular Basalt	7	2.62-2.81	2.65	2.67	2.66	$\pm$ 0.066
Non-Vesicular Basalt/Trachyte	6	2.86-2.93	2.89	2.91	2.90	$\pm$ 0.027
Rhyolite	6	2.58-2.74	2.62	2.66	2.64	$\pm$ 0.048
Pegmatite	3	2.54-2.64	2.56	2.60	2.59	---

Table 4-2 : Densities of Basement and Volcanic Rocks

4.6.1 : Sedimentary Rocks

Firstly, the densities of all the sandstones, excluding the highly ferruginised ones, were combined and analysed. The resulting histogram is shown in fig. 4-3 (a). The mean density obtained was $2.44 \pm 0.150 \times 10^{3} kgm^{-3}$ which is the same value obtained for the Bima sandstones in the Upper Benue (Cratchley and Jones, 1965) and which closely agrees with the value $2.40 \times 10^{3} kgm^{-3}$ obtained for sandstones in the Lafia -Awe region of the project area (Ajakaiye and Ajayi, 1977). Because the sandstones of the project area, except the ferrigenous ones of the Lafia formation, are the lateral equivalent of the Bima sandstones (formation), as discussed in section 2.3 3, the value $2.44 \pm 0.150 \times 10^{3} kgm^{-3}$ was therefore accepted as the average density for the sandstones of the Awe, Keana/Makurdi formations in the Middle Benue. Also, the measured density value for the Albian gritstones and siltstones in the present survey was $2.62 \times 10^{3} kgm^{-3}$. This value compares favourably with the value $2.65 \times 10^{3} kgm^{-3}$ obtained for the Albian shales of the same area (Cratchley and Jones, 1965). Similarly, the value $2.56 \pm 0.186 \times 10^{3} kgm^{-3}$ obtained as the mean density for ferrigenous sandstones of the

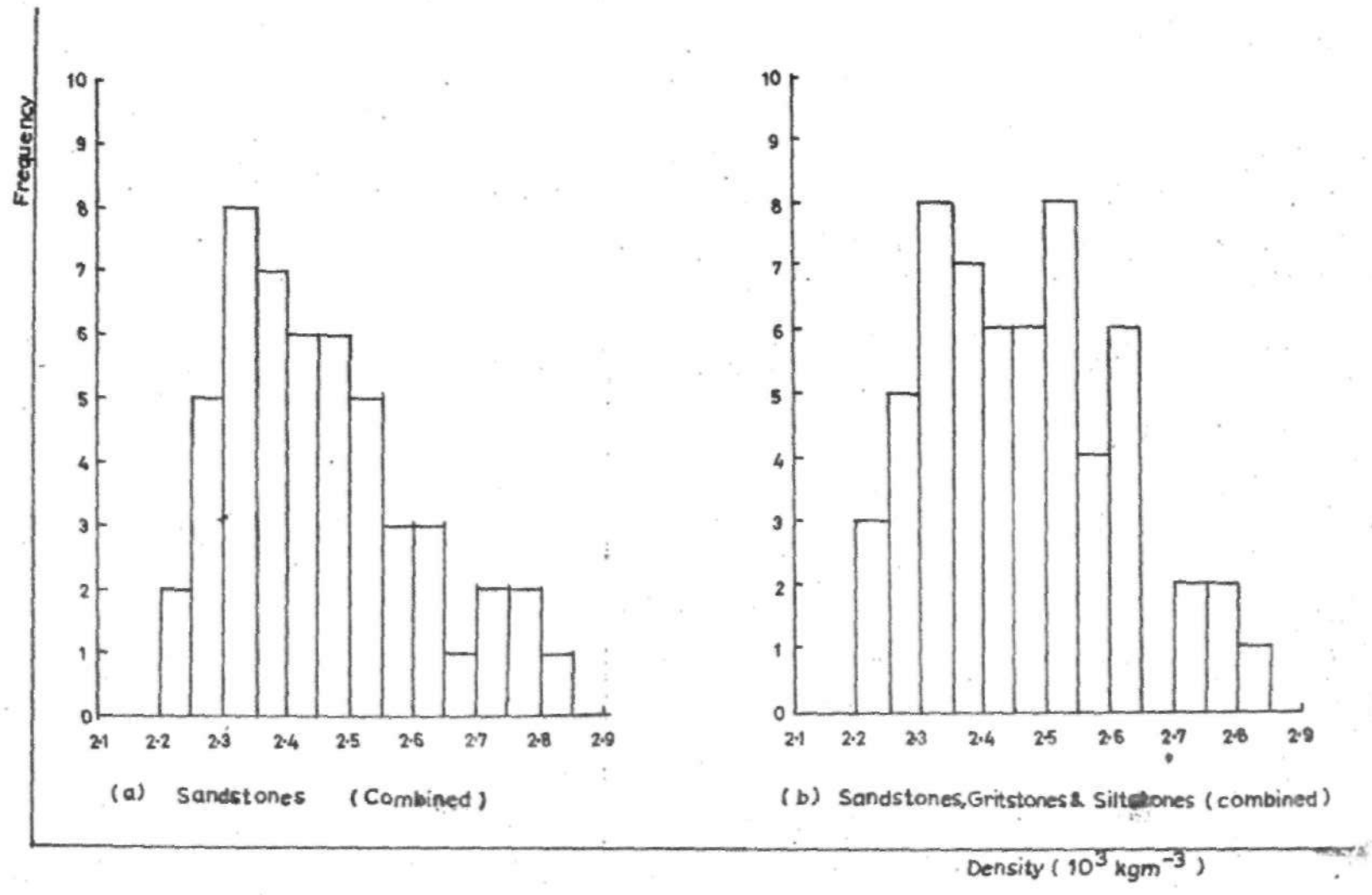


Fig. 4-3 : Combined Density Histograms For Sedimentary Rocks

Lafia formation was considered reasonable because it lies within the range 2.27 to 2.64($x10^3$) kgm^{-3} obtained for ferrigenous sandstones and siltstones in the Niger basin (Ojo, 1974).

The densities obtained for all the sedimentary rocks were then combined and analysed. The resulting histogram is shown in fig. 4-3 (b). The mean density obtained was 2.47 $\pm$ $0.152x10^3 kgm^{-3}$. This density value would be useful during the modelling exerise if the sedimentary rocks are taken as a unit and simply contracted with the basement instead of contrasting them with the basement formation by formation.

4.6.2 : Basement Rocks

A combined histogram for the basement rocks is shown in fig. 4.4(a). It indicates a normal density distribution about 2.56 $\pm$ $0.042x10^3 kgm^{-3}$. This mean density value is rather low in comparison to the standard value ($2.67x10^3 kgm^{-3}$) for basement rocks. The disparity in the two values was due to the fact that granites, with a mean density of $2.56x10^3$ kgm^{-3}, formed about 60% of the samples treated. As stated in section 2.5, gneisses and migmatites are the major components (formations) of the basement in the area and not

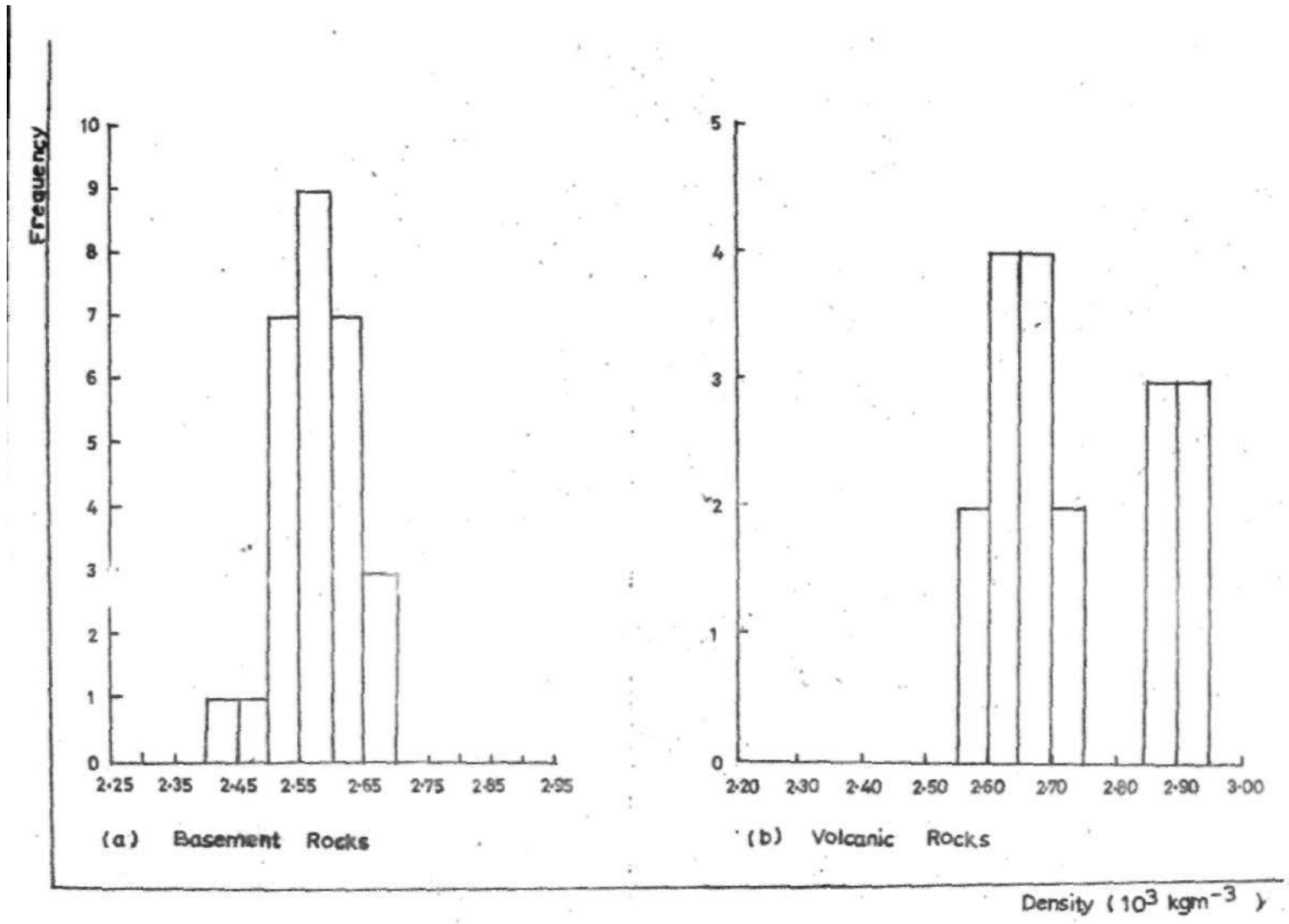


Fig. 4-4: Combined Density Histograms For Basement and Volcanic Rocks

granites. Consequently the mean density of basement rocks ($2.56x10^3kgm^{-3}$) arrived at, here was thought not to be respresentative of the basement rocks in the area. Instead, the mean density value, $2.65x10^3kgm^{-3}$, obtained for quartzites was considered to be perhaps closer to the mean basement density. As earlier mentioned in section 4.5.3, only eight quartzite specimens could be collected during the field work for density analysis. As a result, the value $2.65x10^3kgm^{-3}$ may also not be representative of the density of the basement rocks in the project area. Therefore, the value $2.67x10^3kgm^{-3}$, normally assigned to the mean crustal density, was assumed for the basement rocks in the project area in the modelling exercise.

4.6.3.: Volcanics

Fig. 4.4 (b) shows the combined histogram for the densities of all the volcanic rocks sampled. The histogram clearly shows the existence of two main densities for the volcanics in the area. The vessicular basalts and rhyolites each have a mean density of $2.65x10^3kgm^{-3}$ while the non-vessicular basalts and trachytes have a mean density of $2.90x10^3kgm^{-3}$. These values were adopted because they compare with published values.

ROCK TYPE	DENSITY ($x10^3 kgm^{-3}$
Ferrigenous Sandstones (of Lafia Formation)	2.56 ± 0.186
Sandstones of Awe Keana/Makurdi formations	2.40 ± 0.161
Albian shales, Siltstones and gritstones	2.60 ± 0.151
Granites	2.56 ± 0.041
Rhyolites	2.65 ± 0.048
Vessicular Basalts	2.65 ± 0.066
Non-Vessicular Basalts/ Trachytes	2.90 ± 0.027

Table 4-3: Densities Accepted for Modelling

A summary of the densities accepted for modelling is shown in table 4-3.

4.6.4 : Possible Density Contrasts

On the basis of the density values for the various rock types discussed above coupled with the known geology of the project area. some geologically possible density contrasts have been identified. The density contrasts which range from $\pm$ 0.03 to $\pm$ 0.0.46($\times 10^3$) kgm^{-3} are listed in table 4-4

ROCK TYPE	CONTRASTED WITH	DENSITY CONTRAST gm/cm^{-3}
Ferrigenous Sandstones	Basement	± 0.06
Albian shale/gritstones and siltstones	Non-ferrigenous Sandstones	± 0.13
Granite	Basement	± 0.08
Vessicular basalt or rhylite	Non-Vessicular basalt or trachyte	± 0.25
Vessicular basalt or rhyolite	Albian shales etc.	± 0.03
Vessicular basalt or ryholite	Non-ferrigenous Sandstones	+ 0.21
Non-Vessicular Basalt or trachyte	Non-ferrigenous Sandstones	± 0.46

Table 4-4 : Geologically Possible Density Contrasts in the Middle Benue.

CHAPTER V

ISOSTASY AND REGIONAL GRAVITY IN THE MIDDLE BENUE

5.1 : Isostasy

The term isostasy was originated by Dutton in 1889 to mean the condition of the earth when all readjustments have been made to bring about gravitational equilibrium (Dobrin, 1960). Prior to the introduction of this term, two main hypotheses had been evolved to explain the mistie in a geodetic survey carried out in India in mid-nineteenth century. These were the theories of Airy and Pratt. In the Airy's crustal model, the earth's crust is considered to be a rigid shell which floats on a liquid substratum in such a way that the crust penetrates deeper into the substratum under mountains than it does under land at sea level. As stated in another way by Burrad (1920), "the theory of isostasy ascribes to the earth's crust a peculiar structure in which all mountains and heights standing above sea-level, and all oceans and surface hollows dipping below sea level are compensated by excesses of matter underlying them in the crust".

The Pratt's model, on the other hand, assigns a uniform thickness to the crust. At a certain depth, known as the depth of compensation (Woollard, 1965), the base of the crust everywhere supports a uniform weight per unit area. That is, at this depth, the pressure due to the weight of the overlying crust is everywhere the same.

5.1.1 : Methods employed for Isostatic Studies

According to Woollard (1965) an area which has dimensions of 0.5° of longitude by 0.5° of latitude is considered broad enough for carrying out studies on isostatic compensation. The dimensions of the project area for the present survey was about 2.0° of longitude by 1.0° of latitude. Therefore, isostatic studies, though on a cursory basis, were carried out for the project area. Among the methods commonly employed in carrying out such studies are:

(i) the calculation of the theoretical isostatic anomalies of an assumed crustal model based on, for example, the Airy's method and comparing these anomalies with the observed gravity data.

(ii) comparing the anomalous masses in the crust and the upper mantle, using Gauss' theorem, with masses represented by the topographic relief.

(iii) plotting the free-air and/or Bouguer anomalies against elevations over a broad region to determine the relationship(s) between them.

Results from the first method could be very misleading if the assumed model of the crust differs from what actually exists (Hill, 1963). Also, the method is dependent on the assumed density and dimensions of the compensating (anomalous) mass (LaFehr, 1965a). A major advantage of the second method is the unique determination of the compensating mass which is made possible by the use of Gauss' Law. Though the method is independent of the dimension of the compensating mass (LaFehr, 1965a), it does not provide information on the crustal structure (Hill, 1963).

In this survey, the main method employed in studying whether or not the project area is isostatically compensated is the third method described above. The first method was not used not because of its defect already mentioned but because the emphasis of this work is just to find out whether or not the area is in isostatic equilibrium. Despite the

uniqueness in determining the compensating mass, the second method was not employed for the isostatic studies because in determining the excess mass the method does not only involve gridding the residual map, the residual values at the grid points must also be integrated over an infinite area (Ajayi, 1975). That is to say, the latter condition implied summing the residuals far beyond the boundaries of the trough or area of interest, in general. In this survey, that condition could not be satisfactorily met because the area of data acquisition barely exceeded the trough boundaries. Other limitations of this method such as the error due to the curvature of the earth's surface and the loss of the gravity 'signal' in background 'noise' at infinity have been discussed in detail by Hammer (1945) and LaFehr (1965a, 1965b).

5.1.2 : Isostasy in the Middle Benue

Fig. 5-1 shows the plot of the gravity anomalies (Bouguer and free-air) with height in the project area. The heights of the gravity stations were sampled at every 16.5m (50ft). Then for all stations with heights within each height interval, the statistical average of their heights and their corresponding gravity values were respectively

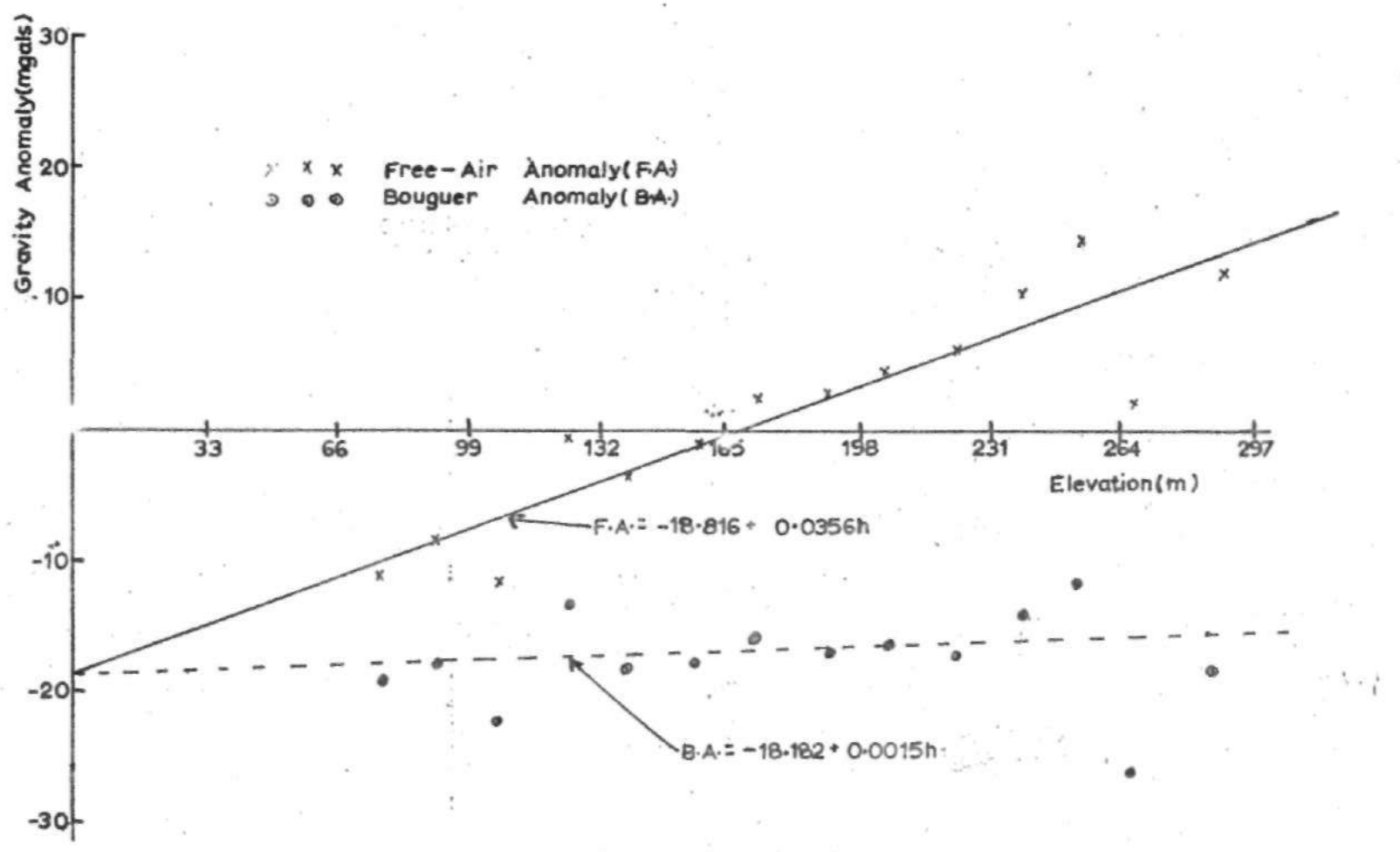


Fig. 5-1: Variation of Gravity Anomalies with Elevation over the entire Project Area

determined. The values for all the intervals were then plotted to give the figure. A linear regression was carried out for each plot to determine the equation of the 'best' straight line passing through the plotted points. Also, the correlation factor of each line was determined. For the free-air anomaly (FA), its variation with height (h) was found to be governed by the equation

$$FA = -18.182 + 0.0356h \quad \ldots\ldots (5\text{-}1)$$

with a correlation factor of 0.81. For the Bouguer anomaly (BA), the equation was found to be

$$BA = -18.182 - 0.0016h \quad \ldots\ldots (5\text{-}2)$$

The corresponding correlation factor obtained was 0.008. The high correlation factor of 0.81 for the variation of the free-air anomaly with height was interpreted to mean that there was an almost direct relationship between the free-air anomalies and heights, as is usually the case. This view is further supported by the fact that the gradient (0.0356 mgals m^{-1}) of the line represented by equation (5-1) above is close to the value of the vertical gradient of gravity (0.03086 mgals m^{-1}). On the other hand, the low correlation between the Bouguer anomalies and the heights showed that the two quantities were independent of each other. Therefore, the low correlation factor between

the two quantities was interpreted to suggest that the density used for the Bouguer correction was probably correct in accordance with the Nettleton(s density profiling technique (Nettleton, 1940, 1973).

The average value of the free-air anomaly over the project area was found to be 0.171 mgals. Near zero values of the average of the free-air anomalies over a bread region in which horizontal dimensions are much greater than the crustal thickness have been interpreted to imply near perfect isostatic compensation of the region (Thompson, 1959; Dobrin, 1960; LaFehr, 1965a) Because of the small value (0.171mgals), of the mean free-air anomaly obtained, the project area was, therefore, thought to be near being completely compensated.

According to Hill (1963) a broad region with an average free-air anomaly ($\bar{FA}$) equal to zero has had the excess mass, represented by the average topographic elevation, compensated by an equal amount of deficiency at depth. He further proved, in the same paper, that the average Bouguer anomaly ($\bar{BA}$) over the area should be equal to the average Bouguer correction ($\bar{BC}$) used in reducing the gravity data over the area. That is

$$\bar{BA} = -2\pi G\rho \bar{H} \quad \ldots (5\text{-}3)$$

then $\overline{FA}$ = 0

ρ_m = density used in Bouguer correction

and $\bar{h}$ = average station elevation in the area

In this work, the average elevation of the project area was found to be 165.73m (502ft.) and the average Bouguer correction using equation (5-3) about was found to be -18.46 mgals. This value favourably compares with the value -18.15 mgals obtained as the mean Bouguer anomaly value for the project area. The agreement between the two values further confirmed that the Middle Benue is in a state of near total isostatic compensation.

Another method for studying isostatic compensation, which is more qualitative than the methods so far discussed, is plotting the Bouguer anomalies along a profile with the corresponding station heights and noting whether or not there is an inuerse relationship between them. Because of the fact that compensated highlands are underlain by light materials, the Bouguer anomalies over such highlands should be negative. Also, the Bouguer anomalies over compensated ocean deeps should be positive because they are underlain

by denser than normal materials, Therefore, an inverse relationship is expected between the Bouguer anomalies and the station elevations over a totally compensated broad region. Fig. 5-2 shows such an inverse relationship, over some sections of the profiles, between the Bouguer anomalies and elevations plotted for certain north-south and West-East profiles. Thus further confirming that the Middle Benue is near complete isostatic compensation.

5.2. : The Regional Gravity

The Bouguer anomalies derived from the observed gravity data are usually considered to be made up of two components - the regional and the residual anomalies. The regional anomalies are usually ascribed to structures of regional extent while the residual, which is what remains when the regional has been subtracted from the Bouguer anomalies, are considered to be of local origin. In order to be able to make any meaningful interpretation of the Bouguer anomaly map (fig. 3-4, in this case), the regional must be removed.

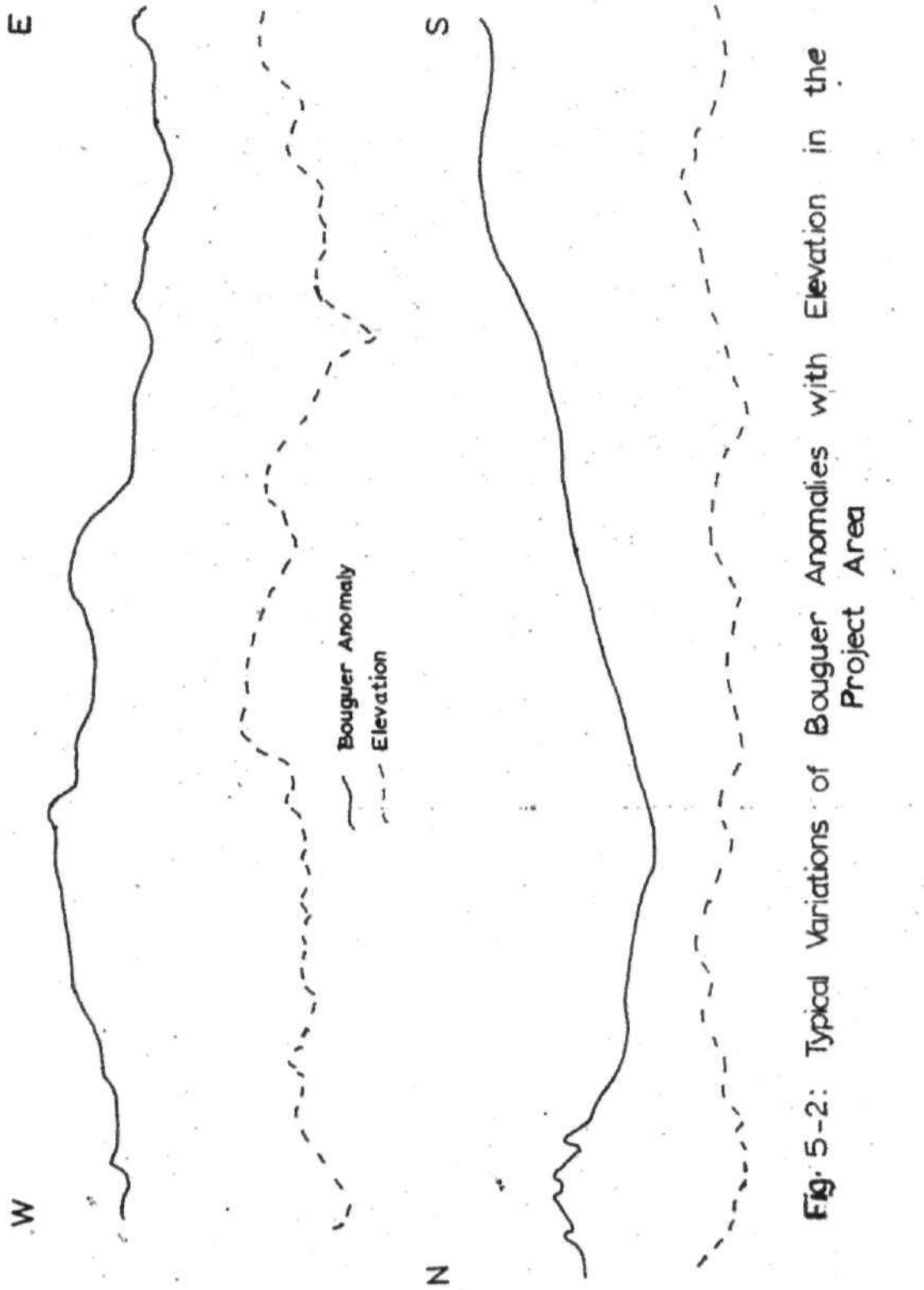


Fig. 5-2: Typical Variations of Bouguer Anomalies with Elevation in the Project Area

5.2.1 : Methods used in Removing Regional Anomalies

Three main methods are used in removing the regional gravity from the reduced observed gravity data (i.e. the Bouguer anomalies). These are the

(i) smoothing (graphical) method

(ii) gridding (moving average) method

and (iii) polynomial surface fitting method.

Any, or the combination, of the above methods can be used for a given survey depending on the complexity of the Bouguer anomaly map.

The first method entails visually examining the plotted Bouguer anomalies and drawing in a smooth curve or line as the regional gravity, if a single profile is involved. If an entire map is involved, the process is carried out over selected longitudinal and transverse profiles using the common (crossing) points as control points. Then a regional map is subsequently deduced from the regional trends on the profiles. Whether the method is employed over a single profile or over a whole map, the method is subject to the personal prejudices of the interpreter (Paul, 1967; Skeels, 1967).

The gridding method, which in essence involves two-dimensional numerical filters, uses concentric circles. It is the method mostly criticised in literature. The major criticism against the method is that it does not posses any definite quantitative relationship with the anomalous mass (Skeels, 1967). Consequently, different results are obtained from different formulas and/or grid spacings. According to Nettleton (1954) and Roy (1961), the only physical significance of the method is the proportionality that exists between the filters and second derivatives. The method is anomaly dependent (Vajk, 1951) but is useful in locating small anomalies and also for resolving overlapping ones (Skeels, 1967). However, the method also changes or distorts the shapes of anomalies (Appel, 1974). Another disadvantage of the method is that contouring errors are propagated to the derived residuals, if the grid spacing is less than the data separation (Romberg, 1958). According to LaFehr (1965a) in order to successfully remove the regional anomalies, using this method, the grid spacing should depend on the size of the residuals to be resolved.

The polynomial surface fitting method was introduced by Skeels in 1967 The method is based on fitting a low order (degree), usually not more than 2nd order, polynomial surface to the Bouguer anomaly map in either the less anomalous parts of the map or over the entire map depending on the complexity of the Bouguer anomaly map. A modified version of the method, was also introduced in 1967 by Paul. In this method, the polynomial fitting is carried out in small areas around the data points. Either of the two methods just discussed has the advantage of using data points in computing the regional. Hence the subsequent regionals are independent of contouring errors on the Bouguer anomaly maps (Skeels, 1967). However the polynomial fitting method involves too much calculations (Appel, 1974). Therefore, a computer may have to be used in carrying out the fitting. This seems to be the major defect of the method.

5.2.2 : Removing the Regional in the Present Survey

As discussed in section 5.2.1 the smoothing method can be used to derive the regional anomaly map from a Bouguer anomaly map. For example, Garland et al (1961) derived the regional gravity map for their survey in the Southern Rocky

Therefore, using the gridding method would have introduced contouring errors carried over from the Bouguer anomaly map to the derived regional and residual anomaly maps as stated by Romberg (1958). Consequently, the method was considered not suitable for this work.

Because of the reasons given above, the Skeel's method of polynomial surface fitting was used in deriving the regional and the subsequent residual anomalies. A first, second and third order polynomial surface was used in fitting the Bouguer anomaly map using data sampled both in the undisturbed area of the map and over the entire map. In each case, the approximate centre of the project area was considered the centre of each of the surfaces. The only reasonable fit obtained was that from the first order surface fitted to the data sampled over the entire Bouguer anomaly map. The other computed surfaces gave either too large regional values or entirely positive residuals over the the project area The polynomial coefficients derived from the 'best' fit were then used to compute the regional anomalies at the data points. The computed regional anomalies were automatically plotted by the computer on the CALCOMP plotter but were manually contoured to give the regional anomaly map shown in fig. 5-3.

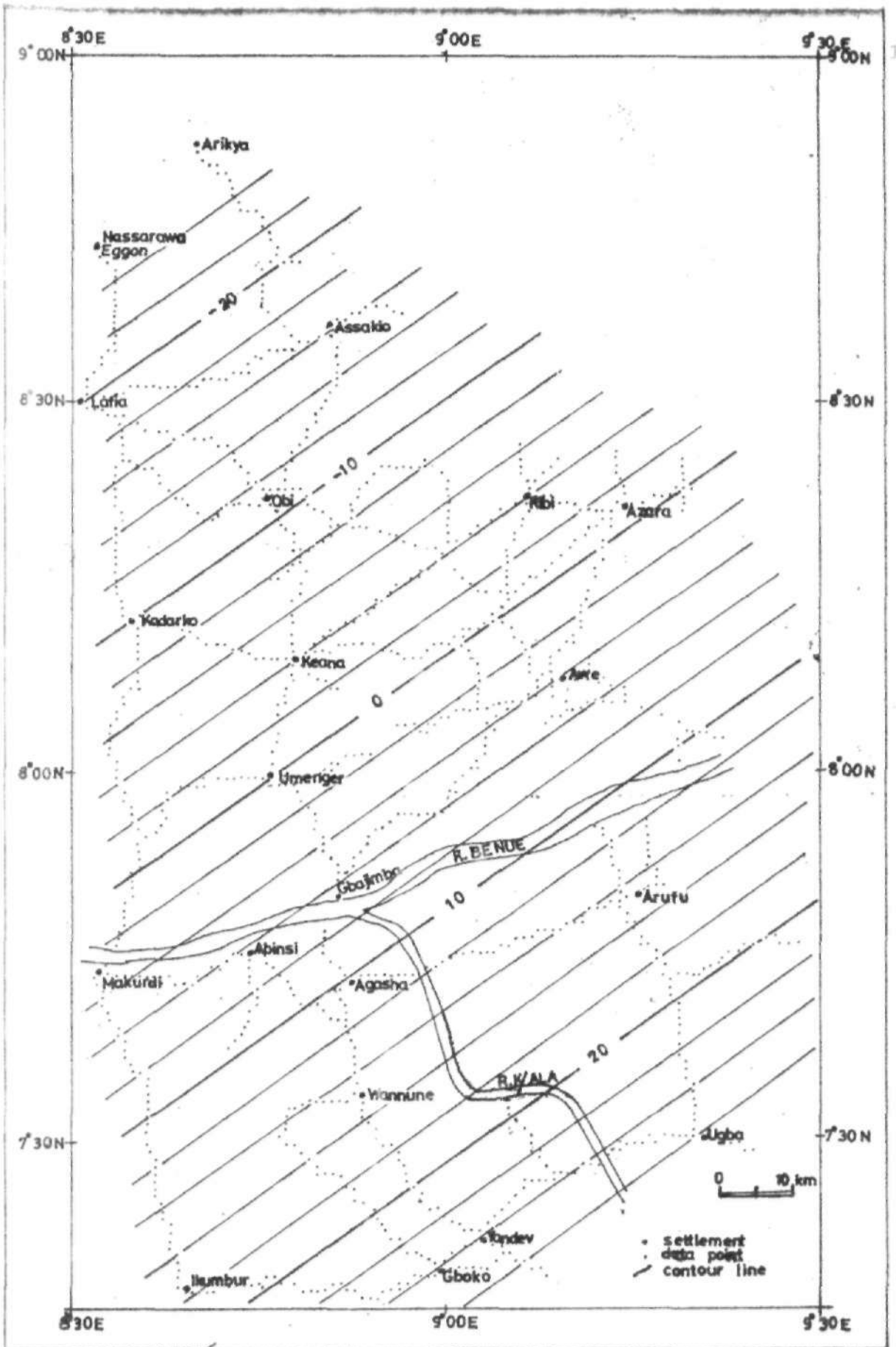


Fig. 3-5: THE REGIONAL ANOMALY MAP OF THE MIDDLE BENUE

5 3 : The Regional Anomaly Map

The contours on the regional anomaly map trend NE-SW parallel to the axis of the trough. Also, the contour lines are almost evenly spaced; probably because of the assumed surface used in fitting the Bouguer anomaly map. The gravity values on the map increase gradually in the north-south direction at the rate of 0.26 mgals km^{-1} towards the south. This value corresponds to the value of the regional gravity gradient observed by Cratchley and Jones (1965) in the Middle Benue. In the west-east direction the regional gradient obtained in the present survey was 0.13mgals km^{-1} towards the east. Because the project area extended from the basement north of the trough to that south of the trough coupled with the fact that the regional gravity gradients are small-valued, the regional gradients obtained for this survey are considered to be what the observed gravity values would have been if the entire project area had been filled with basement rocks. This view is buttressed by the fact that the regional map (fig. 5-3) does not correlate with surface geology (fig. 2-1).

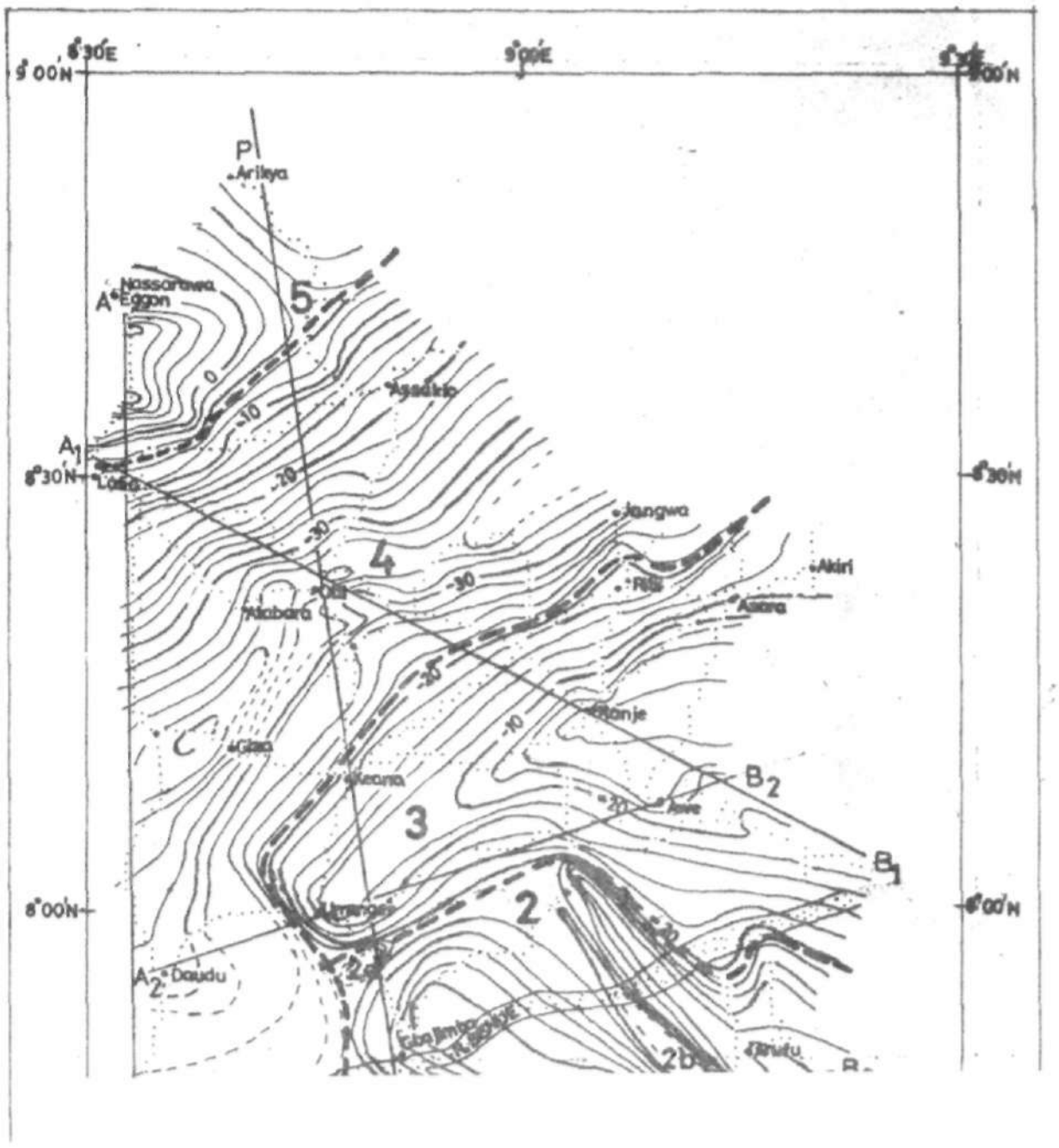
5.4 : The Residual Anomaly Map and Its Correlation with Surface Geology.

Fig. 5-4 shows the residual anomaly map produced for the survey area. Generally, the anomalies trend NE-SW except within the area immediately to the south of the Keana anticline in which the anomalies trend NW-SE. Around Gboko, the anomalies tend to be circular. For the purpose of correlating the residual map (fig. 5-4) with surface geology (fig. 2-1) for a qualitative interpretation, the residual map has been divided into five broad regions discussed in detail below. Fig. 5-5 is a superposition of fig 5-4 on fig 2-1.

5.4.1. : Zone 1

This zone is labelled 1 in the southwest corner of the residual map. The zone appears to be part of a circle with an approximate radius of 30 km centred about 20 km to the north-east of Gboko. This zone also contains the area of positive Bouguer anomalies in the project area (fig. 3-6). There are three main anomalies within the region and they have been labelled 1a to 1c.

Anomaly 1a seems to be that due to a broad anticline or an anticlinerium However, it does not correlate with any


9°00'N
8°30'E
9°00'E
8°30'N
P
Arileya
A
Nassarawa Eggon
A1
Loko
Agadiko
Jangwa
Akiri
Rijis
Asara
Alabara
Kanje
Gitata
Akuma
B2
B1
8°00'N
A2
Daudu
Tabajimbo
Ibaruku
5
4
3
2
2a
2b
-10
-20
-30

of the folds (synclines and anticlines) shown on the geological map (figs 2-1 and 5-5) within the area corresponding to zone 1. These folds were reported by Kogbe et al (1970). Both the Makurdi anticline and syncline which are considered to be major folds (Kogbe et al, 1978) are not reflected on the residual anomaly map. The gravity data in the zone is sufficiently detailed enough to eanble one to delineate the folds if they are major ones. Therefore, it is the author's opinion that if the Makurdi syncline and anticline exist at all within the zone, they may not be major folds. The broadness and the magnitude of the anomaly values in region 1a are similar to those observed over the Keana anticline/ anticlinorium (zone 3). Therefore, the observed anomalies in this zone are tentatively ascribed to an anticline/ anticlinorium which may contain the Asu River formation, possibly with some volcanics at its core, similar to that of the Keana anticline. This anticline which may be called the Igbor anticline, because it passes through Igbor, is neither the one hitherto referred to as the Makurdi Anticline (Offodile, 1976; Kogbe et al, 1978) nor does it appear to be part of the Keana anticline.

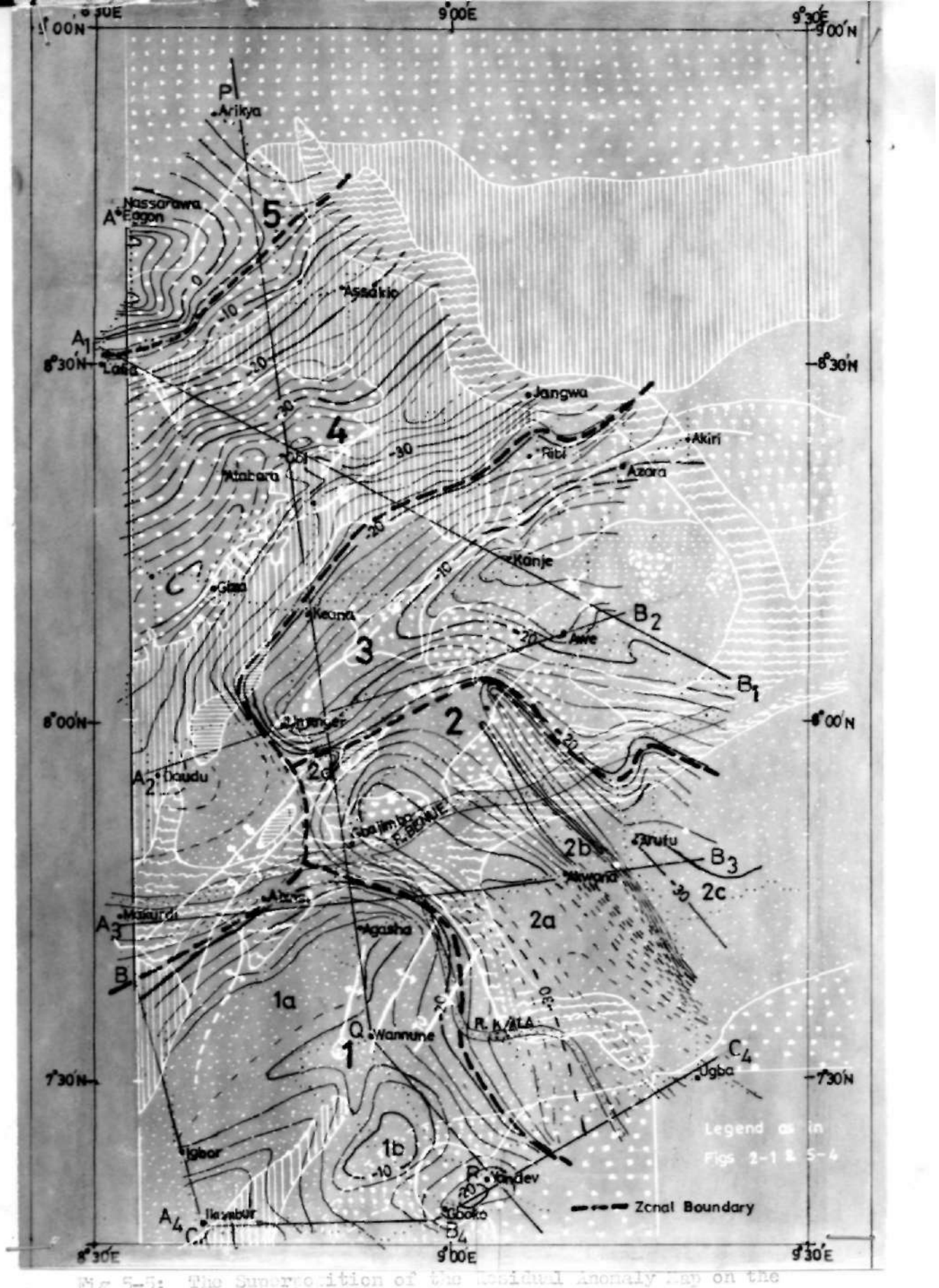


Fig 5-5: The Superposition of the Residual Anomaly Map on the

Anomaly 1b is almost elliptical in shape. The value of the residual anomalies in this section of zone 1 is about the same magnitude as those of anomaly 1a and is positive relative to its surroundings. From the gravity gradients in the region, the anomaly is thought to be due to a basic intrusive. Because of the closeness of this anomaly to the southern sediments/basement contact, the area might have been the centre of volcanic activities in zone 1 since marginal volcanism are commonly associated with continental rifts (Milanovsky. 1972).

Anomaly 1c, which is also almost elliptical in shape and is a region of low residual anomaly values in which the contours are closed. The anomaly occurs entirely within the basement. Granite reaches the surface in Mkar near Gboko where its height above the surrounding had been estimated to be about 260m (Cratchley and Jones 1965). Also a G.S.N. borehole in Yandev (B.H. 1101) encountered granite at a depth of about 18m. Therefore, the low anomaly values in this region have been ascribed to a granitic intrusion whose density is smaller than that of the surrounding basement.

5.4.2 : Zone 2

This zone is just to the south of the Keana anticline (zone 3). The residual anomalies in this zone trend south-eastwards. There are four local anomalies within the zone and they have been labelled 2a to 2d.

Anomaly 2a lies in an elongated area with an approximate axis trending from Gbajimba to Ugba. The value of the residuals in the area decrease from the flanks towards the central axis. The maximum gravity relief from the edges to the central axis is about - 20mgals. The average width of the area occupied by the anomaly is about 30km. Because of the high gravity gradients along the flanks of the area, the anomaly is thought to be due to a graben. The tentative name suggested for it is the Ugba Graben. Also, the gravity data suggests that the graben plunges towards the southeast and that the anomaly 2a subdivides into two narrower anomalies around the southern sediments/basement contact.

Anomaly 2c, like that of 2a, trends to the southeast. The width of the anomaly varies from about 10km around Jangerigeri where it originates to more than 20km around Arufu. It is most probable that the anomaly extends outside the present project area around the south-east edge of the map (fig. 5-4). The approximate axis of the anomaly passes

through Jangerigeri and Arufu. Within the project area, the maximum gravity relief of the anomaly, from the flanks to the central axis, is about-10mgals. As in the case of anomaly 2a, the gravity data suggests the anomaly is due to a graben which also plunges to the south-east. The tentative suggested name for this graben is the Arufu graben. The fact that the gravity relief (-10mgals) of this anomaly is less than that of anomaly 2a, -20mgals, suggests that the floor of the Arufu graben is probably shallower than that of the Ugba graben.

Sandwitched between anomalies 2a and 2c is a narrow elongated anomaly whose residual anomalies are positive relative to those of 2a and 2c. The axis of the anomaly also trends to the southeast. While the length of the anomaly may not exceed 30km, its maximum width is about 5km. Both the eastern and western margins of the anomaly are characterised by very high gravity gradients Consequently, the anomaly is thought to be due to a narrow horst Because the horst passes near Akwana, the name Akwana Horst is tentatively suggested for it.

Anomaly 2d is relatively small in area. It is elliptical in shape and lies bet ween the northwest boundary of anomaly 2a and the southern boundary of zone 3. The anomaly, also lies

just to the northeast of Oku Lake. Relative to anomaly 2a, the residuals of anomaly 2d are positive. Because volcanics exist in the neighbourhood of the area (fig. 2-1) and small volcanic cones have been mapped south of the area (Kogbe et al, 1978) coupled with the sharp gravity gradients along the edges of the anomaly, it is the author's opinion that the anomaly is due to a volcanic intrusion located at a shallow depth.

Two observations are noteworthy in zone 2. Firstly, the boundary between this zone and the neighbouring zones are characterised by high gravity gradients which seems to suggest faulting along the boundaries. Also, the residual anomalies within zone 2 (except in regions 2b and 2d) are negative relative to the residuals in the adjacent zones. On the basis of these two observations, the author would like to suggest that zone 2 is essentially a subsided or rifted area in which the subsidence might have been accompanied with south-east trending block faulting. The block faulting might have, in turn, produced the Ugba and Mufu Grabens separated by the narrow Akwana Horst.

It is also interesting to note that the volcanics in this zone (fig. 2-1) occur along the boundary between this zone and zone 3. It is therefore thought that the volcanic flows in the area might have reached the surface through the fault and fracture planes along which zone 2 might have subsided.

5.4.3. : Zone 3

This is a broad region in which the residual anomalies trend northeast. The region correlates with the Asu River fromation (complex) which is known to be the core of the Keana anticline (Cratchley and Jones, 1965; Offodile, 1976). The broadness seem to suggest that the area is either an anticlinorium/broad anticline or a broad horst. The sharp gravity gradients along the northern and southern boundaries seem to favour the latter suggestion. Based on the geological map fig 2-1 the main structure in the zone, the Keana anticline, is located towards the northern fringe of the zone. This suggests that the axis of the anticline on the ground surface is located to the north of the axis of the anticline as deduced from the residual anomaly map (fig. 5-5).

5.4.4 : Zone 4

The anomalies in this zone also trend northeast. The zone represents the region of maximum thickness of the Cretaceous sedimentary formations. The known main structures in the zone are the Giza syncline (synclinorium), and the Obi anticline whose axis are parallel to that of the Keana anticline, and the Giza fault. The Giza syncline and the Giza fault occur to the west and east of Giza respectively. As can be deduced from the residual gravity map, fig 5-4, the Giza syncline is doubly plunging with its shallowest portion around Obi. From there it plunges both to the SW and NE. In the project area, the deepest part of the syncline, as suggested by the gravity data, lies between Kadarko and Giza where it seems to form a basin. Also from fig 5-5, it can be seen that what has been referred to as the Giza syncline between Agaza and Obi by Offodile (1976) and shown in fig 2-1, may infact be a minor arm of the Giza Syncline rather than the main syncline itself. The gravity data suggest that the axis of the main syncline passes through Atabara to points just north of Obi and Jangwa. The Giza fault and the Obi anticline may be responsible for the deviations from the regional trends of the residual gravity contours in the Obi - Agaza area.

5.4.5 : Zone 5.

This zone is characterised by high residual anomaly values. Because the zone is within the sedimentary region of the trough, the high gravity values in this area relative to those in zone 4 may be due to the basement existing below a thin sedimentary cover. The anomalies could also be due to shallow but broad igneous intrusions also existing at shallow depths. Other evidences in support of this idea is the fact that quartz dykes and Younger gravites are known to exist within the migmatites which form the basement around Nassarawa Eggon (Oyawoye, 1977). Also, alternate injection of deep-seated dykes exist around the basement/sediments contact in the same area (Olatunji, personal communications). The real source of the anomalies could be a combination of these two suggestions.

CHAPTER VI

INTERPRETATIONS OF SOME PROFILES ON THE RESIDUAL ANOMALY MAP

6.1 : Introduction

The method used in deriving the residual anomaly map and a qualitative interpretation of the map have been discussed in Chapter V. Detailed interpretations of some selected profiles on the residual anomaly map are presented in this chapter. The criterion for selecting each of the profiles interpreted was that it had data points throughout or almost throughout its entire length.

For each profile, the regional anomaly shown on the Bouguer anomaly is that determined by the process discussed in section 5.2.2. Consequently, the residual anomaly shown below the Bouguer anomaly, for each profile, is the residual anomaly along the profile as deduced from the residual anomaly map (fig. 5-4). Because the data points on any of the profiles do not lie on a single continuous straight line, most of the profiles have been approximated on the residual map by more than one straight line.

6.1.1 : Modelling

A common feature of the residual anomalies along each of the profiles is that the residual values are more negative over the sedimentary portion(s) of the profile than they are on portion(s) lying over the basement rocks. The assumption made in the interpretation is that the above observation is due to the fact that the sedimentary cover has a negative density contrast relative to the basement.

The residual anomaly map (fig. 5-4) suggests that the lengths of the major anomalies in the project area greatly exceed their widths. As a result, the anomalous bodies causing the gravity anomalies were assumed to be two-dimensional. The theoretical residuals of the assumed two-dimensional model were thus calculated for various points on the profile, using the line integral method (Talwani et al, 1959; Quereshi and Mula, 1971; Jin, 1974) for a two-dimensional body. A computer program was written by the author using the algorithm described by Talwani (1973) to calculate the theoretical residual anomalies at some given points along a profile, for a given model. The program also compared the observed residual with the theoretical residual at each sampled data point and automatically ploted the two types of residual anomalies, at each given point, on the line

Printer. The model was manually adjusted until the root-mean-square of the differences between the observed and computed residuals at the sampled data points was less than a preset value. For the north-south profiles, data points were sampled every 4km while on the shorter cross profiles, the sampling interval was 2km. In modelling the causative bodies beneath the profiles, available geologic information such as the basement/sediments contacts and the approximate locations of the boundaries of the various formations along the profiles, where applicable, were employed in constraining the models. The above constraints combined with the average dips of the beds in the area were utilised in drawing the approximate geologic cross-section for a given profile which was used as the initial model for interpreting the profile. Where faults are inferred from the interpretations, they are shown in the appropriate places in the models. Also, in modelling the intrusives, each intrusive body was assumed to be homogeneous and therefore assumed to have a constant density.

6.1.2 : Density Contrasts

Along the profiles in which the approximate geological contacts are known, the density values determined in Chapter IV.

were employed in the modelling exercise. On the basis of the density values obtained in this work, the six formations (the Asu River, Awe, Keana (Makurdi), Ezeaku, Awgu and Lafia formations) encountered in the project area have been grouped into three major layers (Asu River, Awe/Keana (Makurdi) and Ezeaku/Awgu/Lafia) of sedimentary rocks. The criterion for the combination of any two or more of the formations into a single layer was the nearness or similarity of their density values. The Albian Asu River formation, consisting of shales and sandstones with an average density of 2.62×10^{3} kgm^{-3}, was treated as a single stratum because of its distinctively high density value. Most of the sandstones samples collected for density analysis during the field work belonged to the Awe and Keana (Makurdi) formations. As a result, the value $2.44\times10^{3}kgm^{-3}$ obtained as the average density of the non-ferrigenous sandstones collected during the survey, was assumed as the average density of either of the two formations. No rock samples of the Turonian Ezeaku formation and the Senonian Awgu formation could be collected for density analysis due to lack of outcrops in the areas traversed during the survey. Consequently, the value $2.50\times10^{3}kgm^{-3}$ obtained by Cratchley and Jones (1965) for the shales of these ages in the entire Benue Trough, was assumed for the

two formations since they mainly consist of shales. The average density of the Maestrichtian ferrigenous sandstones of the Lafia formation obtained in the present survey was $2.56x10^{3}$ kgm^{-3}. The data obtained from the NGDA boreholes in Kadarko (BH2) and Agwatashi (BH6) listed in Offodile (1976) show that the ferrigenous sandstones do not exist below 35m from the ground surface. Due to the fact that the thickness of this layer of ferrigenous may not exceed 20m, the layer was considered along with the Ezeaku and Awgu formations with an average density of $2.50x10^{3}kgm^{-3}$.

Where the same rock type (formation) outcrops along the entire length of a profile, there were insufficient geologic controls for resolving the formation in addition to the ones underlying it into the three sedimentary strata discussed above. Consequently, the sedimentary cover was considered as a single layer with a density equal to the average density of the sedimentary rocks in the area.

From the density analysis, the average density obtained from the sedimentary rocks collected was $2.47x10^{3}kgm^{-3}$. According to Offodile (1976), the estimated thickness of the Asu River formation, with a density value of $2.60x10^{3}kgm^{-3}$, could be up to 3kms. Because of the considerable thickness

of this high density formation coupled with the fact that not many samples of the rocks of this formation were available for the density analysis, due to lack of outcrops, it was considered that the true average density of the sedimentary rocks could be higher than $2.47 \times 10^3 kgm^{-3}$. An average density thought to be more likely to closely approximate the true gross density of the sediments in the area was determined using the equation.

$$\rho_m = \sum_{i=1}^{n} \frac{\rho_i t_i}{t_i} \qquad \text{.....(6-1)}$$

where ρ_i = density of the ith bed

t_i = thickness of the ith bed

and n = number of beds

Equation (6-1) assumes that the beds are either horizontal or at least parallel to each other. At the anticlines and synclines where the number and thinckness (es) of the beds may change, the true average density of the sedimentary rocks may deviate significantly from the value derived using equation (6-1) if used for an intensely folded area. In this work, the error in the computed average density that may arise due to the

folding at the anticlines and synclines may not be very significant owing to the fact that the angles of fold in the project area hardly exceed 10^{o}. By substituting the density values listed in table 4-1 and the approximate thicknesses of the six formations encountered in the project area (table 2-1), in equation (6-1, the computed average density of the sedimentary rocks was $2.52 \times 10^{3} kgm^{-3}$.

Altogether, six profiles were interpreted in detail. Two of these profiles were in the north-south direction, one in the west-east direction, one in the northwest-southeast direction and the other two in the southwest-northeast direction. Their interpretations are discussed in detail below.

6.2 : Interpretation of the North-South Profiles

The north-south profiles which run across the trough, were interpreted in order to study the existing regional structures giving rise to the observed residuals along the width of the trough. It was also hoped that the structures beneath these profiles might throw some light on the origin of the Benue Trough.

6.2.1: The Nassarawa Eggon to Ikumbur Profile.

The profile begins in Nassarawa Eggon which lies on the basement just to the north of the trough and terminates in

Ikumbur which is within the sedimentary region of the trough. The profile could not be extended to the basement outcrop south of the trough due to lack of access road. The profile, shown in fig. 6-1, is about 16 km long and is approximately represented on the residual gravity may (fig 5-4) by the straight lines AB and BC. The residual gravity along the profile has a single broad minimum with a gravity relief (amplitude) of -50 mgals but with two maxima existing at about 10 km south of Nassarawa Eggon and at Igbor. A major geological constraint employed in modelling this profile is that the basement/sediments contact on the northern side of the trough occurs at about 4 km south of Nassarawa Eggon (Olatunji, personal communication). The surface geology along the profile is shown in fig. 6-1.

The interpreted model for this profile (fig. 6-1) shows that the profile is basically over a major syncline and a major anticline. The syncline correlates with the Giza syncline on the geological map (fig 2-1) while the anticline is the Igbor anticline discussed in section 5.4.1. The axis of the syncline, where the thickness of the sediments is maximum (7 km), occurs at about 13 km south of Kadarko. The axis of the anticline,

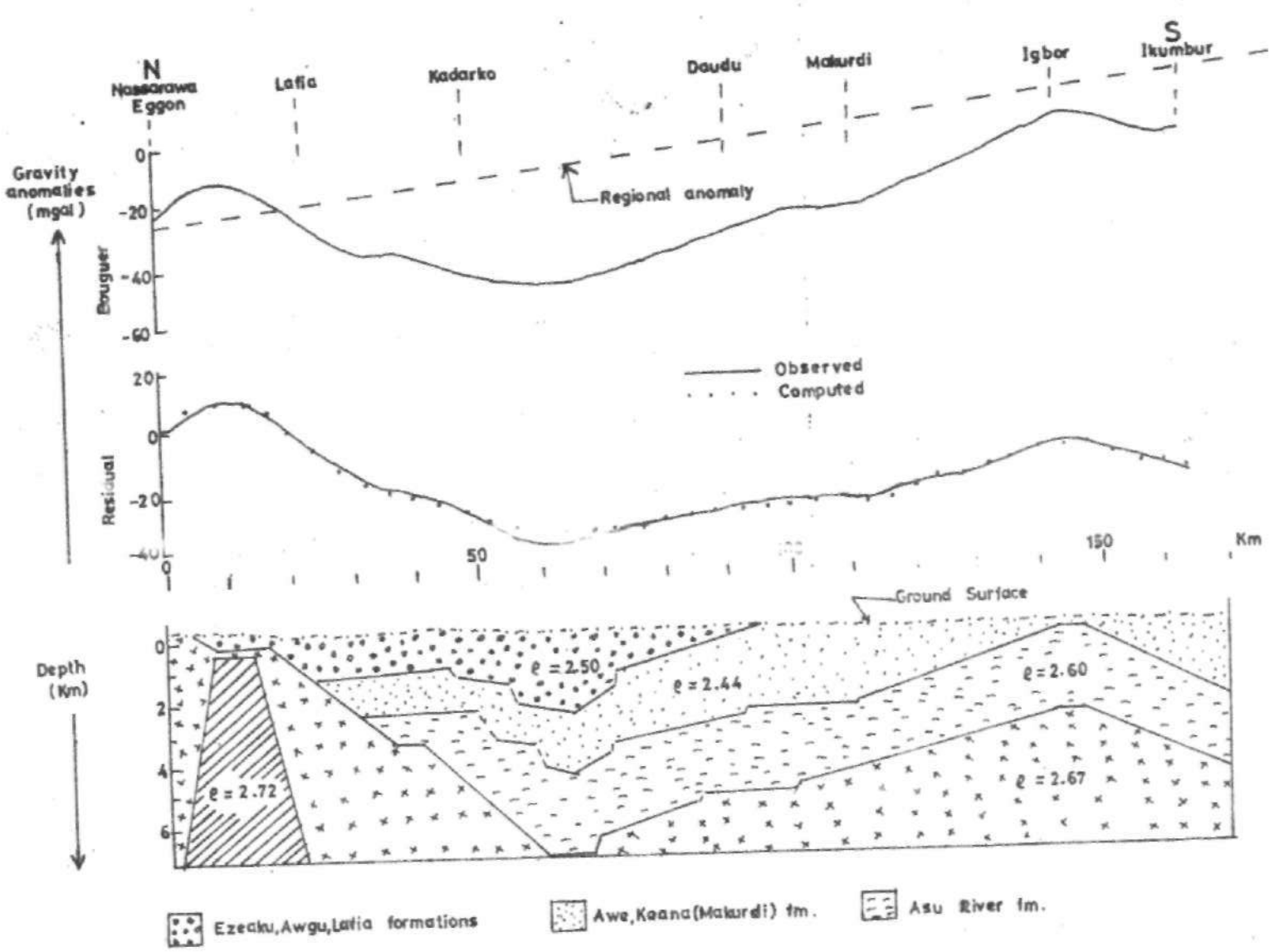


Fig 6-1 : Interpretation of the Nassarawa Eggon to Ikumbur profile

on the other hand, passes through Igbor. The interpreted model (fig. 6-1) suggests that the region lying between 40 and 90 km south of Nassarawa Eggon has been downthrown by normal faults (whose throws range from about 0.3 to 0.8 km.). The axis of the Giza anticline lies almost midway between this region (fig. 6-1). Also, it can be deduced from the model that the thickness of the Asu River formation varies from about 1km to about 3km with an average thickness of about 2.5km. The Awe and Keana/(Makurdi) formations have an average thickness of about 2km. On this profile, the maximum thickness of the uppermost layer made up of the Ezeaku, Awgu and Lafia formations, is about 2.5km. The maximum thickness of the overall sedimentary cover occurs at the axis of the Giza syncline where it may exceed 7km. The significant difference indicated by the throws of the faults in the basement and the sediments suggests at least two stages of normal faulting. The first stage might have been the initial rifting of the trough in the Albian times then followed by post-Albian normal faulting of both the sediments and the underlying basement, along existing planes of weakness due to the increase in sediment loading. That is, the post-Albian normal faulting (vertical movement) might be contemporaneous with the excessive deposition of sediments as described by Shelton (1968).

On this profile, the interpreted model shows that the average thickness of the Asu River formation is about 3 km except in the area just to the south of Keana whete its thickness may not exceed 1 km. The combined thickness of the Awe and Keana formations varies from about 1 km around Assakio to about 2.5 km in the Keana area. The layer consisting of the Bzeaku, Awgu and Lafia formations is thickest around Obi where its thickness could be over 3 km. The fact that the layer which consists of the Awe and Keana fromations is overlain and underlain by denser rocks (fig. 6-1) confirms the suggestion of Offodile (1975) that the layer is a good aquifer. Furthermore, the interpreted model shows that the positive residual anomalies between Nassarawa Eggon and Lafia can be accounted for by an igneous intrusion of density 2.72×10^3 kgm^{-3} shown in fig 6-1. The top of the intrusion is about 0.5 km below the ground surface.

6.2.2 : The Arikya to Yandev Profile

This profile extends from Arikya to Tse M'kovur, about 12 km south of Yandev, on the basement to the north and south of the trough respectively. Unlike the Nassarawa Eggon to Ikumbur profile, this profile starts on the basement, traverses the entire width of the trough and terminates on the basement on the opposite side of the trough. The profile which is about

208 km long is approximated on the residual map by the lines PQ and QR in fig. 5-6. The residual anomaly along the profile has three minima with amplitudes ranging from -37 mgal to -15 mgal over the sedimentary portions and a single minimum with amplitude of -20 mgals over the basement just to the south of the trough.

The interpreted model for the profile (fig. 6-2) indicates the existence of three distinct synclines, two major ones and a minor one, corresponding to the three gravity minima which exist within the sedimentary portion of the profile. The largest syncline occurs between 20 km and 95 km south of Arikya with its axis at about 60 km south of Arikya. This syncline is believed to be a northeast continuation of the Giza syncline discussed in section 6.2.1. However, the maximum thickness of the sedimentary cover on the present profile is about 6.5 km compared with 7 km obtained in the Nassarawa Eggon to Ikumbur profile. Also, as in fig 6-1, the interpreted modelfor the present profile (fig 6-2) suggests a normal faulting (subsidence) of the region between 40 and 80 km south of Arikya which again contains the axis of the Giza syncline. The faults responsible for the subsidence of this region are considered the northeast extensions of those discussed in section 6.2.1 for the interpreted model of the Nassarawa Eggon

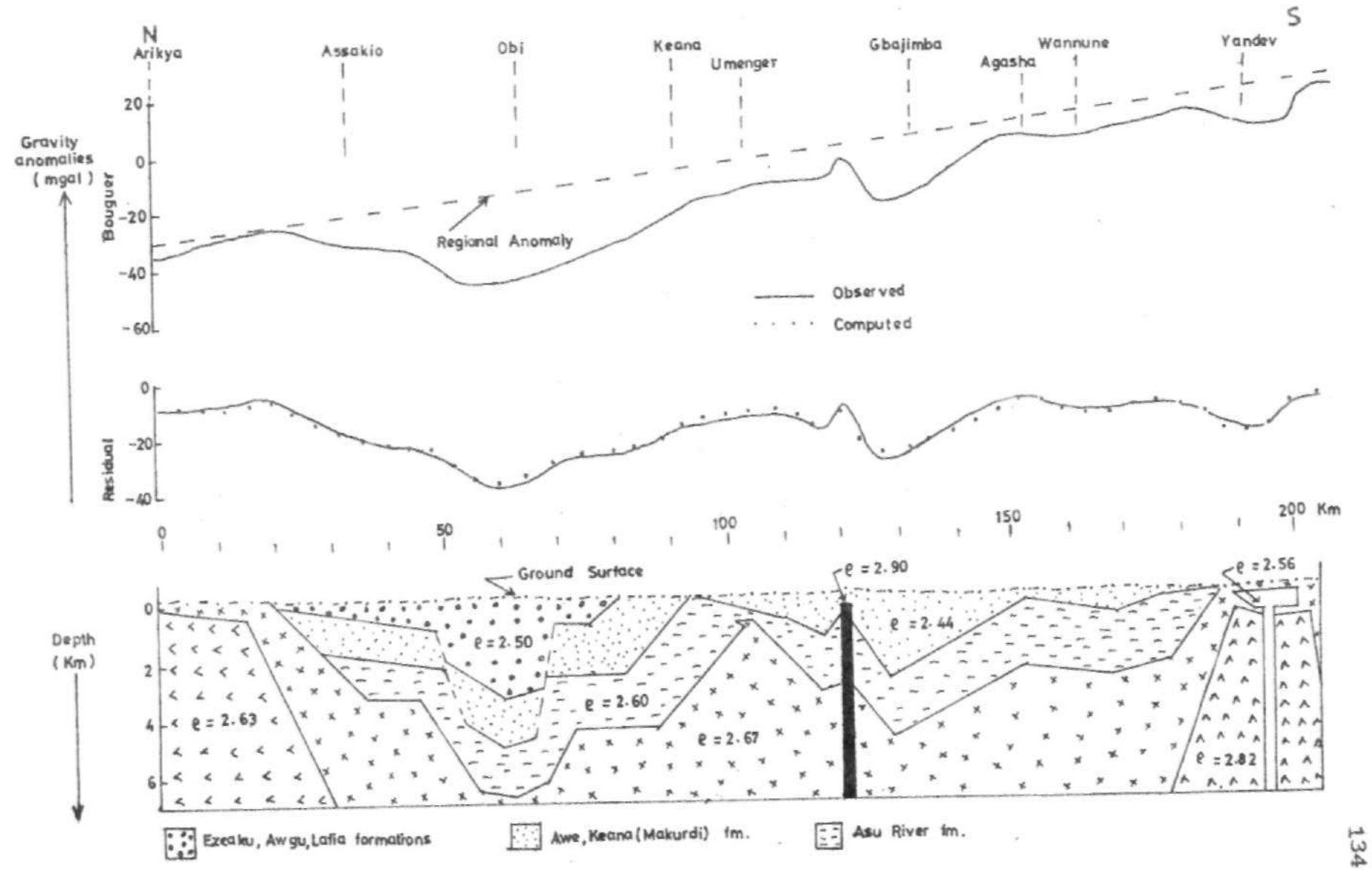


Fig 6-2 : Interpretation of the Arikya to Yandev Profile

to Ikumbur profile in fig 6-1 because of the similar y in their approximate locations on the two profiles and the magnitudes of their throws. In addition to the normal faulting of this zone, the interpreted model also suggests the existence of a low-angle thrust fault between Keana and Umenger. Similarly, the two stages of normal faulting or vertical movements discussed in section 6.2.1 might have taken place along this profile too. The model also shows that the sediments on the southern flank of the syncline along this profile are more folded than those in similar location in fig. 6-1. The possible existence of the thrust fault near Keana, in the present profile but which is absent in the last profile, might account for the different degrees of folding of the southern flank of the Giza syncline on the two profiles.

The second syncline on this profile lies approxmiately between 90 km and 152 km south of Arikya. The syncline consists of two arms. The axes of the major and the minor arms of the syncline exist at about 5 km and 18 km north of Gbajimba respectively. The minor arm of the syncline corrosponds to the Makurdi syncline, on the geological map (fig 2-1), which was identified by Kogbe et al (1978). The major arm, on the other hand, has not yet been recorded in literature. As a result, the name Gbajimba syncline has been tentatively suggested

for it because its axis exists just to the north of Gbajimba. The third and smallest syncline on the profile occurs in the area between 152 km south of Wannune along the road to Gboko. This syncline correlates with the Wannune syncline on the geological map (fig 2-1). In addition, the interpreted model suggests that the three synclines discussed in this paragraph are part of a synclinorium which may be bounded by a thrust fault, to the north and a normal fault to the south. The anticline whose axis lies at about 15 km south of Keana on the interpreted model (fig 6-2) correlates with the Keana anticline. On the geological map, however, the axis of the anticline passes through Umenger which is about 10 km south of Keana. The discrepancy between the location of the axis of the anticline on the ground surface and its actual location at depthfavours by the existence of the thrust fault shown in the model.

The average thickness of the Asu River formation along this profile is about 2 km except in the area just south of Keana where its thickness may not exceed 1 km. The combined thickness of the Awe and Keana formations varies from about 1 km around Assakio to about 2.5 km in the Keana area. The third layer consisting of the Bzeaku, Awgu and Lafia formations is thickest around Obi where its thickness could be up to 3.2 km. The layer thins out on both sides of the axis of the Giza syncline.

The interpreted model also shows that igneous intrusions exist on both sides of the trough adjacent to the basement/ sediments contacts in addition to a volcanic dyke which exists just south of the central axis of the trough where it separates the two arms of the Gbajimba syncline. Between Arikya and Assakio an igneous intrusion with a density value of 2.62×10^3 kgm^{-3} and with its top at about 200 m below the ground surface had been modelled to account for the relatively low residuals in the area. The density value suggests that the intrusion might be Younger granite because the density value compares with the density value 2.62×10^3 kgm^{-3}, obtained from surface measurements, for Younger granites in the Jos Plateau (Ajakaiye, 1970) about 50 km north of the present project area. In the Yandev area, the interpreted model shows the existence of a two-body composite intrusion. The outer intrusion, thought to be composed of intermediate rocks, has a density of 2.82×10^3 kgm^{-3} ascribed to it whilst the inner intrusion has a density of the 2.56×10^3 kgm^{-3}. The latter density value was obtained as the average density of the granite rocks collected in the area during the field work. On the other hand the density value of 2.82×10^3 kgm^{-3} used by other workers as the mean density of the continental crust for surveys in other parts of

the world (Thompson and Talwani, 1964; Fairhead, 1976) was assumed for the intermediate intrusions because this category of rocks was thought to be responsible for the positive Bouguer anomalies observed in the area. The dyke which forms the core of the small anticline separating the two arms of the Gbajimba syncline between Umenger and Gbajimba is about 1 km wide, its top is about 400 m below the ground surface and was thought to be of volcanic origin because of the existence of volcanics on the ground surface in the area coupled with the relatively high gravity gradients (about 2 mgals km^{-1}) observed over the area. As a result, the density value of 2.90×10^3 kgm^{-3} obtained for non-vessicular basalt/trachyte collected in the area during the field work was assumed for the intrusion. According to Kogbe (personal communication), the existence of the volcanic intrusion in the area has been confirmed by drilling carried out recently by the Nigerian Mining Corporation after the completion of this work.

6.3 : The Cross Profiles

Four cross profiles were drawn and interpreted in order to have an insight into the possible geologic structures in the direction parallel to and perpendicular to the axis of the trough. Again, it was hoped that the interpretations of the

profiles might also reveal some information which might be useful in resolving the problem of the origin of the trough.

6.3.1 : The Lafia to Tsofon Tunga Profile

The profile, which is approximately perpendicular to the geologic and gravity trends in the area, is represented by A_1B_1 on the residual map (fig 5-4). The profile spars across sedimentary rocks throughout its entire length, from a road junction 8 km southeast of Lafia on the Lafia-Makurdi road to about 8 km southeast of Tsofon Tunga on the bushpath to Wukari. The geological contacts on the surface, along the profile, are shown in fig 6-3.

The interpreted model (fig 6-3) shows that the profile is essentially over a major syncline and anticline. The major syncline, which correlates with the Giza syncline, may also be normally faulted on both flanks as in the interpretations of the profiles shown in figs. 6-1 and 6-2. On this profile, the Giza syncline contains a small fold between Obi and Agwatashi. This small fold correlates with the Obi anticline (fig 2-1). The normal faults within the syncline are also thought to be a continuation of those shown in figs 6-1 and 6-2 for the same reasons proposed in section 6.2.2. Similarly,

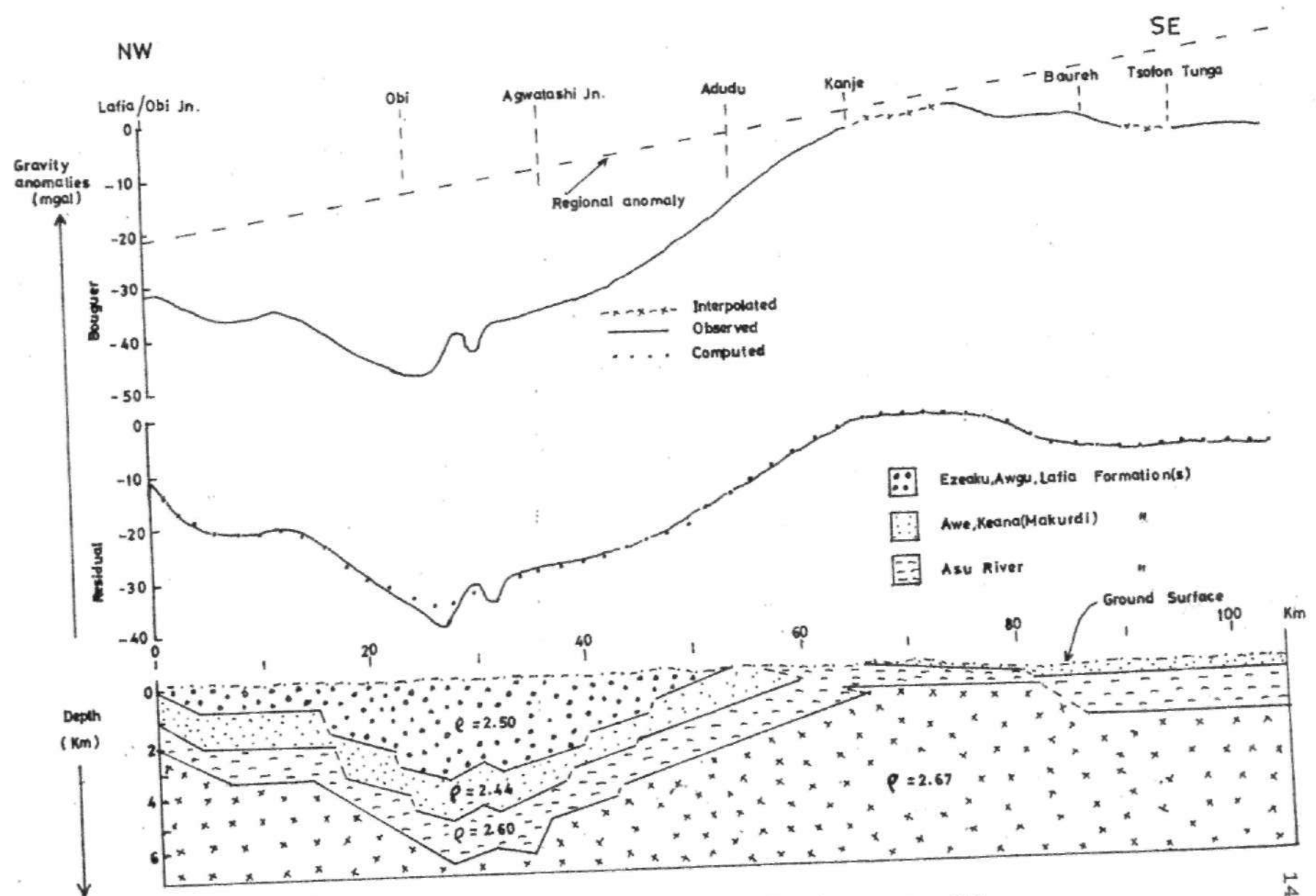


Fig 6-3 : Interpretation of the Lafia to Tsofon Tunga Profile

the thrust fault located about 2 km southeast of Idudu in the model is thought to be a northeast extension of that shown between Keana and Umenger in fig 6-2. The interpreted model (fig 6-3) also shows that the sediments in the first 15 km of this profile are well folded. The folding is possibly due to the existence, in the area, of the Lafia anticline (fig 2-1) whose axis of fold is perpendicular to the axis of the trough (Offodile, 1976), that is parallel to the direction of this profile.

The major anticline on this profile is not a straightforward one in that it might have been thrust faulted on its northern flank and faulted normally on its southern flank. The normal faulting of the southeastern limb of the anticline might be related to the subsidence of zone 2 in fig 5-4 while the thrust faulting of the northwestern limb of the anticline might be related to the folding of the sediments in the trough and the offset obtained between the geologically mapped axis of the anticline and that deduced from the present survey, as explained in section 6.2.2. It is most probable that the two modes of faulting of the anticline occured at different times.

On the geological map (fig 2-1), the anticline correlates with the Keana anticline but there is a discrepancy in the location of the axis of the anticline as shown on the residual map, from which the residuals in fig 6-3 are extracted. For example, on this profile, the axis of the anticline deduced from fig 2-1 passes through Kanje while the location of the approximate axis of the anticline in fig 6-3 is about 7 km to the southeast of Kanje. As earlier explained in section 6.2.2, the discrepancy in the location of the axis of the anticline as deduced from the ggological and residual maps in thought to be due to the possible existence of the thrust fault within the anticline.

On this profile, the average thickness of the Asu River formation is about 1.5 km although in the Obi-Agwatashi area, the thickness of the formation may be up to 2 km while in the Kanje-Baureh area, the formation could be only 0.5 km thick. Similarly, the combined average thickness of the Awe and Keana formations may not exceed 1.5 km and it could be considerably thinner, about 0.1 to 0.3 km between Kanje and Tsofon Tunga. The combined thickness of the Bzeaku, Awgu and Lafia formations, on the other hand, could be up to 3.5 km in the Obi-Agwatashi area but the

formations gradually thin out on both flanks of the Giza syncline. Along the profile, the greatest thickness of the sedimentary cover, about 6.5 km, occurs just to the northwest of Obi while the thinnest cover, about 0.5 km, occurs between Kanje and Baureh.

6.3.2 : The Daudu to Baureh Profile

This profile, which extends from Daudu on the Lafia-Makurdi road to Baureh, is entirely over sedimentary rocks (fig 6-4). The direction of the profile is almost southwest-northeast which is the direction of trend of the axis of the Benue Trough. The profile is approximately represented on the residual map (fig 5-4) by A_2B_2 which indicates that the profile is over the Keana anticline between Umenger and Baureh.

In view of the fact that the entire profile lies over the same rock type (formation), the sediments could not be resolved into the usual three sedimentary strata due to lack of adequate geologic controls. Thus, the sediments, consisting of the exposed formation and the older ones underlying it, were treated as a single stratum for a preliminary interpretation of the gross structures along the profile. As previously discussed in section 6.1.2, two average densities

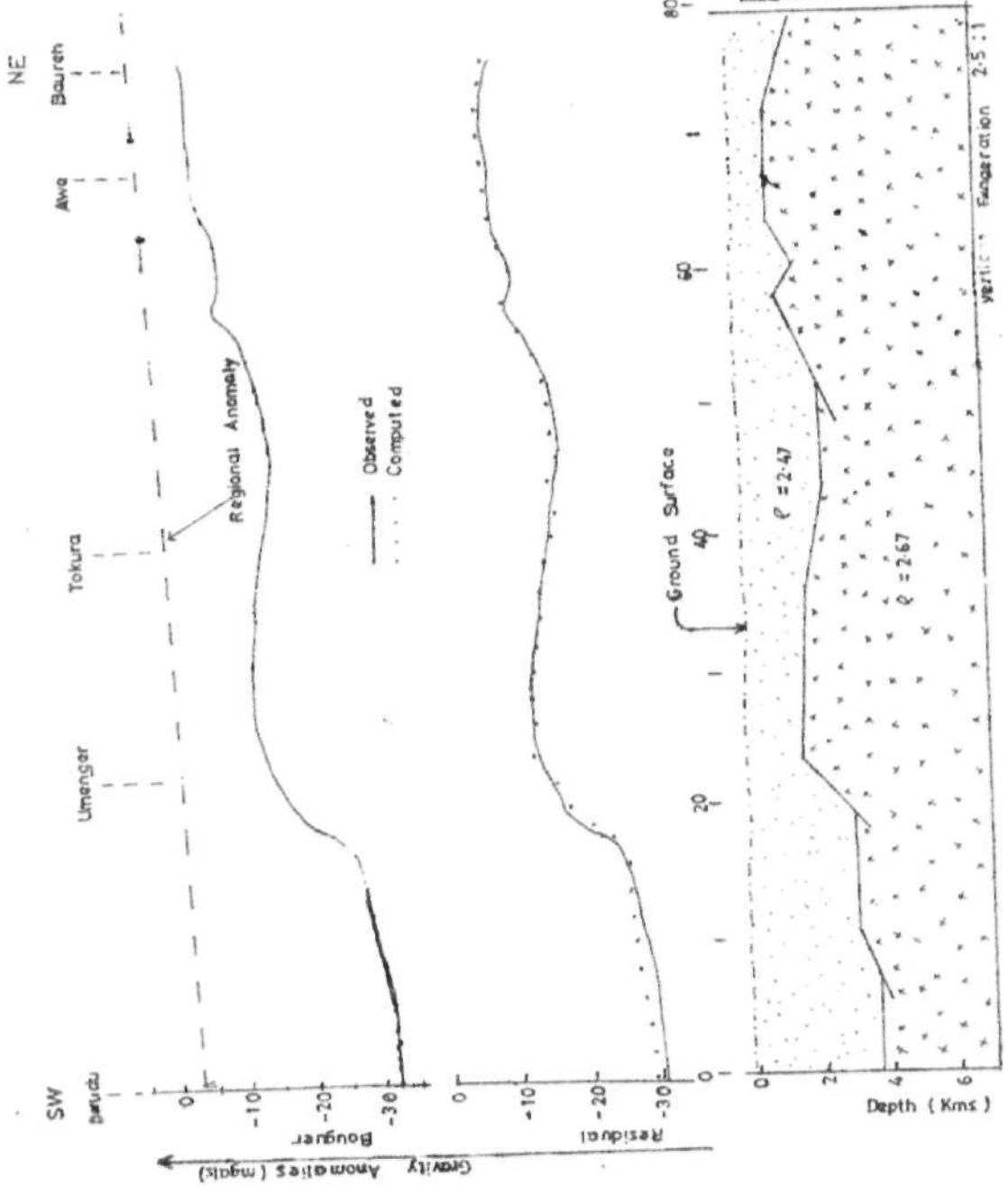


Fig. 6-4 : An interpretation of the Bauresh Profile

of the sedimentary rocks (2.47×10^3 and 2.52×10^3 kgm^{-3}) were employed in interpreting the gravity anomalies along the profiles. The former density value is that determined for sedimentary rocks collected during the field work while the latter value is the average theoretical density for the three layers derived using equation (6-1). Fig. 6-4 shows the interpreted model when the average density of the sedimentary rocks was assumed to be 2.47×10^3 kgm^{-3}. The interpeted model shows that between Umenger and Awe, the Keana anticline essentially plunges to the southwest with a depression occuring around Tokura. This depression correlates with the Tokura Syncline reported by Offodile (1976) in the area. From the interpretation, the axis of this syncline occurs at about 10 km northeast of Tokura where the sedimentary cover is about 3 km. The interpreted model also shows that the Keana anticline is truncated by a normal fault whose throw may be up to 2 km at about 1 km southwest of Umenger. As a result of the fact that this major fault has not been recorded in literature, the name Umenger fault is suggested for it. To the southwest of Umenger, the average thickness of the sedimentary cover is about 3.5 km while that to the northeast is only about 2 km.

When the average density of the sedimentary rocks obtained by using equation (6-1), 2.52×10^3 kgm^{-3}, was employed for the modelling, the resulting interpreted model is shown in fig 6-5. The gross structures in this model are the same as those in fig 6-4. The only major difference in the two models is that the top of the basement is now deeper, as expected, because of the higher density value of the sedimentary cover. In this model, the thickness of the sediments about the axis of the Tokura syncline is now about 3 km. Also the average thickness of the sedimentary cover southwest of Umenger has increased from 3.5 km (fig 6.4) to about 5 km.

Of the two models discussed for this profile, the alternative model (fig 6-5), in which the average density of the sedimentary cover was assumed to be 2.52×10^3 kgm^{-3} is more likely a better approximation of the structures in the area for the following reasons. The thickness of the sedimentary cover at Daudu on the interpreted model of the Nassarawa Eggon to Numbur profile (fig 6-1) is about 4.8 km which is close to the value 5.2 km obtained for the same location in the interpreted model of the Daudu-Baureh profile (fig 6-5). Also, the thickness of the sediments at Baureh on the interpreted model of the Lafia to Tsofon Tunga profile (fig 6-3) is about

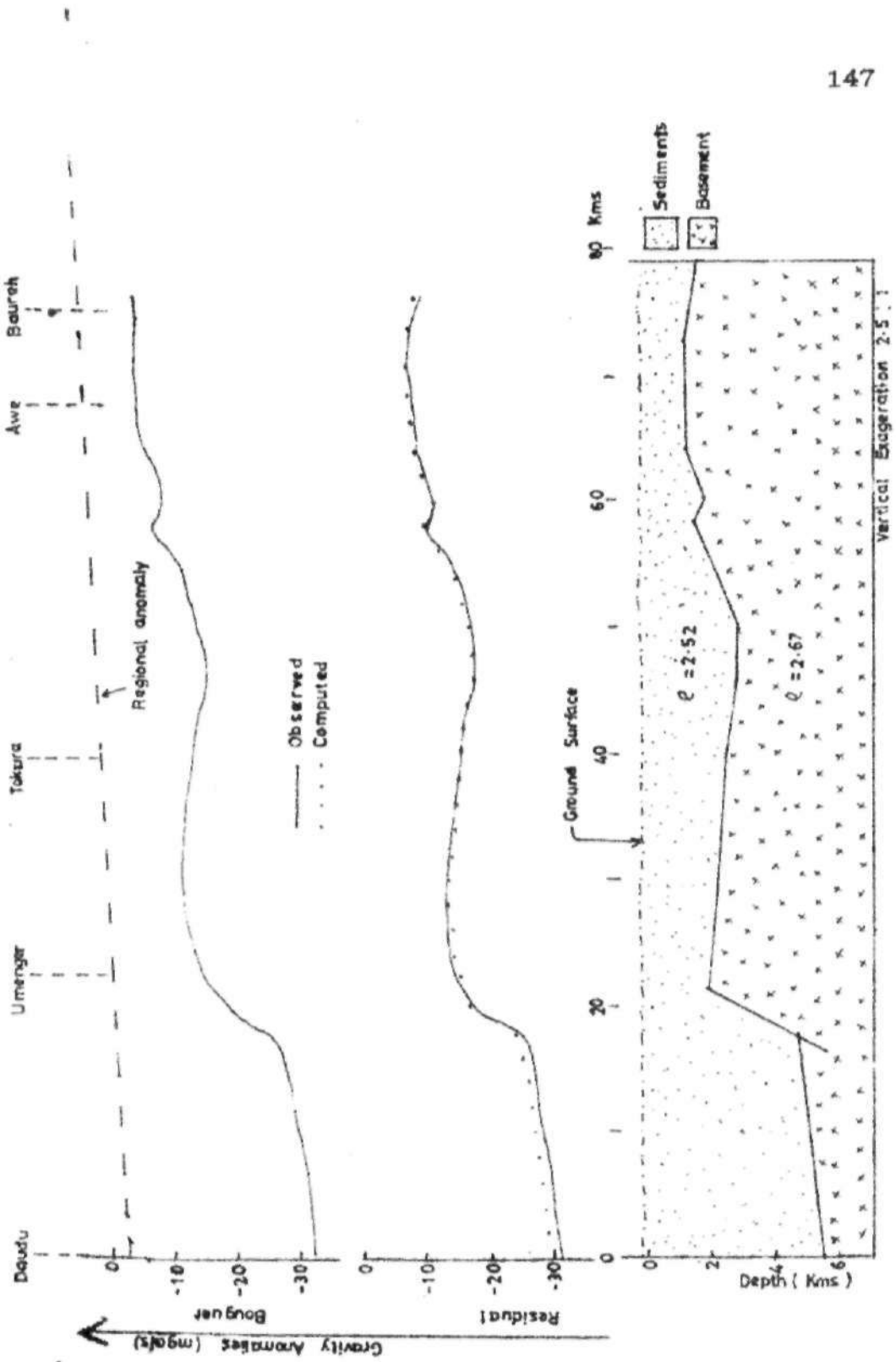


Fig. 6-5 : An Alternative Interpretation of the Daudu to Baureh Profile

2 km which fairly compares with the value of 1.6 km obtained for the same location in fig 6-5. On the other hand, the thickness of the sediments at Daudu and Baureh as deduced from fig 6-4 are about 3.5 km and 1 km respectively which do not compare with the values obtained at the same locations in figs 6-1 and 6-3 respectively. Due to the fact that the interpretations in figs 6-1 and 6-3 are based on resolving the sediments into the three layers, they are considered to be more representative of what geologically obtains along the profiles. Consequently, the closeness of the interpreted depths-to-basement at those two locations in figs 6-1 and 6-3 to those in fig 6-5 than those in fig 6-4 make the model in fig 6-5 more acceptable. Furthermore, the density of the sedimentary rocks should increase with depth due to the weight of the overlying sediments. In view of the tremendous thickness of the sedimentary cover encountered in the project area, the average density of the rocks should be higher than the value of 2.47×10^3 kgm^{-3} obtained for the rock samples collected from the outcrops during the field work.

6.3.3 : The Makurdi to Arufu Profile

This profile runs from the Gboko junction in Makurdi and terminates in a village 6 km east of Arufu on the Arufu-Wukari road . On the residual map (fig 5-4), the profile is

interpretation was carried out by considering the sediments as a single layer, using the two average densities (2.47 and 2.52 ($x10^3 kgm^{-3}$)), as described in section 6.3.2 above.

Figure 6-6 shows the interpreted model when the average density of the sedimentary rocks was assumed to be $2.47x10^3$ kgm^{-3}. In this model, the maximum thickness of the sediments, which is about 4km, occurs below Makurdi and the region between the River Katsina Ala and Akwana. The basement is shallowest around Agasha where it is about 1.2km below the ground surface. Block faulting of the basement appear to have been widespread along the profile resulting in the formation of two horsts and possibly three grabens. The horst-like structures are located below Agasha and at about 2km east of Akwana. The two fairly well defined grabens are located in the region between the River Katsina Ala and Akwana and below Arufu and beyond. The former graben correlates with the Ugba graben while the latter one correlates with the Arufu graben which were both discussed in section 5.4.2. Similarly, the interpreted horst near Akwana is part of the Akwana horst which was also discussed in section 5.4.2.

The interpreted model just discussed above is considered a close approximation of the true situation along the profile. However, the same profile is interpreted, for a comparison purpose, using the density value of 2.47×10^3 kgm^{-3}, obtained as the average density of the sedimentary rocks collected during the survey, as the density of the sedimentary cover. The resulting interpreted model is shown in fig 6-7. As expected, the features on the models are essentially the same as those in fig 6-6 except that the sedimentary cover in the present model is shallower than that shown in fig 6-6. For example, the maximum thickness in the present model is about 4 km while it is about 5 km in fig 6-6. This observation is again due to the fact that a higher density contrast between the sediments and the basement is involved in the present model than that shown in fig 6-6.

The structure below Agasha, on the present profile, whose cross-sectional view looks like an anticline may infact be a domal structure (intrusion). This observation is based on the fact that the structure between Gbajimba and Wannune on the Arikya to Yandev profile (fig 6-2), which is approximately perpendicular to the present profile, also looks like an anticline with its axis occuring below Agasha. As discussed in the above paragraph, the depth-to-basement

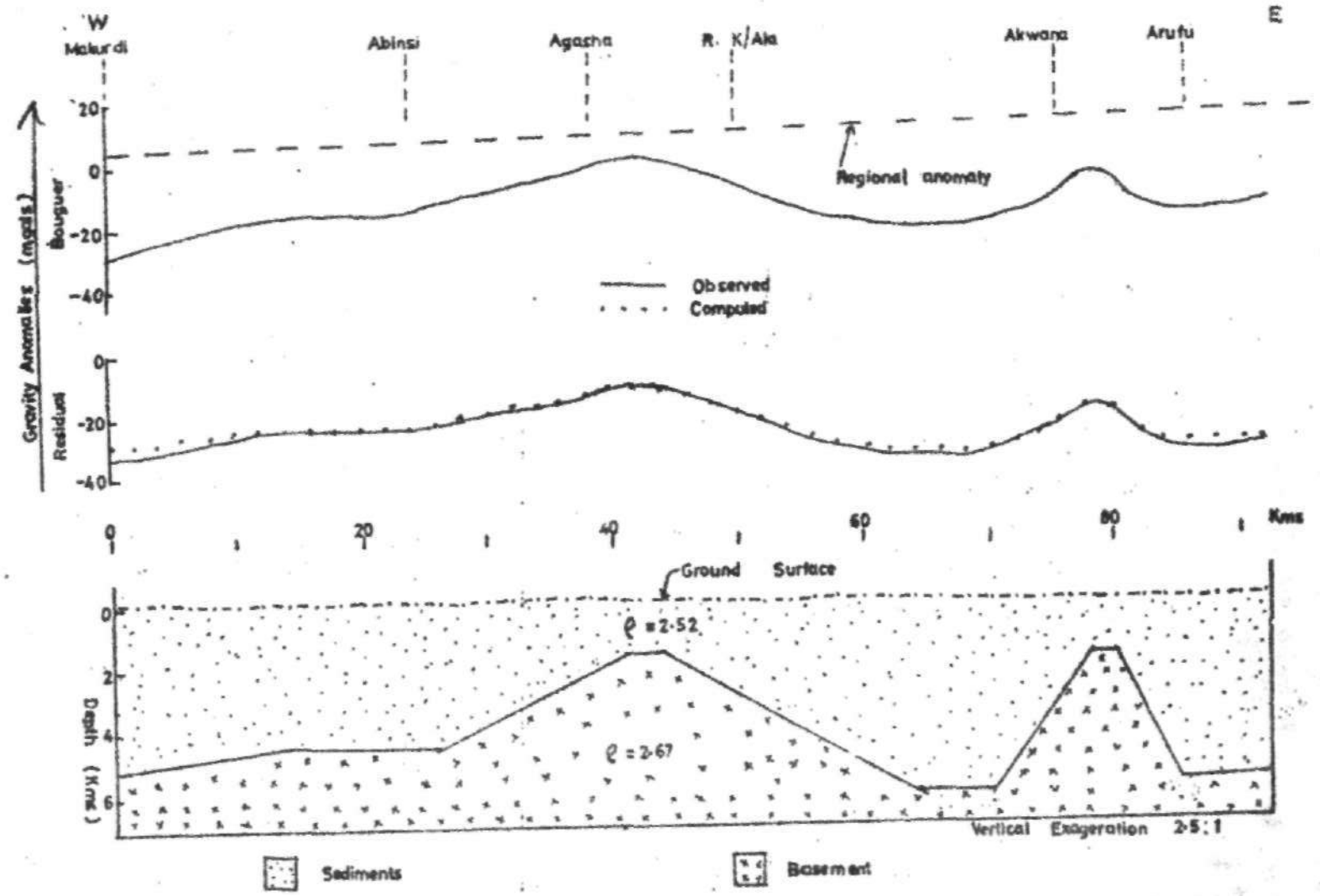


Fig. 6-6 : Interpretation of the Makurdi to Arufu Profile

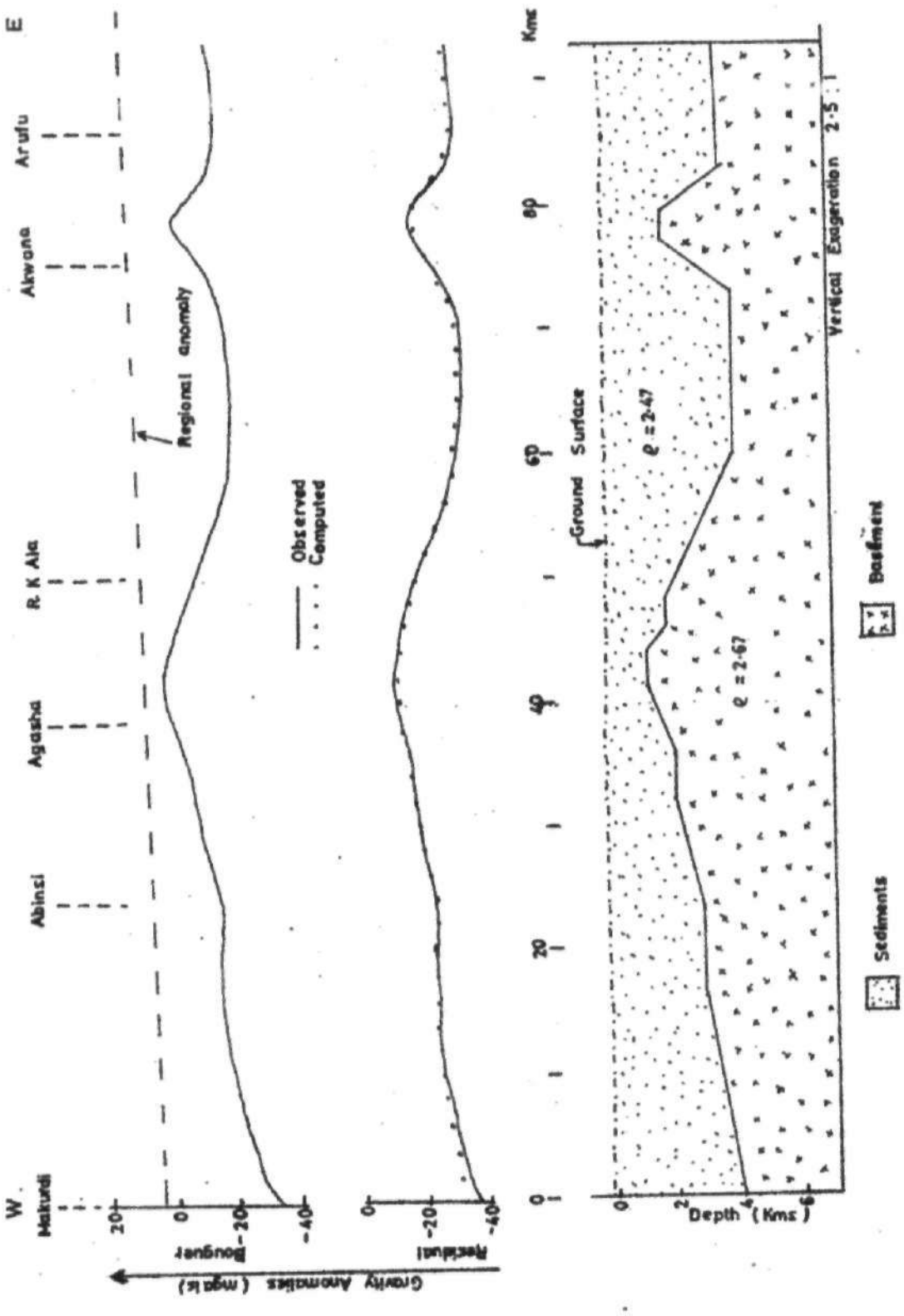


Fig. 6-7 : An Alternative Interpretation of the Makurdi to Arufu Profile

at Agasha in either of the interpreted models of the two perpendicular profiles (figs 6-1 and 6-7) is equal to 2 km. These interpretations represent two cross-sectional views of the same domal structure.

6.3.4 : The Ikumbur to Ugba Profile.

This profile is represented by $A_4B_4C_4$ on the residual map (fig 5-4). The profile extends from Ikumbur through Gboko and terminates in Abeda, 8 km east of Ugba on the Ugba-Zaki Biam-Wukari Road. Unlike the other three cross profiles already discussed which are entirely located within the sedimentary region of the project area, only the first 30 km of this profile and a short portion (about 5 km) of the profile near the River Katsina Ala lie on sedimentary rocks. The profile, therefore, largely lies on the basement just south of the Benue trough. Another feature of the profile is the existence of large negative residual anomalies (about - 20 to - 40 mgals) in the basement area east of Yandev. The tongue of sediments and alluvium around the River Katsina Ala cannot account for such large negative residuals over such a bread region. Consequently, in the absence of any surface features, the anomalously low Bouguer values in that region was ascribed to lateral changes in density within the basement relative to which the normal granitic basement has a negative density contrast was considered most plausible. As in the other profiles, the surface geology is also incorporated in fig 6-8.

The shape of the anomaly between Akpagher and the River Katsina Ala suggests the existence of a high density materia- within which there is an intrusion of smaller density in the Gboko-Yandev area. Owing to the fact that sediments do not exist in the latter area, the high and low density bodies were assumed to be igneous intrusions. Furthermore, granite out-crops in Mkar near Gboko and as earlier mentioned in section 5.4.1, granite was encountered at a depth of 18 m in A GSN borehole (BH IIOI) in Yandev. As a result of these facts, the lower density intrusion in the Gboko - Yandev area was ascribed to a granitic body with an average density of 2.56×10^3 kgm^{-3} which was the value obtained as the average density of the granite samples collected in the area during the field work. This density value was used because the granite intrusion on this profile is assumed to be the same as that discussed in section 6.2.2 for the same area of the Arikya-Yandev profile (fig. 6-2). Similarly, because the zone of positive Bouguer anomalies on this profile lies within the region of positive anomalies discussed in section 6.2.2, the outer intrusion thought to be responsible for the positive anomalies, was assumed to be the same rock type as that discussed in section 6.2.2. Consequently, the density value 2.82×10^3 kgm^{-3} was assumed for it as in section 6.2.2.

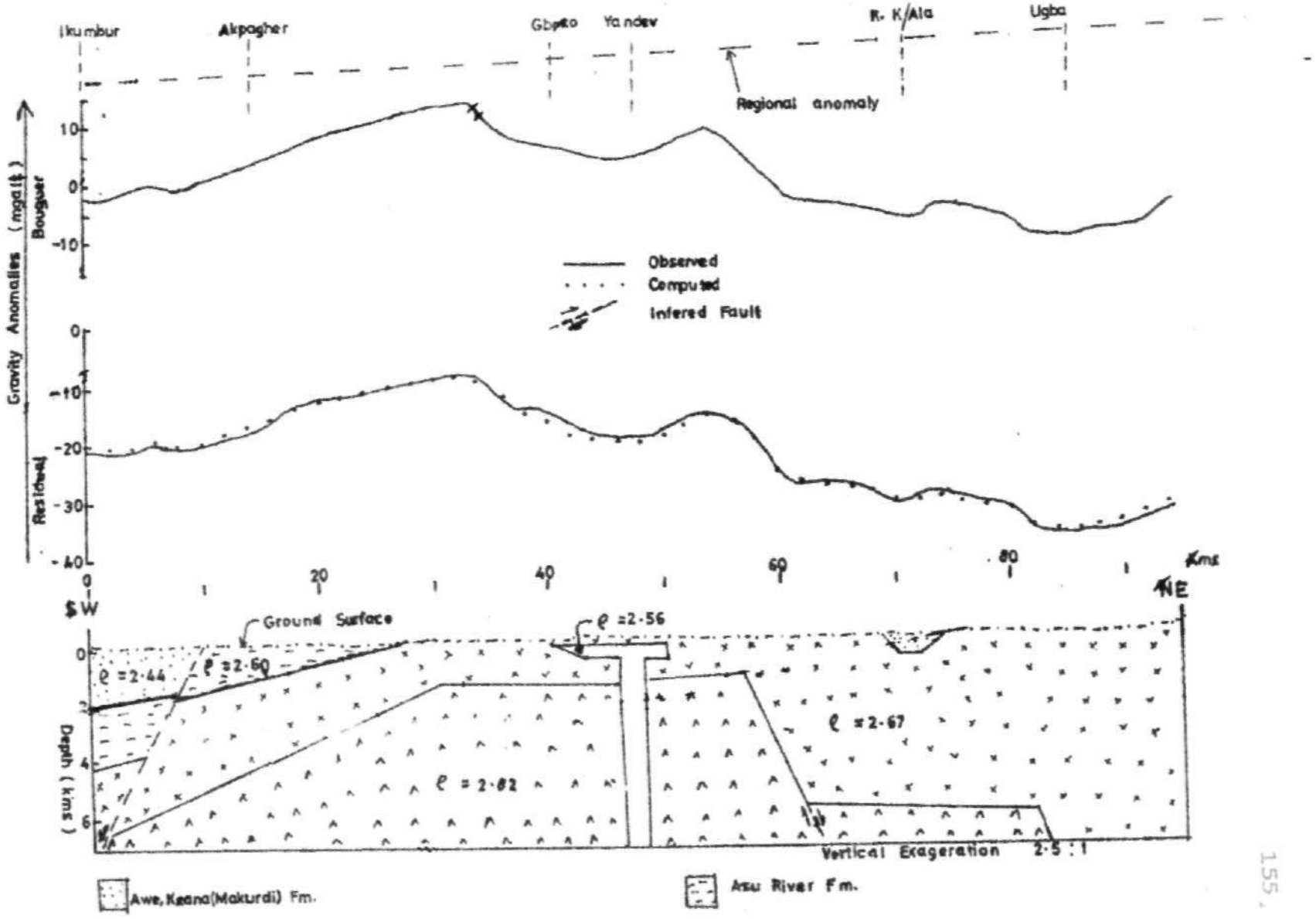


Fig 6-8 : Interpretation of the Ikumbur to Ugba Profile

The interpreted model for this profile (fig 6-8) shows that the negative anomalies between Gboko and Yandev can be accounted for by a hammer-shaped granite intrusion in which the pipe representing the handle of the hammer is about 2 km in diameter. The top of the intrusion is about 10 km long and is about 200 m below the ground surface. In that region, the thickness of the head of the hammer may not exceed 0.5 km. In the same region, the depth-to-top of the intermediate intrusion ranges from 1.0 to 1.5 km. To the east of Yandev, the high gravity gradients (about 3 mgals km^{-3}) at about 6 kms north-east of Yandev may be due to the existence of a normal fault along the boundary of the intermediate intrusion and the normal granitic basement. The local residual anomalies around the River Katsina Ala, which are negative relative to the broad negative anomalies in the region, have been ascribed to the small tongue of sedimentary rocks of the Makurdi formation and alluvium in the area. In the interpreted model, the thickness of the sediments in this region may not exceed 0.5 km. On the other hand, the local negative anomalies around Ugba may possibly be due to further normal faulting of the basement in the area between the River Katsina Ala and Ugba. The two inferred normal faults east of Yandev are possibly the extensions of the bounding faults of the two arms of the Ugba Graben (fig 5-4) into the basement area.

As earlier mentioned, the first 30 km of this profile lies over sedimentary rocks. The interpreted model shows that there may be a normal fault at about 10 km east of Ikumbur. The throw of this fault may be up to 2 km. Around Ikumbur, the thickness rapidly thins out towards Gboko. Similarly, the thickness of the normal granitic basement in this region of the profile, rapidly thins out towards Gboko from a thickness of about 4 km near Ikumbur to about 1 to 1.5 km in the Gboko area.

6.4:Summary of Interpretations

The interpretation of the north-south profiles show that the Benue trough essentially consists of two parallel synclinoria separated by the axially placed Keana anticline. The Giza synclinorium which contains a minor fold, the Obi anticline

in the Obi-Agwatashi-Agaza area occurs to the north of the Keana anticline while the Gbajimba synclinorium occurs to the south of the Keana anticline. The models also show that the central part along the width of the Giza synclinorium might have subsided between normal faults. Furthermore, the models indicate normal faults affecting both the sediments and the basement, with throws different from those associated with the marginal fault, within the trough. These suggest at least two stages of normal faulting in the area. In addition, the models also indicate the existence of a thrust fault within the Keana anticline. This fault might be responsible for the folding of the sediments in the area and the discrepancy observed between the location of the axis of the Keana Anticline on the geological map (fig 2-1) and the residual map (fig 5-4). In addition, the interpretations of the north-south profiles show that the maximum thickness of the sedimentary cover, about 6.5 to 7.0 km, occurs along the axis of the Giza syncline. Also, the models show the existence of igneous intrusions just beyond the northern and southern boundaries of the trough and the existence of a volcanic dyke just to the south of the central axis of the trough.

The interpretation of one of the cross profiles (fig 6-3) supports the possible subsidence between normal faults, of the

central part of the Giza syncline and the possible existence of a thrust fault within the Keana anticline. On the other hand, the models which best fit the observed anomaly along the Daudu-Baureh profile (figs 6-4 and 6-5) indicate that the Keana anticline plunges to the southwest and is truncated by a previously unknown normal fault at about 1 km southwest of Umenger. Also the interpretations of the Makurdi to Arufu profile (figs 6-6 and 6-7) indicate the existence of a basin-and-range type of region in the southeast quadrant of the project area. In addition, the interpretation of the other cross profile (fig 6-8) indicates the existence of a two-body composite intrusion, in the Gboko-Yandev area, in which the outer and inner bodies may be composed of intermediate rocks and rocks of granitic origin respectively. The basement to the east of Yandev might have been faulted due to the continuation of the basin-and-range type of region into the basement in the area as shown in fig 5-4.

6.5 : Concluding Remarks

The interpretations, so far discussed, are tentative because of the inavailability of adequately accurate geologic maps and lack of sufficient borehole data, all of which would have helped to minimise the ambiguities normally

inherent in gravity interpretations (Nettleton, 1940,1973; Bott and Smithson 1977). Also, the sedimentary strata used in the interpretations of some of the profiles were assumed to be parallel and of uniform density irrespective of depth of burial. In reality, these may not be the case. Similarly, the densities of the intrusions assumed constant in each intrusion may not be so due to either lateral inhomogeneity or increase in density with depth. Consequently, the interpreted models may not adequately represent the subsurface structures in the area although all available geological constraints were used. Also, the regional gravity map obtained for this survey was a linear one owing to the reasons given in section 5.3. Consequently, it is obvious that the effect of crustal thinning normally associated with the axial regions of rifts was not reflected in the regional map. The resultant effect of using the regional map to deduce the residual map is that the residual anomalies along the axial region of the trough might be more positive than they actually are. Thus the thickness of the sedimentary cover along the axial region could be greater than what the models shown in figs 6-1, 6-2 and 6-3 portray.

It is pertinent to mention here that in presenting the results of the interpretations of the observed anomalies along each of the profiles, only one model is shown and discussed for each profile. During the interpretation stage several combinations of the thicknesses and dips of the layers were tried for each profile and a few gave good fits. Only the model considered to be the most acceptable out of the models that gave good fits was presented, for a given profile. Also, vessicular basalt of density 2.65×10^3 kgm^{-3}, which is much denser than the Awe/Keana sandstones (whose density is 2.44×10^3 kgm^{-3}) outcrop between Umenger and Gbajimba on the Arikya-Yandev profile (fig 6-2) and between Tokura and Awe on the Daudu-Baureh profile (figs 6-4 and 6-5). In the interpretation of the observed anomalies along these two profiles, this layer of basalt is neglected because it was assumed to be thin for the following reasons. A gravity minimum occurs over each of the areas where such basalt outcrop. If the basalt layer is considerable at such locations, a local positive anomaly would have been observed superimposed on the gravity minimum generally observed in the area because of the large positive density constrast (0.21×10^3 kgm^{-3}) of such basalts relative to

the Awe/Keana sandstones. Secondly an aeromagnetic profile over the Awe basalts to the northeast, reported by Creatchley and Jones (1965), reveal no significent anomaly. Thus suggesting that the basalt layer in the area is retatively thin.

CHAPTER VII

DISCUSSION OF RESULTS

7.1 : Introduction

Even though the interpretations presented in the preceeding chapter are tentative, as discussed in section 6.5, a review of these interpretations is discussed in this chapter in the light of proposed theories on the origin and the observed peculiarities of the Benue trough and the anomalous areas discovered from this survey.

7.2 : The Giza Syncline and the Keana Anticline

A block diagram of the Giza syncline based on the correlation of the interpreted features on the two north south profiles (figs 6-1 and 6-2) over the syncline is shown in fig 7-1. The portion of the syncline shown in the last figure is that between Obi and Kadarko. The block diagram shows the syncline with the sediments "scooped out" to reveal the basement topography and structure. The diagram indicates that the syncline which is about 130 kms wide on the Nassarawa Eggon to Ikumbur profile (i.e. along longitude $8^{o}30'E$), trends northeast and becomes about 70 kms wide on the Arikya to Yandev profile. The block diagram also shows that the syncline is step-faulted and downthrown on each limb thus forming a graben.

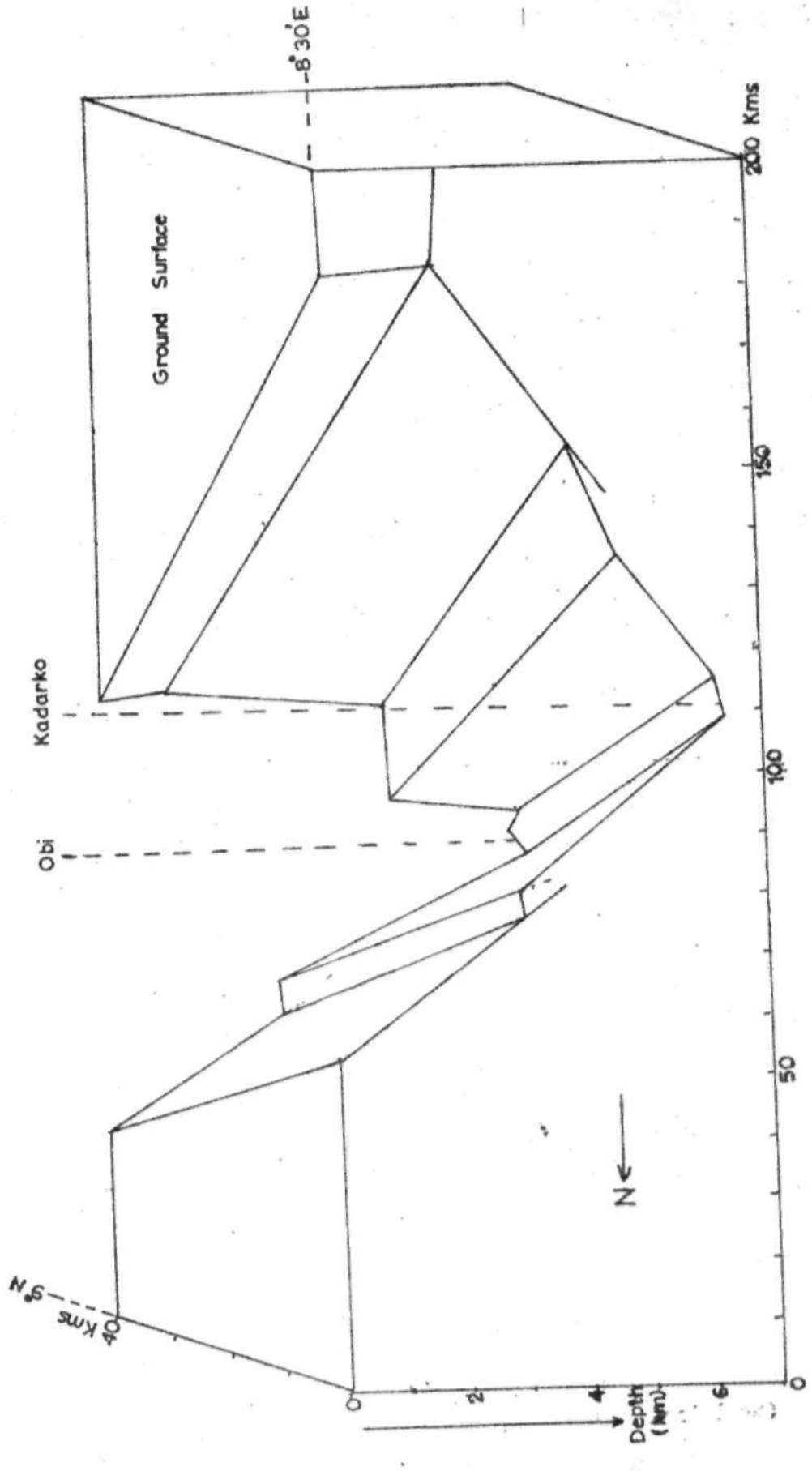


Fig 7-1: A Block Diagram of Part of The Giza Syncline

The slope angle of the sides of the inner depression is about 30^{o} which falls within the range of angles (30^{o}-65^{o}) associated with normal faults (Leet and Judson, 1971), while that of the outer depression is much less than 30^{o}. In view of this observation, the inner depression is considered to be the initial graben while the outer depression might be caused by the weight of the overlying beds in the manner described by Beaumont and Sweeney (1978). Because this graben is elongated, about 40 km in the project area, it can be regarded as a rift valley following the definitions of Gregory (1896, 1920), Wilson (1966) and Mohr (1978). It is speculated that the rift nature of the Giza syncline extends throughout its length, that is beyond its length within the project area. Furthermore, the diagram shows that the Giza syncline, within the portion of the project area represented by the diagram, plunges to the south-west with an average angle of plunge of 1^{o}.

A block diagram of the Keana anticline, which exists just to the south of the Giza syncline, deduced from the interpretations of the Arikya to Yandev and the Lafia to Tsofon Tunga profiles (figs 6-2 and 6-3 respectively) is shown in fig 7-2. The portion of the anticline shown by the figure is that between Kanje and Umenger. As was done in the case of the Giza syncline, the sediments on the

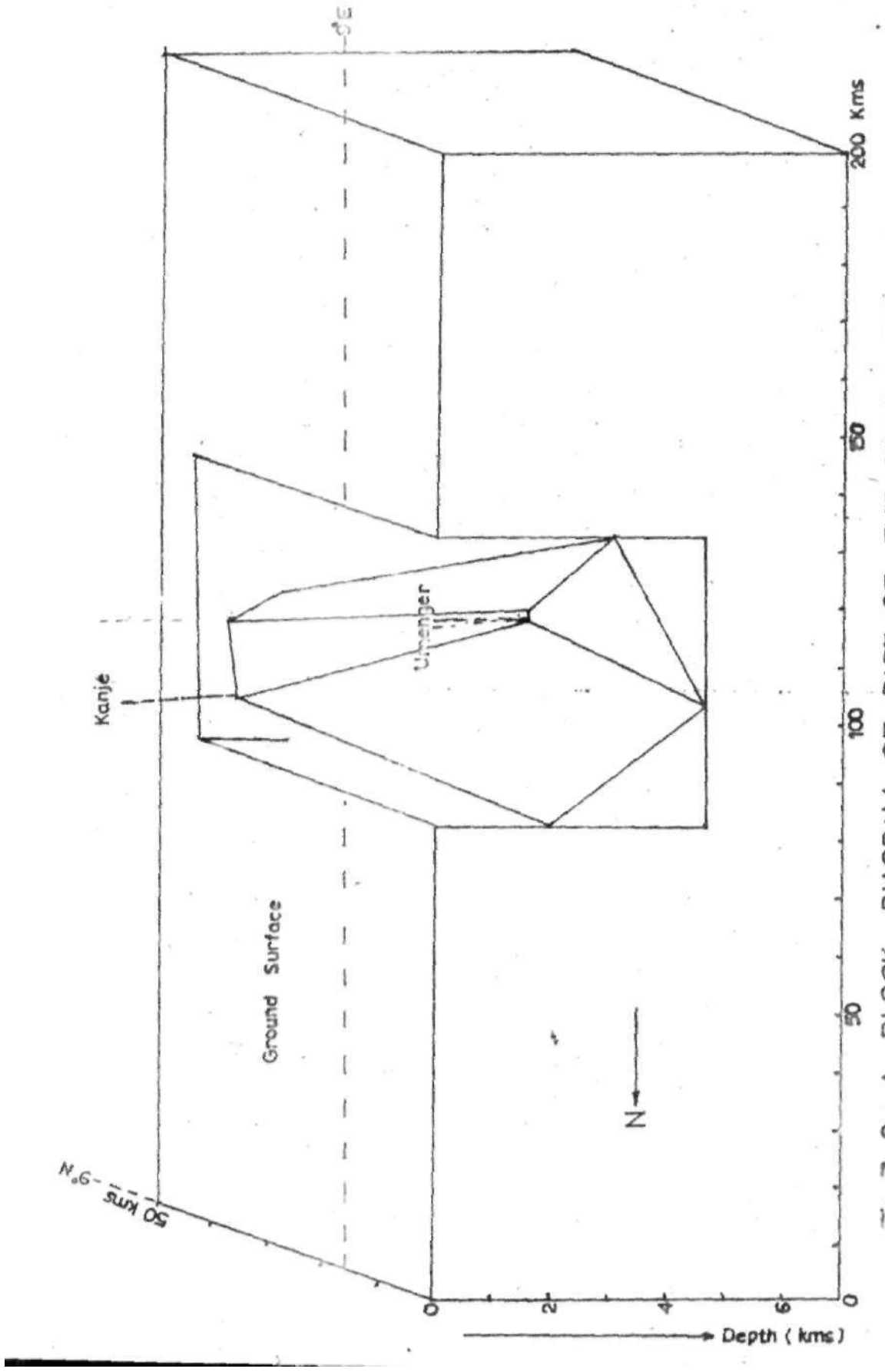


Fig. 7-2 : A BLOCK DIAGRAM OF PART OF THE KEANA ANTICLINE

anticline have been removed, in the diagram, in order to reveal the basement topography and structure. Also, similar to the Giza syncline, the Keana anticline trends northeast but unlike the Giza syncline, it gets wider to the northeast. For example, the width of the anticline may not exceed 2 km at Umenger whereas it could be up to 15 kms in the area between Kanje and Baureh. Also, the depth to the granitic basement along the anticline may not be more than 0.5 km in the Kanje area while it could be about 1.0 km at Umenger. Thus, the anticline plunges to the southwest similar to the Giza syncline with about the same angle of plunge. Also, this anticline and the Giza syncline are both assymetrical. The angles of plunge(1^{o}-2^{o}) reported in this work for the Giza syncline and the Keana anticline may be rather too low when compared with the value 8^{o} reported by Offodile (1976) for structures in the Middle Benue. The reasons for the low values quoted in this work are as follows. For the Giza syncline, the average angle of plunge was calculated from the depths-to-basement obtained at the axis of the syncline along the two profiles from which the block diagram was deduced. The deepest part of the Cretaceous sediments in the syncline lies between the two profiles. Consequently, the deepest

part of the syncline was not utilised in computing the angle of plunge. On the other hand, the profile from which the angle of plunge of the Keana anticline was calculated, lies to the south of the central axis of the anticline. Consequently, the angle of plunge along the profile may not represent the maximum value obtainable for the anticline.

7.3 : The Origin of the Trough

As discussed in section 2.6, King (1950) conjecturally arrived at the rift theory for the origin of the Benue trough. Despite the fact that the trough is a belt of Cretaceous sediments in which elevations do not reach 300m and which is sandwitched between two highlands of crystalline rocks (basement), the major argument so far advanced against its being a rift valley is the absence of marginal faults on the surface (Lees, 1952). From the interpretations of the two north-south profiles in this work (figs 6-1 and 6-2) and the subsequent block diagram of the Giza syncline (fig 7-1) two significant deductions can be made. These are the subsidence, between parallel faults, of the axial region of the Giza syncline and the average width of this subsided region which is about 40 km. This value falls within the range of widths, 50 ± 15 km, normally associated with rift valleys. Secondly, the interpreted models indicate the existence of

intermediate igneous intrusions, which are up to 7 kms deep, within the basement areas just beyond the northern and southern basement/sediment contacts. These intrusions occur around Nassarawa Eggon (fig 6-1) and Arikya (fig 6-2) within the basement in the northern section of the trough and around Gboko (fig 6-2) on the basement in the southern section of the trough. The models also indicate the existence of a deeply rooted volcanic intrusion within the trough, between Umenger and Gbajimba (fig 6-2). The existence of these deeply rooted basic intrusions implies the existence of deeply penetrating fractures in the area (Olatunji, personal communication). This view seems to be in conformity with that of Offodile (1976) who observed the existence of basic intrusions and fractures near the basement/sediments contact in the Nassarawa Eggon area. The above facts suggest a rift origin for at least the Middle Benue. The argument could be extended to cover the whole trough because Cratchley and Jones (1965) inferred a fault along the basement/sediments boundary between Donga and Wukari, which is in the Middle Benue but outside the present project area. Also, Osazuwa (1978), quoting Chukwu-Ike (1977), reported a major fault which has been

confirmed by LANDSAT 2 images occuring along the basement/ sediments boundary in the Kaltungo area of the Upper Benue. On the basis of the above facts, the present author, like Cratchley and Jones (1965) and Offodile (1976) is of the opinion that the Benue trough originated through rifting even though there may not be any obvious surface evidence(s) for it today. The surface evidences might have been obliterated 1) by erosion as the margin of the trough advanced to its present position from its initial position and/or 2) by the Cretaceous sediments overlying it since the rifting of the trough predated the deposition of the sediments.

7.4 : The Width of the Trough

One of the peculiarities of the trough, discussed in section 2.1, is its abnormal width (about 130 to 250 km, as deduced from this study) when compared to the widths (about 35 to 65 km) normally associated with rift valleys. From the interpretation of the Arikya to Yandew profile (fig 6-2) which traverses the entire width of that part of the trough, the trough has been shown to consist of two major synclinoria separated by the Keana anticline. The Giza synclinorium which contains the Obi anticline exists to the north of the Keana anticline while the Gbajimba

synclinorium which is made up of the Makurdi, Gbajimba and the Wannune synclines occure to the south of the Keana anticline. On each limb of either of the two synclinoria is a fault. Consequently, each synclinorium is a graben. As a result of the fact that each graben is elongated, it can be termed a rift as earlier defined in section 7.2. Thus the section of the Benue trough in the survey area can be said to consist of two parallel rifts separated by the Keana anticline which may be regarded as a horst. Though this suggestion may not be obvious from the Bouguer and residual maps of the project area (figs 3-6 and 5-4 respectively), the Bouguer anomaly maps of Cratchley and Jones (1965) and Ajakaiye and Burke (1972), which cover the entire Benue trough, show that the trough consists of an axial gravity high flanked on each side by a gravity minimum. Also, the gravity minimum south of the axial ridge on each of the two north-south profiles discussed in this work (figs 6-1 and 6-2) cannot be accounted for by the Giza syncline or rift.

The width of each of the rift, about 70 to 130 km which is more than the width of about 50 $\pm$ 15 kms normally associated with rift valleys (Holmes, 1964) could also be partly explained by the excessive loading of the grabens due to the rapid

deposition of sediments. Beaumont and Sweeney (1978) demonstrated that through the process of regional isostatic adjustment to sediments and water loading of large grabens, surface depressions up to five times the original width of the graben could be produced. As has been previously reported, rapid deposition of sediments did take place in the Benue trough (Stoneley, 1966). Also, the result of this present work as stated in Chapter V, has shown that the present project area is in a state of near perfect regional isostatic equilibrium. Therefore, the abnormal width of the Benue trough could be due to a combined effect of the fact that the trough consists of two parallel rifts separated by the Keana anticline, and the lateral depressions that was possibly produced as a result of the lithosphere in the region isostatically readjusting itself to the weight of the sediments and water above each of the grabens making up the trough.

7.5 : The Central (Axial) High Anomalies

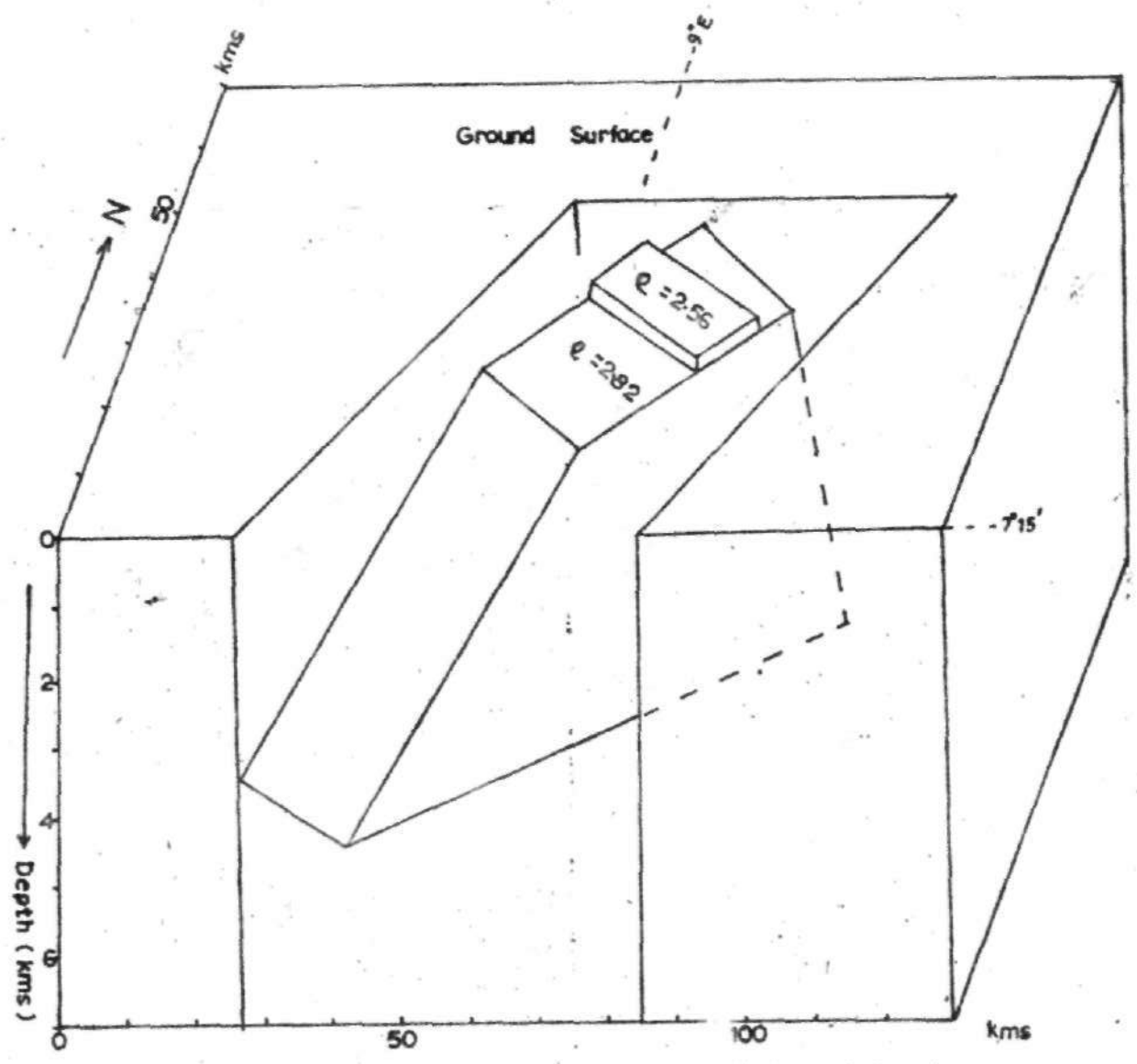
The coincidence of the axial belt of mineralization of the trough with the zone of high Bouguer and residual anomaly values have been mentioned by Cratchley and Jones (1965). Even though the Bouguer anomaly values over this

zone are positive relative to the values over the adjacent zones of maximum thickness of the sedimentary rocks lying on both sides of it the Bouguer anomalies over the belt are not in themselves positive as those observed over the axial zone of the Red Sea (Drake and Girdler, - 1964; Tramontini and Davies, 1969; Galveson, 1978). In the Benue trough, the basement has been reported to outcrop along the axis of the trough in the Upper Benue (Hatchley and Jones, 1965. Burke et al, 1970; Adeleye, 1974; Osazuwa, 1978). Therefore, The existence of the normal granitic basement, at shallow depths, along the Keana anticline, as shown in fig 7-2, relative to the subsided basement below the flanking zones of thick Cretaceous sedimentary cover is considered to be the dominant factor responsible for the relatively high gravity anomalies observed along the belt. Other factors are the localized injection of volcanics into the shallow basement and the general thinning of the crust normally associated with the central (axial) regions of rift zones.

7.6 : The Zone of Positive Bouguer Anomalies (Gboko Area)

Different interpretations have been given to positive Bouguer anomalies observed over different parts of the world, depending on the geology of the area over which the anomalies

were observed. For example, Thompson and Talwani (1964a) explained the mid-continental positive anomaly zone in the United States of America in terms of the Precambrian volcanics and intrusive rocks that occur in the belt. Also, Girdler et al (1969) ascribed the axial belt of positive anomalies observed over the East African rifts to a basaltic or gabbroic zone feeding the volcanoes in the belt. In this survey, the Bouguer anomalies, within which there is a local gravity low, observed in the Gboko area can be explained by the block diagram (fig 7-3) deduced from the interpreted models of the Ikumbur to Ugba profile (fig 6-8) and the portion between Wannune and Yandev on the Arikya to Yandev profile (fig 6-2). From the three figures, the positive Bouguer anomalies and the local low in the area can be ascribed to a two-body composite intrusion in which the outer intrusion has a density of 2.82×10^3 kgm^{-3} while the inner intrusion, thought to be a granitic intrusion has a density of 2.56×10^3 kgm^{-3}. The former density value was assumed for the denser intrusion as discussed in section 6.3.4 while the latter value was that determined for the granitic rocks which outcrop east of Gboko. The present model of the intrusions confirms the model proposed by



Fig· 7-3: A Block Diagram of The Gboko Intrusions

Cratchley and Jones (1965) to explain the Gboko positive anomalies. There are two major differences between the 1965 model and the present one. In the present model, a higher density is assumed for the outer (intermediate) intrusion and the inner intrusion was assumed to be of granitic origin, because of the reasons stated in sections 5.4.3. and 6.2.2, rather than ascribing the two intrusions to intermediate rocks of different densities as proposed by Cratchley and Jones. Also, a two-dimensional model was used in present work instead of a three-dimensional one used by the authors because the residual anomaly (fig 5-4) seems to suggest that the length of the anomalous body may be much bigger than its width.

7.7 : The Downwarped or Subsided Zone

The downwarped or subsided zone is represented by Zone 2 on fig 5-4. From fig 6-8, the low residual values which exist in the region between Yandev and Ugba can be explained in terms of subsidence of the crust east of Yandev. The subsidence might have taken place along a fault plane at about 6 km northeast of Yandev. This fault plane is also the contact between the denser intrusion and the normal granitic

basement. Also, figs 6-6 and 6-7 confirm the suggestion stated in section 5.4.2 that the area between Agasha and Arufu is a subsided area consisting of two grabens the Ugba and Arufu grabens, separated by a thin horst - the Akwana Horst. Each of the grabens is elongated, and can thus be termed a rift as discussed in section 7.2. This zone could therefore be a subsidiary rift of the Benue trough whose direction of trend is approximately perpendicular to that of the Benue trough. In addition, figs 5-4 and 2-1 show that the downwarping or rifting of the zone extend into the basement south of the trough. Tertiary volcanic activities in the zone occured along the northwest fringes of the downwarped area. The above facts respectively suggest that the subsidence (rifting) of the zone most likely postdated the initial rifting of the Benue trough and that the volcanics reached the surface along the deeply penetrating fractures existing within the boundary of this zone and the Kenna anticline. Furthermore, due to the fact that some volcanisms are caused by rifting (Salveson, 1978), the presence of volcanics in the zone suggests that the volcanism might be related to the rifting of the zone. Also, owing to the fact that this rift zone trends southeast, the southeast trending faults reported by Offodile (1976) in the Lafia-Awe area might be related to the tension which caused the rifting of this zone.

7.8 : Other Observations

From the three main synclines shown in fig 6-2, it could be noticed that the thickness of the Cretaceous sediments, within the synclines progressively decreases from the Giza syncline in the northern part of the trough-towards the Wannune syncline in the southern part of the trough. Conversely, the surface sediments in the synclines get older from the Giza syncline towards the Wannune syncline. For example, Albian limestones of the Asu River Complex (formation) overlie the basement in the area adjacent to Yandev (Cratchley and Jones, 1965) while the Turonian Makurdi formation form the major rocks in the Gbajimba - Makurdi area (fig 2-1). But for local outcrops of the Lafia formation near Makurdi (Kogbe et al, 1978) the Maestrichtian Lafia sandstones are the Youngest rocks in the area north of Daudu (Offodile, 1976). The above facts suggest that the area north of Daudu was submerged for a longer time than the area south of Wannune. It is, therefore, likely that the gradual upwarping of the crust in the Gboko area, zone 1 of fig 5-4, probably due to the emplacement of the two-body composite intrusion discussed in section 7.6, was responsible for the gradual blocking of the area east of zone 1 (fig 5-4) from the transgressive and regressive

activities of the inundating sea then existing in the trough. The gradual blocking of the zone 2 (figs 5-4 and 5-5) might have probably started in Late Albian in the Gboko area(near where the oldest sediments exist) and later moving towards the Wannune - Agasha area. The total blocking of the zone from the sea might have been completed by the end of the Turonian since Turonian sediments exist almost throughout zones 1 and 2 (fig 5-5).

The width of the Benue trough was not the same on the two north - south profiles interpreted (figs 6-1 and 6-2). For example, on the Arikya to Yandev profile which traverses the entire, trough, the width of the trough was found to be about 170 km and the axis of the Keana anticline is the approximate axis of the trough. On the Nassarawa Eggon to Ikumbur profile which does not traverse the entire width of the trough, the width of the Giza syncline, was found to be about 130 km. The latter width represents the distance between the basement/ sediments contact near Nassarawa Eggon and the axis of the Igbor anticline. Taking the axis of this anticline as the centre of the trough, similar to the Keana anticline on the Arikya Yandev profile, then the approximate width of the trough on this profile would be about 260 km. Thus, there appears to

be a significant lateral shift in the axis of the trough on the two profiles. The change in the width of the trough due to the shift in the central axis of the trough could be as a result of a variation in the magnitude of the tension σ which caused the rifting of the trough, thereby making the different parts along the length of the trough to have different extension rates during the period of rifting.

Finally, mention must be made of the fact that the formation of the River Benue, after which the trough is named, is a geologically recent event. Among the evidences for this observation is the non-symmetrical nature of the structures underlying it except within the Gbajimba-Makurdi area where the river flows along the axis of the Gbajimba syncline. On the other hand, the River Katsina Ala, which is smaller than the River Benue appears to be controlled by the structures underlying zone 1 of fig 5-4 as the river approximately flows along the boundary of zones 1 and 2.

7.9 : A Rift Model for the Benue Trough

Wright (1970) attempted giving a rift model for the Benue trough. His model was a simple graben, similar to the graben model proposed by Vening-Meinesz and Heiskanen (1958), in which the crust was either flat or buckled prior to rifting.

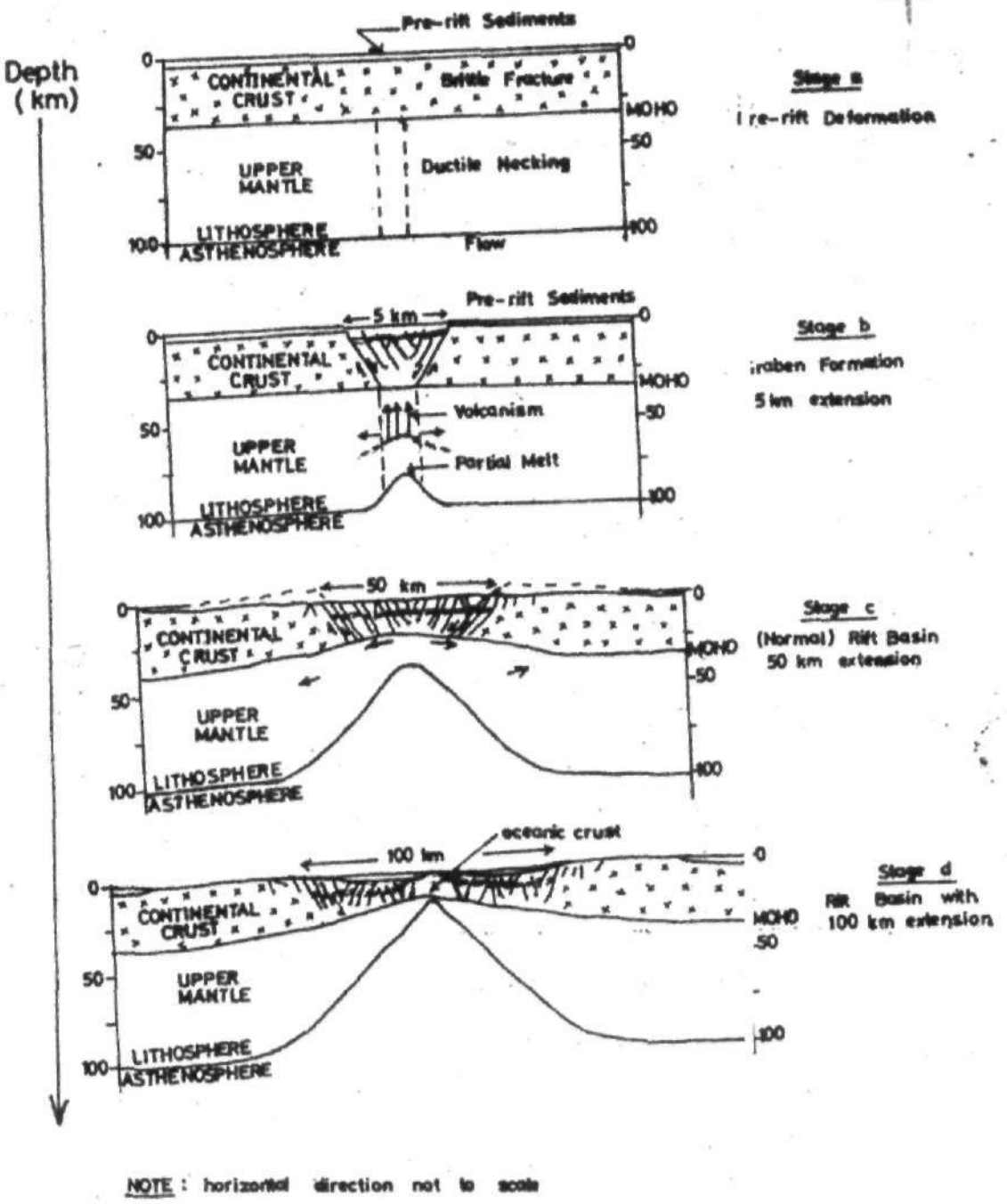
On the basis of the results from the present survey, it is the author's opinion that a simple graben cannot explain the shape, width and other peculiarities of the Benue trough. Olade (1975) proposed a different rift model for the trough similar to the asthenospheric diapir model of rifting discussed by Yungul (1976), based on the existence of a periodic "on-and-off" Cretaceous hotspot beneath the present day Niger Delta. As earlier discussed in section 2.6.5., the periodic upwelling and cessation of mantle plumes in the area is assumed to have culminated into the rifting of the trough and the subsequent folding of the sediments it contained. Olade's strongest support for this model is the apparent lack of thrust faults within the trough. However from the results of the present work, a thrust fault likely exists along the northern limb of the Keana anticline. The assymetric nature of both the Giza syncline (rift) and the Keana anticline coupled with the existence of the axis of the anticline on the surface peristently located to the north of the axis of the anticline at depth as deduced from the gravity data, is a further evidence of the possible existence of a thrust fault along the northern limb of the anticline. In dddition, Burke et al (1970) have identified large scale thrust faulting in the Upper Benue.

Even though Olade's model accounted for the existence of the Abakaliki horst, the horst is not centrally located within the width of the trough as the Keana anticline is in the present project area. Similarly, the modest width of the Benue trough, about 80 to 90 km, upon which the model is based, is much smaller than the actual width of 140 to 260 km found in the present project area. In view of the above it would appear that Olade's model does not satisfactorily explain all the geological occurrences in the Benue trough. Hence there is a need to rethink the rift model of the trough in the light of new deductions from the present work. These deductions include the possible existence of buried marginal faults, the existence of localized volcanic intrusions along the central axis of the trough, the non-positive nature of the Bouguer anomalies observed along the central axis of the trough, the possibility of the trough consisting of two parallel rifts and the possible existence of a thrust fault along the central ridge of the trough.

A new rift model is here being proposed for the Benue trough. The model is based on the evolution of rift basins proposed by Salveson (1978). In the new model, no

prior buckling of the crust is assumed as in Wright (1970). and failure involves the whole lithosphere and extends into the asthenosphere. By the application of tension, the brittle crust fractures and/or deforms by shearing while the upper mantle fails by elastic necking (stage a, fig 7-4). The result is the formation of a graben, about 5 km wide, due to extension (stage b, fig 7-4). If the tension continues to exist, the crust thins through further faulting, extension continues and further necking of the mantle allows the asthenosphere to rise (stage c, fig 7-4). At this stage, the extension of the graben is now about 50 km which is within the range 50 $\pm$ 15 km normally associated with rift valleys. Further extension allows the asthenosphere to reach the base of the thinned continental crust and oceanic crust is consequently emplaced along the axis of the rift (stage d, fig 7-4). At this stage, the originally single rift now becomes two parralel rifts separated by a central ridge of oceanic crust. The total extension of the rift is now about 100 km.

The Red Sea rift is presently at stage (d) described above, whereby oceanic crust occupies the axial belt of the rift. The presence of this crust accounts for the



NOTE : horizontal direction not to scale

Fig 7-4 : Model of Rift Basin Formation (After Salveson, 1978)

axial positive Bouguer anomalies observed within the rift. As mentioned in section 7.6, the Bouguer anomalies obtained along the central axis of the Middle Benue in the present survey were not positive though they were of higher magnitude than the surrounding ones. Therefore, oceanic crust may not underlie the axial belt in the project area. If at all it does underlie the belt, it would be deeply buried beneath both the sediments and the shallow normal granitic basement. Consequently, based on this new model, the most likely stage of rift basin formation attained by the Benue trough, before the cessation of the tension responsible for the rifting of the trough, must be between stages (c) and (d) above. That implies that the tension for rifting the trough existed long enough for the trough to attain its present form (shape) which is similar to that in stage (d) above, for the crust below the central axis of the trough to be thinned enough to enable local injection of upper mantle material into the shallow basement along the axis but ceased to exist before the asthenosphere could reach the bottom of the thinned crust. Hence, there was no crustal separation to enable the oceanic crust to outcrop. Therefore, the axial ridge of the trough within the project area and possibly within the entire

length of the trough might be a sort of short-lived zone of lithosphere spreading as proposed by Grant (1971) and not a short-lived spreading ridge, of oceanic crust, as proposed by Burke et al (1970) and Burke and Dewey (1974). In addition to the deficiences of the Burke's model of crustal spreading, such as lack of surface geological evidence and the geologically unacceptable rate of spreading and/or subduction, discussed by Nwachukwu (1972) Olade (1975) and Wright (1975), the gravity results from the present survey do not suggest the existence of oceanic crust in the Middle Benue. However, it is important to add that a single rift model cannot explain the geological events that took place in the Middle Benue. For example, the rifting of the trough, the cuplift of the axial region of the trough and the subsidence of the zones flanking the axial region might have occurred contemporaneously while the formation of the axial thrust fault could be a later event.

The thrust fault within the Keana anticline shown in figs 6-2 and 6-3 cuts through the Asu River and the Awe/Keana layers of Albian and Albian-Cenomanian ages respectively overlying the basement. As a result, the age of the thrust fault is likely to be post-Cenomanian. Consequently, either the Santonian or the Maestrichtian folding of the sediments

might be contemporaneous with the thrust fault. The thrust fault might, in turn, be due to the Congo craton colliding with the West African craton, as suggested by Nwachukwu (1972) possibly due to the elastic readjustment of the cratons of the African plate, in the manner suggested by Wright (1970), to the final separation of the African continent from the South American continent. Also, as earlier discussed in section 7.4, the abnormal width of each of the two parallel rifts which make up the trough can be ascribed to the rapid overloading of each of the grabens which resulted in the formation of surface depressions which could be much wider than the original width of each of the rifts.

Another point worthy of note is the tremendous thickness of the Cretaceous sediments within both the Ciza and Gbajimba synclines which flank the central axis of the trough on either side. Within the present project area, the thickness of the sediments in the former graben was interpreted to be between 6 to 7 km while that in the latter syncline was interpreted to be about 5 km. Also, from figs 6-1, 6-2 and 6-3, it was deduced that the basement and the sediments subsided simultaneously with the rapid deposition of the sediments. The shallowness of the basement along the central

axis of the trough could also be interpreted to imply that the basement participated in the folding of the sediments as is usually the case during the deformation of geosynclines (Billings, 1960), as has been assumed by Lees (1952) and Cratchley and Jones (1965). The possible existence of a thrust fault within the Keana anticline seems to support such a conclusion. Because the above observations characterise geosynclines, which are large linear troughs often characterised by subsidence due to a thick sedimentary sequence, one might therefore be tempted to conclude that the Benue trough, especially the Giza syncline (rift), is a type of geosyncline as proposed by Lees (1952) and Stoneley (1966) even though the geosyncline may not be as large as those described in Leet and Judson (1971) in which sediment thickness could be up to 12 to 15 km. As earlier mentioned in section 7.4, rapid loading of grabens are known to result in the development of thick sedimentary sequence over such grabens (Beaumont and Sweeney, 1978). In view of the above, the author is of the opinion that the tremendous thickness of the sediments (about 5 to 7 km) in the zones flanking the axial ridge of the trough, on each side, was most likely due to a combination of rapid

deposition of sediments and the sinking of the underlying basement, and not because the trough is a geosyncline. The subsequent subsidence of the basement might in turn be due to the combined effect of the weight of the rapidly deposited sediments and the block faulting, caused by the prolonged existence of the tension forming the rift basin as in fig. 7-4, stages (c) and (d).

CHAPTER VIII

CONCLUSIONS

8.1 : Findings from the Present Work

The major findings from this work, deduced from Chapters VI and VII, are as summarised below:

(i) The interpretations of the north-south profiles and the subsequent block diagram of the Giza syncline indicate that the syncline is rift in which the initial rift occurs at about 20 kms on either side of the axis of the syncline. Also the interpretations of the north-south profiles indicate the existence of deeply rooted intermediate intrusions along the present margins of the trough and volcanic intrusions near the central axis of the trough. The existence of these intrusions suggest that the Benue trough originated as a rift valley.

(ii) In addition, the interpretations of the north-south profiles indicate that the Middle Benue, and possibly the entire trough, contains two parallel rifts separated by the axially placed Keana anticline. This interpretation partly explains why the width of the trough (about 140 to 260 km) is two to three times that of the width of a normal rift (about 35 to 65 km) and it also explains the shape of the

gravity anomaly (an axial high flanked on either side by a minimum) observed across the trough.

(iii) Contemporaneous faulting and subsidence of the basement and sediments, in the grabens (rifts) flanking the axial ridge of the trough, with deposition of sediments due to the rapid loading of each of the grabens, most likely occured after the initial rifting of the trough. This geologic occurrence might be responsible for both the development of thick sedimentary sequences along the grabens, as in geosynclines, and the excessive width of each of the grabens as a result of the lateral surface depression generated by the weight of the sediments. Also, the prolonged existence of the tension which caused the rifting of the trough, about 30 m.y. (Grant, 1971; Wright, 1975b), might have resulted in the excessive extension of each of the grabens. The combined effects of the lateral surface depression due to the loading of each graben making up the trough and the excessive extension of each of those rifts as a result of the prolonged existence of the tension, might have also contributed in making the width of the trough much larger than that normally associated with a rift.

(iv) An area of crustal subsidenc
subsidence was possibly accompanied wit
faulting and which may be a subsidiary
rift, has been identified just to the s
anticline. The gravity anomalies in th
The model proposed for the area contain
trending and plunging grabens (rifts) s
parallel horst (figs. 6-6 and 6-7). Th
the grabens and horst and the Ugba and
Akwana Horst respectively. The southe
reported by Offodile (1976) in the Lafi
may be related to the rifting of this a
(subsidence) of this area likely postda
rifting of the trough.

(v) The proposed models in figs 6
a thrust fault along the northern flank
The existence of this thrust fault coul
northward shift in the location of the
anticline on the ground surface, as sho
map (fig 2-1), relative to the actual l
at depth, as shown on the residual anom
thrust fault could also account for the
within the trough.

(vi) The volcanic activities in the Umenger-Gbajimba Jangerigeri area exist along the boundary between the Keana anticline and the subsided area discussed in (iv) above (fig 5-5). Therefore, the volcanics might have reached the surface through the deeply penetrating fractures that exist in this boundary zone. In addition, the volcanism in this area might be sequal to the subsidence or rifting of the area discussed in paragraph (iv) above since some volcanisms are caused by rifting (Salveson, 1978).

(vii) The Giza syncline is a step-faulted rift which is both assymetric and doubly plunging within the project area (fig 7-1). The deepest part of the syncline, in the project area, lies between Kadarko and Giza while its shallowest portion occurs around Obi from where it plunges both to the northeast and the southwest. The depth-to-basement along the axis of the syncline varies between 6 to 7 km in the project area. The sediments are generally more folded on the southern flank of the syncline than on its northern flank, possibly due to the presence of a thrust fault on its southern flank. A minor arm of the syncline occurs between Obi and Agaza and it is separated from the main arm by the Obi anticline.

(viii) Another deduction from this study is that a new syncline has been identified in the vicinity of Gbajimba (fig 6-2). The name Gbajimba syncline has, therefore, been suggested for it. The River Benue seems to flow along the axis of this syncline between Gbajimba and Makurdi (fig 6-2). The Makurdi syncline, identified by Kogbe at al (1978), may be a minor arm of the new syncline.

(ix) The interpretation of the gravity data also indicate a new broad anticline possibly a horst, located south of Makurdi. Because its axis passes through Igbor (fig 6-1) from where it trends northeast, the name Igbor naticline has been suggested for it. This anticline seems to occupy the axial region of that part of the trough just as the Keana anticline occupies the axial region of the trough in the area to the northeast of Makurdi (fig. 5-4).

(x) Similar to the Giza syncline, the Keana anticline is also assymetrical, it trends to the northeast and plunges to the southwest with an angle of plunge of about 2° (figs 6-4 and 6-5). The southeast extension of the anticline has been truncated by a previously undocumented major fault which exists at about 2 km southwest of Umenger (figs 6-4 and 6-5). The name Umenger fault has been suggested for this fault. The shallow depth-to-basement along the anticline coupled with the local injection of volcanics into the basement is thought to account for the high but not positive Bouguer anomalies observed over the anticline.

(xi) From isostatic studies carried out in this work the entire project area is in a state of near perfect isostatic equilibrium.

(xii) The interpreted model for the Gboko area which is characterised by positive Bouguer anomalies is made up of a two-body composite igneous intrustion which occurs at shallow depths (about 0.5 to 1 km). The outer intrusion assumed to be composed of intermediate rocks, is thought to be responsible for the positive Bouguer anomalies observed in the area while the the inner intrusion, thought to be of granitic origin, accounts for the local gravity low which occurs within the positive anomalies in the area.

(xiii) In view of the fact that oceanic crust did not out-crop in the Benue trough coupled with the fact that local volcanic injections exist along the central ridge of the trough, it is most probable that the Benue trough did not attain the present stage of rifting in the Red Sea, before the complete separation of the African and the South American continents was achieved. However, during the rifting process, the crust beneath the axial region of the trough became thin enough for upper mantle material (volcanics) to be locally injected into the shallow granitic basement along the axis of the trough.

8.2 : The Benue Trough Compared With Other Rifts

The characteristics of the Benue trough, so far discussed, are similar to those observed in other rift zones in different parts of the world. For example, the width of the trough, found in this work to be about 170 to 260 km, compares with that of the Red Sea which is about 200 to 300 km (Drake and Girdler, 1964). Also, the shape of the Bouguer anomaly, a central high with a negative (low) value on each flank observed over the Benue Trough by Cratchley and Jones (1965) and in the current survey (fig. 6-2) is similar to that observed over (a) the Red Sea (Drake and Girdler, 1964; Tramontini and Davies, 1969), (b) the East African rifts (Girdler et al, 1969) and (c) the San Luis Basin, Colorado (Davis, 1978). The major difference between the Red Sea and the Benue trough is that the former is an intercontinental rift (Milanovsky, 1972) which is capable of developing into an ocean basin (Burke, 1978) while the latter has been proposed to be a failed continental rift or aulacogen (Olade 1975). Thus the relatively high-valued positive Bouguer anomalies, in the case of the RedqSea, are due to the oceanic crust in which there are zones of volcanic injection (Drake and Girdler,

1964). In the case of the Benue trough, the axial Bouguer anomalies although high valued are not positive and these are due to a combination of the existence of the granitic basement at shallow depths beneath the sediments and the existence of localized volcanic intrusions within the basement (Cratchley and Jones, 1965; present survey). In the present project area the high valued Bouguer anomalies have been ascribed to the occurrence of the basement at shallow depths.

The amplitude of the observed gravity anomaly over the Middle Benue (-20 to -50 mgals) compare with those observed in different rift zones of the world. For example, Thompson and Talwani (1964a) observed an amplitude of -50 mgals over the Sacramento Valley in California; Qureshi et al (1968) also observed the same value (-50 mgals) over the Godavari rift in India and Girdler et al (1968) observed the same range of values (-20 to -50 mgals) over the East African rifts. Other characteristics of the gravity anomalies observed in the Middle Benue in this study include closed minima within the trough similar to those discussed by Sutton (1960) for fift-like structures and observed by Garland et al (1961) over the Southern Rocky Mountain Trench, British Columbia, Canada; and weak marginal positive anomalies,

(about + 10 mgals) similar to those discussed by Quereshi et al(1968)

From the results of this study, the Benue trough has been proposed to consist of two parallel rifts separated by the axially placed Kenna anticline. Other rifts in different parts of the world which are known to contain more than a single graben or rift include the East African rifts which were resolved into the Western and Eastern rifts by Girdler et al (1969), the Lake Baikal rift (Florensov, 1969) and the San Luis Basin, Colorado (Davis, 1978) each of which has two grabens separated by a parallel horst. The results of the present survey also indicate that the Benue trough is a rift buried under Cretaceous sediments. A precambrian rift discovered in Western Canada (Kanasewich et al, 1969) had no surface indications because the rift was buried 2.5 km beneath the younger sediments. Similarly, a recently discovered Early Mesozoic graben in the Southeastern United States (John et al, 1978) is buried under younger sediments. These three rifts share the common characteristic of being buried under younger sediments and, hence, have no surface expressions, typically associated with rift structures.

8.3 : The Benue Trough as Part of the World Rift System

According to Milanovsky (1972), all rift belts in the ocean floor and the majority of those in the continents join to form the World Rift System, defined by Heezen (1969) to include the world-girdling Mid-oceanic Ridge as well as rift valleys which cut deeply into the continents, dominating the oceans and affecting half of the earth's surface. The Benue trough is a continental rift whose origin has been linked with the separation of the African continent from the South American continent (Wright, 1968, 1970). Reviewing the gravity surveys of Gordon-Smith (1939), Hospers (1964) and Cratchley and Jones (1965) carried out in different portions of the Benue Valley, Ajakaiye and Burke (1972) showed that the gravity low of the valley existed throughout its entire length - that is from the Lake Chad to the Coast. This characteristic gravity anomaly had earlier been shown to continue into the continental shelf area of Nigeria (Hospers, 1964). Thus, the rift trend can reasonably be assumed to continue into the continental shelf. Also, the existence of transform faults have been reported in the Gulf of Guinea (Grant, 1971). According to Drake and Girdler (1964) and

Heezen (1969), the World Rift System usually extends into the continents in form of grabens (rifts) or strike-slip faults through transform faults. Therefore, the transform faults in the Gulf of Guinea provide the link between the Benue trough and the Mid-Atalantic Ridge, which makes the trough part of the World Rift System.

8.4 : Suggestions for Future Work

There is no doubt that the project area is presently much more accessible than it was during the survey of Cratchley and Jones (1965). As a result, the project area could be covered with a more detail gravity stations in the present survey, than was possible in 1965. Despite the general improvement in the accessibility of the project area, certain portions of it could still not be reached owing to lack of roads. Consequently, a uniform data coverage of the entire project area was impossible. Thus one could not accurately predict the trends of the gravity field in some vital areas. One such area is the Daudu-Umenger-Gbajimba-Makurdi quadrangle which is supposed to contain both the Makurdi (Keana?) anticline and the Makurdi syncline (Kogbe et al, 1978) and also the link between the Keana anticline and the Makurdi and/or Igbor anticline (fig 5.4). Neither the Makurdi anticline nor the

Makurdi syncline features prominently on the residual anomaly map (fig 5.4) in the quadrangle, possibly due to insufficient data. Therefore, a detailed gravity survey of the area is recommended whenever its accessibility improves in order to verify the existence of these anticlines and synclines and also to determine the relationship between the folds (the anticlines and synclines) and the Keana anticline. In addition, such a survey could throw more light on the nature and extent of the proposed fault (Umenger) which cuts across the southeast extension of the Keana anticline around Umenger (fig 6-4). Also, such a survey could throw more light on the extent and origin of the volcanics in the quadrangle in relation to the gross structure of the area.

The interpretations of the north-south profiles (figs 6-1 and 6-2) and the subsequent block diagram of the Giza syncline (fig 7-1), indicate (a) that the original rift of the Giza syncline is of normal width (about 40 km) and lies in the central portion parallel to the axis of the syncline and (b) that the trough may consist of two parallel rifts separated by a parallel horst. An ordinary reflection seismic survey of the area along two or three north-south profiles running from basement to basement across the trough could be carried

out to verify the interpretations. A similar survey could also be carried out on three to four longitudinal profiles to verify interpretations in that direction.

Though the emphasis of the present work was determining the gross structures within the sedimentary sequence of the project area in relation to the origin of the trough, a detailed modelling of the crust, using gravity data, could have thrown more light on whether or not the trough is a rift. This is due to the fact that such modelling would show which areas of the crust are thinned or have anomalous desities which in turn could confirm or disprove the rift model proposed here for the trough. For this type of modelling profiles which exceed the margins of the trough over fairly long distances are needed in order to determine the regional gravity over a very broad region as has been carried out by Girdler et al (1969) and Fairhead (1976) for the study of the lithosphere beneath the East African Rifts. Owing to the fact that the profiles in the present survey barely exceed the margins of the trough, as earlier mentioned in sections 5.1.2 and 5.2.2., the lithosphere beneath the Middle Benue could not be studied. Consequently, such a study, as a fellow-up to the present survey, is recommended for

the Benue Trough using either the refraction seismic method or the gravity method or both. Again, two or three north-south seismic refraction (and/or gravity) profiles, each starting from the basement north of the trough and ending on the basement south of the trough would be adequate. The seismic reflection method has also been successfully used for deep crustal studies in other parts of the world (Kanasewich et al, 1969; Mueller et al, 1969). If the cost difference will not be much, this method could be used on the above profiles rather than the refraction method to achieve the same aims.

In the present survey and that of Cratchley and Jones (1965), the positive anomalies in the Gboko area have been interpreted to be due to a two-body composite intrusion. As earlier mentioned in section 7.6, the densities of the intrusions assumed in the two interpretations differ. A definite way of knowing what types of intrusions the bodies are is by drilling. Though the interpreted depth-to-top of the intrusions was about 0.7 km in the Gboko area, drilling to such a depth could be expensive. However, if funds are available, such a drilling could be carried out in the area in order to ascertain what these intrusions are.

As of now, no results of any systematic geochemical/ petrological study of the volcanics along the central axis of the trough have been published. For example, such a survey carried out in the Kenya rift showed that the rift is characterised by alkaline volcanism more than 50% of which are of basaltic origin (Williams, 1972). Such a systematic study is therefore, recommended not only for the Middle Benue but for the entire Benue trough because the results could show whether or not the volcanics found in the trough are the types which characterise rifts, oceanic ridges or regions of plate accretion in other parts of the world. This could throw more light on the problem of the origin of the Benue trough.

A major characteristic of rift zones is high seismicity (Milanovsky, 1972) which are usually of shallow epicentres (Kumarapelli, 1966; Heezen, 1969). Though no earthquake has been recorded in the enue trough in recent history, it is possible that some microseisms may occur in the area, if crustal adjustment is still going on. A microseismic survey of the Gulf of Aden and the Red Sea by Fairhead and Girdler (1972) revealed that the epicentres were related to the spreading zones and areas of recent faulting. The direction

of tension responsible for rifting in East Africa was also deduced by the same authors from the same survey. Therefore, such a survey could be carried out in the project area with identical intentions. The results of the survey would reveal whether or not the project area is still presently active. Alternatively, the activity of the area could be monitored through frequent geodetic levelling. A vertical movement of the crust in the Rio Grande Rift, New Mexico was recently detected through such a survey (Reilinger et al, 197

In addition, a systematic sampling of the rocks in the area, for density determinations purpose, should be carried out. As discussed in section 4.2, the geology of the Middle Benue is largely hidden under alluvium cover, thus, not many rock samples could be collected for density determinations in the present survey. Since the interpreted data are dependent on density values assumed for the rocks, the importance of such an exercise cannot be overestimated. The measured density values should also be correlated with borehole logs, where available.

APPENDIX I (Tables)

Table 2 (Appendix)

Comparison of Heights computed from Altimeter Readings with Benchmark values at some stations.

STATION NUMBER	(a) CALCULATED HEIGHT (m)	(b) KNOWN* HEIGHT(m)	(b-a) DIFFERENCE (m)
1200	154.35	154.35	0.00
1201	161.79	161.67	0.13
1202	151.09	149.90	-1.19
1203	137.62	137.01	-0.61
1204.	137.40	137.37	-0.03
1205	112.93	114.09	1.16
1206	108.94	109.24	0.30
9005	119.15	119.15	0.00
9028	108.02	108.02	0.00
1161	108.66	108.11	-0.55
9004	175.05	175.05	0.00
1153	159.04	159.26	0.22
1154	157.70	158.31	0.61
1155	139.17	140.09	0.92
1156	128.84	129.30	0.46
1157	139.08	139.54	0.46
1158	136.46	137.37	0.91
1159	115.98	116.86	0.88

* known heights from benchmarks

TABLE 3 (APPENDIX)
PRINCIPAL PARAMETERS OF THE BASE STATIONS

STATION NO.	LONG-ITUDE	LAT-ITUDE	HEIGHT(m)	OBSERVED GRAVITY (IGSN) (mgals)	FREE-AIR ANOMALY (mgals)	BOUGUER ANOMALY (mgals)
9000	8.39	8.39	190.46	978061.803	-25.74	-45.39
9001	8.81	8.29	164.05	075.374	-17.21	-34.14
9002	8.85	8.33	201.32	069.486	-13.61	-34.39
9003	9.00	8.29	196.27	084.786	+ 1.39	-18.87
9004	9.08	8.23	189.50	099.680	+24.23	+ 1.64
9005	9.13	8.11	129.05	108.523	+10.66	- 2.66
9006	9.12	8.37	162.17	090.893	- 4.27	-21.00
9007	9.25	8.37	137.90	103.052	0.98	-13.25
9008	9.16	8.42	146.09	087.649	-13.45	-28.52
9009	9.12	8.39	204.65	079.491	- 4.21	-25.33
9010	9.11	8.44	118.19	089.898	-19.75	-31.95
9011	9.24	8.43	145.26	092.017	- 9.45	-24.46
9012	9.31	8.37	120.30	108.625	+ 1.49	-10.93
9013	9.21	8.26	143.53	105.392	+11.03	- 5.01
9014	9.33	8.38	138.86	104.566	+ 2.43	-11.90
9015	8.33	8.42	129.35	105.687	- 0.10	-13.45
9016	9.22	8.35	131.43	104.616	- 1.06	-12.50
9017	9.05	8.19	165.24	104.450	+ 4.32	-12.73
9018	9.21	8.13	200.89	096.612	+18.66	- 2.07
9019	9.18	8.09	144.64	103.718	+10.75	- 4.18
9020	9.25	8.11	165.70	101.084	+13.59	- 3.51
9021	9.32	8.01	98.79	068.646	+ 8.40	- 1.80

STATION NO	LONG-ITUDE	LAT-ITUDE	HEIGHT (m)	OBSERVED GRAVITY (IGSN) (mgals)	FREE-AIR ANOMALY (mgals)	BOUGUER ANOMALY (mgals)
9022	9.05	8.09	198.68	978089.606	+12.08	- 8.42
9023	8.97	8.06	165.07	089.248	+ 1.49	-15.03
9024	8.80	8.15	140.21	088.834	- 6.91	-21.38
9025	8.77	7.99	157.15	090.160	+ 3.28	-12.94
9026	9.00	8.39	195.77	071.206	-14.82	-35.02
9027	8.88	8.33	209.64	068.646	-12.08	-33.71
9028	9.14	8.13	117.00	113.954	+12.05	- 0.02
9029	9.13	8.08	214.16	087.701	+14.64	- 7.46
9031	8.41	8.91	477.06	080.661	+ 9.71	-39.52
9032	8.52	8.49	212.55	086.405	+ 2.30	-19.63
9033	8.82	8.58	160.32	085.256	-16.06	-32.61
9034	8.59	8.47	208.81	077.752	- 6.84	-28.39
9036	8.57	8.23	196.76	055.230	-24.25	-44.56
9036	8.60	7.91	131.56	075.803	-16.54	-30.12
9037	8.86	7.82	101.25	090.859	- 7.74	-18.19
9038	8.54	7.73	89.40	088.225	-11.60	-20.83
9039	9.05	7.36	243.84	078.557	+31.26	+ 6.09
9040	8.89	7.56	209.64	085.864	+24.24	+ 2.61
9041	9.14	7.31	130.31	093.326	+14.89	+ 1.44
9042	8.78	7.30	177.65	088.516	+23.84	+ 5.51
9043	8.75	7.75	99.04	094.636	- 3.02	-13.24
9044	8.61	7.41	233.87	078.300	+26.13	+ 2.00
9045	9.05	8.00	211.75	080.259	+ 6.51	-15.34
9046.	8.86	7.80	70.98	098.781	- 7.99	-15.31

STATION NO.	LONG ITUDE	LAT- ITUDE	HEIGHT (m)	OBSERVED GRAVITY (mgals)	FREE-AIR ANOMALY (mgals)	BOUGUER ANOMALY (mgals)
9047	8.87	7.71	162.40	978098.045	+20.81	+ 4.05
9048	8.87	7.71	189.57	091.137	+20.21	+ 0.64
9049	8.97	7.73	79.33	104.238	+ 1.52	- 6.67
9050	9.15	7.44	193.27	080.620	+17.07	- 2.88
9051	9.21	7.46	95.77	096.047	+ 4.25	- 5.63
9052	9.34	7.501	191.38	075.531	+10.09	- 9.66
9053	9.31	7.71	227.07	076.313	+16.04	- 7.39
9054	9.24	7.83	164.34	085.135	+ 4.12	-12.84
9055	9.13	7.78	174.44	078.853	+ 1.98	-16.03
9056	9.30	7.84	168.70	085.001	+ 5.00	-12.40
9057.	9.28	7.93	106.44	100.069	+ 0.05	-10.93
9058	8.81	8.69	164.64	095.343	- 7.72	-24.71
9059	8.67	8.83	204.69	082.851	-12.54	-33.67

APPENDIX 2

Computer Listing of the Program for Performing the Reduction of Raw Gravity Data To the IGSN System.

(written for the University's CDC-Cyber 72 Computer)

```
C       THIS PROGRAM CORRECTS FOR GRAVIMETER DRIFT
C       AND MAKES THE USUAL CORRECTIONS FOR GRAVITY DATA
C       WHERE:-
C       NO = NO OF TRAVERSES IN SURVEY
C       N = NO OF STATIONS IN A TRAVERSE
C       IS(M) = STATION NO OF THE MTH STATION IN A TRAVERSE
C       T(M) = OBSERVATION TIME AT "     "     "  "    "
C       GO(M) = GRAVIMETER READING "     "     "  "    "
C       PHI(M) = LATITUDE OF THE   "     "     "  "    "
C       BLEV(M) = HEIGHT   "   "   "     "     "  "    "
C       ABG(M) = ABS. GRAVITY "     "     "     "  "    "
C       BLCOR(M) = BLEV. CORRN "     "     "     "  "    "
C       TGRAV(M) = THEO. GRAV "     "     "     "  "    "
C       BCOR(M) = BOUG CR     "     "     "     "  "    "
C       FA(M) = FREE-AIR ANOM "     "     "     "  "    "
C       BOUG(K) = BOUGUER CR  "     "     "     "  "    "
C       DAY(J) = DAY READINGS ON JTH TRAVERSE TAKEN
C       MTH(J) = MONTH READINGS ON JTH "       "
C       YR(J) = YEAR      "     "   "  "       "
C       N(J) = NO OF STATIONS  "   "  "       "
C       DR(J) = CHANGE IN GRAVIMETER READINGS BETWEEN
C               BASE STATIONS A/R ON TRAVERSE TAKEN
C               (FROM BASE LOOPING, IN GRAVIMETER UNITS).
```

```
C       ABGA(J) = ABSOLUTE GRAVITY AT BASE STATIONS A ON TRAVERSE
        INTEGER DAY, YR
        DIMENSION N(90),DR(90),IS(50),T(50),GO(50),DG(50),ABG(50),
      1 DG1(50),DT(50),GRAD(50),DT2(50),DGC(50),DOUG(50),ELEV(50),
      2 DAY(90),PHI(50),ABGA(90),ELCOR(50),ALPHA(50),TEMP(50)TGRAV(50)
      3 ECOR(50),DH(50),MTH(90),YR(90),FA(50),B(50,50),PSI(50)
        CON = 0.09406
        CON2 = 978.03185
        C1 = 0.0052789
        C2 = 0.000023462
        C3 = 0.01276
        C4 = 0.08829
C       C4 = GRAVIMETER CONSTANT (SPECIFY FOR GRAVIMETER USED)
        C5 = 978030.661
        RHO = 2.67
        H = 0.0
C       H = REFERENCE ELEVATION (E.G. GEOL LEVEL)
        NO =        (SPECIFY FOR SURVEY)
C
C       PART FOR CORRECTING THE GRAVIMETER DRIFT
C       DO 10,J = 1, NO
```

```
      READ(4,*) N(J), DAY(J), MTH(J), YR(J), DR(J), ABGA(J)
      IF(DR(J) .EQ.0.0) GO TO 15
      DO 40 M=1, N(J)
      READ (4, *)IS(M),T(M),GO(M),PHI(M),ELEV(M)
   40 CONTINUE
      DG(J) = GO(N(J)) -GO(1)
      DG1(J) = DG(J) - DR(J)
      DT(J) = T(N(J)) - T(1)
      GRAD(J) = DG1(J)/DT(J)
      WRITE(6,3) IS (1), IS(N(J)),DAY(J), MTH(J), YR(J)
      DO 30 I = 1, N(J)
      DT1(I) = T(I) -T(1)
      DGC(I) = GO(I) - DT2(I) *GRAD(J)
      ABG(I) = C4 * (DGC(I)-DGC(1)) +ABGA(J) +C5
   30 CONTINUE
      GO TO 11
C     PART FOR CORRECTING GRAVIMETER DRIFT IF LOOPING WAS ABA TYPE
   15 DO 20 L = 1, N(J)
      READ (4, *) IS (L), T(L),GO(L),PHI(L), ELEV(L)
   20 CONTINUE
      DT(J) = T(N(J)) - T(1)
```

```
      DG(J) = GO(N(J)) - GO (1)
      GRAD(J) = DG(J)/DT(J)
      WRITE(6,3) IS (1), IS(N(J)), DAY(J), MTH(J), YR(J)
      DO 50 NI = 1, N(J)
      DT2(NI) = T(NI) -T(1)
      DGC(NI) = GO(NI) - DT2(NI) * GRAD(J)
      ABG(BI) = C4 * (DGC(NI) - DGC(1)) +ABGA(J) +C5
   50 CONTINUE
C
C     PART FOR MAKING THE FREE-AIR LATITUDE AND BOUGUER
C     CORRECTIONS
C
   11 DO 60 IC = 1,N(J)
      DH(K) = ELEV(K) - H
      PHI(K) = PHI(K) * 0.01745
      ELCOR(K) = CON * DH(K)
      TA = SIN(PHI(K))
      CC = C1 * TA * TA
      ALPHA(K) = TA * TA * TA * TA
      CD = C2 * ALPHA (K)
      TD = CON2 * (1.+CC+CD)
      TGRAV (K) = 1000. * TD
```

```
      BCOR(K) = C3 * RHO * DH (K)
      FA(K) = ABG(K) + ELCOR(K) - TGRAV(K)
      B(J,K) = FA(K) - BCOR(K)
      BOUG(K) = B(J,K)
      PHI(K) = PHI(K)/ .01745
      WRITE (6,5)IG(K), T(K), GO(K), ELEV(K), PHI(K),TGRAV(K),
     1 ELCOR(K), BCOR(K),FA(K),BOUG(K), ABG(K)
   60 CONTINUE
   10 CONTINUE
    3 FORMAT(1,2X, * DATA BETWEEN STATION *, I4,AND STATION*
     1, I4,* WERE COLLECTED ON *, 3I4/2X,*STA NO*, 2X,
     2 * TIME*, 3X, *GRV RDG*, 4X, *ELEV*, 5X, *LAT*, 5X,
     3 * LAT COR*, 4X, *F.A.COR*, 4X, *BOUGCOR*, 4X,
     4 * F.A. ANO*, 4X, *BOUG ANO*, 6X, *ABSGRV*)
    5 FORMAT(3X, I4, 2X, F5.2, 2X, F7.2, 2X, F7.2, 5X, F7.3,
     13X, F10.3, 3X, F7.2, 4X, F7.2, 4X, F7.2, 4X, F6.2,
     25X, F12.3)
    8 FORMAT(2X, I4, 2X, 5F9.2)
      STOP
      END
```

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