GRAVITY AND AEROMAGNETIC INVESTIGATION OF THE GONGOLA ARM OF THE UPPER BENUE TROUGH, NIGERIA

BY

ELISHA MUTUM SHEMANG Jr.
B.Sc. (Hons) Geology and Mining
M.Sc. Applied Geophysics

A DISSERTATION SUBMITTED TO THE POSTGRADUATE SCHOOL OF AHMADU BELLO UNIVERSITY, ZARIA NIGERIA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF DOCTOR OF PHILOSOPHY (Ph.D.) DEGREE IN APPLIED GEOPHYSICS.

May, 1997

DEDICATION

DEDICATED TO MY WIFE ROSE, AND MY CHILDREN BRISKA AND VERA. ALSO TO MY PARENTS, MUTUM SHEMANG AND AMINA SHEMANG (LATE 24/12/93) AND TO ALL MY FRIENDS RELATIVES THAT MISSED MY ASSISTANCE AND COMPANY DURING THE PERIOD OF THIS WORK.

DECLARATION

I Declare that this thesis is my own work and has not been submitted in any form for another degree or diploma at any other University or Institution. Information derived from published and unpublished work of others has been properly acknowledged in the text.

Elisha Mutum Shemang Jr.

CERTIFICATION

This thesis entitled **"GRAVITY AND AEROMAGNETIC INVESTIGATION OF THE GOANGOLA ARM OF THE UPPER BENUE TROUGH NIGERIA"** by Elisha Mutum Shemang Jr. meets the regulation governing the award of the degree of Doctor of Philosophy in Applied Geophysics of Ahmadu Bello University, Zaria, Nigeria and is approved for its contribution to *Scientific knowledge and literary presentation.*

.....
Professor C.O. Ajayi
Chairman, Supervisory Committee

Date: 15/7/97

.....
Dr. M.N. Umego
Member, Supervisory Committe

Date: 27/8/97

.....
Professor I.B. Osazuwa
Head of Department of Phyiscs
ABU, Zaria

Date: 29/8/97

.....
Professor J.Y. Olayemi
Dean, Postgraduate School
ABU, Zaria

Date: 4/5/98

ACKNOWLEDGEMENT

I acknowledge with thanks the assistance of all individuals who have contributed in different ways towards the successful completion of this project. In particular, I wish to express my profound gratitude to Professor C.O. Ajayi my, main supervisor for his material and moral help rendered during the course of this work. His inspiring thoughts, suggestion and accessibility have greatly contributed in no small measure to the completion of this work. I am greatly indebted to him for these great commitments more especially in offering very useful suggestion everytime he goes through a draft copy of this thesis. I am also grateful to Dr M.N. Umego my co-supervisor for his moral and material support and encouragement throughout the work which had great bearing towards the preparation of this thesis. My sincere thanks to him.

I am also greatly indebted to Professor W.M. Moon of the University of Manitoba, who made his computer facilities available to me during my 9 months stay at the Department of Geological Sciences, University of Manitoba, Canada. His constant reminder that with hard work the sky is the limit, made it possible for me to achieve the very difficult task of interpretation of my data while working in his Laboratory I thank him very much. I want also to thank Professor G.S. Clark the head of Department of Geological Sciences University of Manitoba Canada for making my visit and stay in Canada for 9 months possible. My special gratitude also goes to Professor D.H. Hall and Dr. Ian Ferguson of the Geophysics group, Department of Geological Sciences, University of Manitoba for their interest and

advice during the course of data interpretation. Dr. Ferguson made available, free of charge almost all of the software used for the interpretation of this work.

I am greatly indebted to those who made the field work possible. These include; Abubakar Tafawa Balewa University Bauchi, that partly Funded this Project, and the Director Geological Survey of Nigeria for the release of the aeromagnetic maps. I also thank Prof I.B. Osazuwa for putting at my disposal equipment used for this field work and for allowing me access to bench marks established by him in the area of study. I wish also to acknowledge Professor E.F.C Dike, the former head of Department of Geology ATBU who made available to me the departmental Land Rover for the field work. My sincere thanks go to Mr Samuel Arobami and Ibrahim Adamu who drove the vehicles during the field work and also Mr Basil Nwosu the technical field Assistant who worked very hard to make sure the equipment are in a functional order.

I also wish to thank Professor S.B. Ojo, the head of Physics department ABU Zaria for his assistance especially in making his journals available to me for consultations and also his advice during the course of this project. To the present Co-ordinator of Geology Programme ATBU, Bauchi, Dr. S.S. Dada who kept reminding me that there is still some unfinished business and even lent a helping hand to me in teaching some of my courses, I am very grateful to you.

To my colleagues and friends especially Messrs O.K. Likkason, C.E. Suh and W.A. Wudiri who contributed immensely to the success of this work, I want to say thank you. To others, Dr W.A Istifanus, S.L Kela, S.D Abdul, A. Tokan, J.A. Jatau, J.A. Egwurube, T. Age. My gratitude also goes to Barrister Luka Gwaza

Maza, the entire Ma-Billliyok Family and others too numerous to mention, I want to say thank you for your moral and financial assistance.

To Lambert Ochibe who helped with the drafting of some of the diagrams and Yakubu Hussaini who helped in digitising the aeromagnetic data, I say thank you.

To the World Bank Project Implementation Units of ATBU Bauchi and NUC Abuja who funded my 9 months stay in Canada I say thank you.

Abstract

A regional gravity survey of the Gongola Arm of the Benue Trough was carried out with the aim of determining structures of local and regional interest. A total number of 1005 detailed gravity stations and 95 base stations were occupied during the survey which took place in June/July 1992 and May/June 1994. Aeromagnetic data of the area was also digitised and the interpretation carried out alongside the gravity interpretation.

The results of the study indicate that the area is characterised by negative Bouguer anomalies that basically trend in the NE-SW direction and range in values between -75 to -10 mGal, with an average value of-42 mGal. The Free-Air anomalies in the area range between -10 to 45 mGal and generally suggest that the area is isostatically compensated. A first order polynomial was used to approximate the regional anomalies in the area. The results showed that the regional in the area is a plane dipping NNE-SSW at a rate of 0.04 mGal/ km, and range in value from -46 mGal in the eastern part of the area to -35 mGal in the western part. The residual gravity map of the Gongola arm of the upper Benue trough showed anomalies that range in value from -25 mGal to 20 mGal. A detailed interpretation of these gravity anomalies of the area is hereby presented along with the magnetic anomalies with the sole aim of determining the source, type and nature of the anomalies.

The total magnetic intensity composite map showed intensity values ranging from 7400 nT to 8100 nT, with a dynamic range of 700 nT. A major prominent lineament that trends NE-SW passing through the axis of the trough in the form of a continuous narrow belt that has an average width of about 25 km, and stretches for a

distance of over 250 km was observed in the area. This lineament is believed to be associated with the history of the trough and most probably a geosuture zone.

Two and Three-Dimensional modelling of the residual gravity and magnetic anomalies suggest that the structure of the area is that of a horst and graben, with the grabens being as large as 80 km in width and are filled with sediments that are up to 4.5 km thick. The interpretation of the residual gravity anomalies also showed that most of the positive anomalies are caused by basement uplift (horst): a reflection of the structure of the trough. Basic to ultrabasic rocks are also considered possible sources of the prominent positive residual anomalies. Models of the magnetic anomalies also suggested that these anomalies are caused by basic to ultrabasic bodies at depth in the area. Some of these bodies were seen to occur as deep as 8 km, while others occur at shallow depth at instances 1 km. The magnetic modelling results also suggest the existence of a geosuture zone in the area, which passes through the axis of the trough forming a continuous narrow belt and trending NE-SW direction. This geosuture zone stretches for a distance of about 250 km from around Wikki to Bajoga and beyond and has an average width of 25 km.

The crustal structure of the area of study suggests that the area has undergone crustal thinning (Moho uplift) of about 7 km, with the smallest crustal thickness not less than 27 km.

The general indications from the results of these interpretations is that the area is characterised by horst and graben structures, with associated magmatic intrusion at depth, thus suggesting that the area is a rifted structure.

TABLE OF CONTENTS

Chapter		page
	Tittle page	i
	Dedication	ii
	Declaration	iii
	Certification	iv
	Acknowledgements	v
	Abstract	viii
	Table of Contents	x
	List of Tables	xvi
	List of Figures	xvii
	List of Appendices	xxi
1	INTRODUCTION	1
1.1	The Benue Trough	1
1.2	Scope of The Present Work	4
1.3	Aims of the Study	6
2	REGIONAL GEOLOGY AND STRUCTURE	7
2.1	Introduction	7
2.2	The Basement Complex	7
2.3	The Major Structural Units	9
2.4	The Sedimentary Rocks	11
2.4.1	Lithostratigraphic units	12
	Rocks of the Albian and Older Age	12
	The Cenomanian-Turonian Rocks	14

	Coniacian, Senonian, Campanian and Maestricthtian Rocks	15
	Tertiary Rocks	16
2.5	Magmatism	16
2.5.1	Cretaceous magmatic activity	17
2.5.2	Tertiary volcanism	18
2.6	Structure and Tectonics	18
2.6.1	Transcontinental and Atlantic features	20
2.7	Economic Geology	22
2.8	Origin and the Evolution of the Benue Trough	27
2.8.1	The Rift Origin	28
2.8.2	The Strike Slip Tectonics	33
3	GEOLOGY OF THE AREA OF STUDY	37
3.1	Introduction	37
3.2	The Crystalline Basement	39
3.2.1	The Metasediments	39
3.2.2	The Older Granites	40
3.3	The Cretaceous Rocks	41
3.3.1	The Bima Sandstone	41
3.3.2	The Yolde Formation	43
3.3.3	The Pindiga Formation	44
3.3.4	The Gombe Sandstone	45
3.4	The Tertiary Kerri-Kerri Formation	45
3.5	The Biu Basalts	46

4	PREVIOUS GEOPHYSICAL INVESTIGATION IN THE BENUE TROUGH	48
4.0	Introduction	48
4.1	Gravity Studies	48
4.2	Magnetic Studies	54
4.3	Seismic Studies	59
4.4	Other Geophysical Studies in the Trough	59
5	DATA ACQUISITION AND PROCESSING	60
5.1	Gravity Measurement and Data Reduction	60
5.1.1	Fundamental Principle of Gravity Prospecting	60
5.1.2	Gravitational Acceleration	61
5.1.3	Application of Newton's Law to Gravity Exploration	61
5.1.4	Global Variation of Gravity Field	65
5.1.5	Instrumentation	67
5.2	The LaCoste and Romberg Gravity meter	69
5.2.1	Drift of Gravimeters	71
5.3	Gravity Data Collection	71
5.3.1	Adjustment for Drift	75
5.4	Determination of Elevation of Stations	77
5.5	Gravity Data Correction	77
5.5.1	Latitude Correction	79
5.5.2	Elevation Correction	79
	Free-Air Correction	80
	Bouguer Correction	81
5.5.3	Terrain Correction	82

5.6	Gravity Anomalies	85
5.6.1	Accuracy of the Bouguer gravity anomaly	87
5.7	Magnetic Data	90
5.7.1	Data Sources	90
5.7.2	Digitisation	91
5.7.3	Interpolation	91
5.7.4	Merging	92
6	INTERPRETATION OF GRAVITY DATA	94
6.1	Introduction	94
6.2	The Bouguer Anomaly Map and It's qualitative Interpretation	94
6.3	Regional- Residual separation	100
6.3.1	Concept of Polynomial Fit	103
6.4	The Regional Anomaly Map	105
6.5	The Residual Anomaly Map and It's qualitative Interpretation	107
6.6	Quantitative Interpretation of the Residual Anomalies	114
6.6.1	Introduction	114
6.6.2	Method of Interpretation	115
6.6.3	3-Dimensional Interpretation	115
	Model Fitting Procedure	116
6.6.4	3-Dimensional Interpretation of residual Anomalies	118
	Profile AA'	118
	Profile BB'	120
	Profile CC'	121

6.6.5	2-Dimensional Interpretation of Residual Anomalies	123
	Profile XX'	124
	Profile YY'	127
	Profile ZZ'	129
6.7	Crustal Structure of the Area of Study	132
7	INTERPRETATION OF AEROMAGNETIC DATA	138
7.1	Introduction	138
7.2	Qualitative Interpretation	139
7.3	Quantitative Interpretation	145
7.3.1	Introduction	145
7.3.2	Magnetic Depth Estimates	147
7.3.3	The Computational Method Used in this Work	149
7.3.4	Basic Theory of the Werner Deconvolution Technique	150
7.4	Interpretation Procedure	152
7.5	Estimation of Depth-to-magnetic Basement	155
7.6	3-Dimensional Interpretation of Magnetic Anomalies	161
7.6.1	The Interpretation	163
	Profile AA'	163
	Profile BB'	166
7.7	2-Dimensional Interpretation of Magnetic Anomalies	167
7.7.1	Profile XX'	170
7.7.2	Profile YY'	172
7.7.3	Profile ZZ'	174

8	DISCUSSION, DEDUCTION AND CONCLUSIONS	177
8.1	Correlation of Gravity and Magnetic Data Results	177
8.2	Discussion of Results and Deductions	179
8.2.1	Marginal Volcanism/Basic Intrusives	180
8.2.2	Dukku Sub Basin	183
8.2.3	A Geosuture within the Trough?	185
8.3	The Origin of the Benue Trough	195
8.4.2	On the Origin of the Gongola Arm of the Upper Benue Trough	196
8.5	Suggestion for future work	199
8.6	Conclusions	202
	REFERENCES	206
	APPENDIX A	217

LIST OF TABLES

Table		Page
2.1	Stratigraphic Sequence of the Lower-Middle-Upper Benue trough of Nigeria	13
3.2	Stratigraphic Succession of the Upper Benue Trough	42
5.3	Density values of rocks in the Gongola Arm of the Benue Trough	84
5.4	Generalised rock densities obtained in the Benue Trough	84

LIST OF FIGURES

Figure		Page
1.1	Location Map of The Benue Trough	2
1.2	Location Map of the area under study	5
2.1	Regional Geology Map of the Benue Trough of Nigeria	8
2.2	Minor Depositional basins of the Benue Trough	10
2.3	Equatorial fracture zone pattern for the Atlantic and Mid-Atlantic Ridge	21
2.4	Map of Economic Mineral Occurrences in the Benue trough	24
2.5	Map showing the Opening of the Atlantic at 90 Ma and at 60 Ma before present	34
2.6	Sketch of extensional features associated with a zone of transcurrent movement	36
3.1	Geologic map of the area under study	38
4.1	Bouguer Anomaly Map of the Benue Trough	50
4.2	Basement Isobaths Map of the Benue Trough	56
5.1	Sketch for determination of gravitational acceleration caused by irregular two dimensional sheet	62
5.2	Schematic representation of the operation of the Lacoste and Romberg gravimeter	62
5.3	Plot of Gravimeter and altimeters drift curves obtained over a period of 24 hrs	72
5.4	Map showing the distribution of Gravity Data Stations	74
5.5	Plot of Base tie for Old Post Office Gombe and Deba Junction	76
5.6	Plot of Heights above Mean Sea level for the area of study	78
5.7	Composite Magnetic Anomaly Map of the Gongola Arm of the Benue Trough of Nigeria	93

7.3	Composite Magnetic anomaly map of the Gongola arm of the Benue Trough of Nigeria showing location of Interpreted profiles (AA' and BB', XX', YY' and ZZ')	148
7.4	Typical plot of total field intensity along profiles AA' and BB'	153
7.5	Werner Plot for Profile AA'	156
7.6	Werner Plot for Profile BB'	157
7.7	A Werner Profile of AA' showing interpreted basement surface	159
7.8	A Werner Profile of BB' showing interpreted basement surface	160
7.9	Plan of the 3-dimensional model of bodies used for major anomalies interpreted	162
7.10	Cross Section of interpreted 3-Dimensional models for profile AA'	164
7.11	Cross Section of interpreted 3-Dimensional models for profile BB'	168
7.12	Typical plot of total field intensity along profiles XX', YY' and ZZ'	169
7.13	2-Dimensional Interpretation of profile XX'	171
7.14	2-Dimensional Interpretation of profile YY'	173
7.15	2-Dimensional Interpretation of profile ZZ'	175
8.1	Composite magnetic map of the area of study showing location of profiles RR', SS', and TT'	186
8.2	Plot of Werner profile interpreted for profile RR'	187
8.3	Plot of Werner profile interpreted for profile SS'	188
8.4	Plot of Werner profile interpreted for profile TT'	189
8.5	2-Dimensional Interpretation of magnetic anomalies along profile RR'	191
8.6	2-Dimensional Interpretation of magnetic anomalies along profile SS'	192

8.7 2-Dimensional Interpretation of magnetic anomalies along profile TT' 193

8.8 Sketch of the schematic geologic and tectonic history of the Benue Trough 200

LIST OF APPENDICES

Appendix		Page
A	Coefficients of polynomials by Least-squares method	217

CHAPTER 1

INTRODUCTION

1.1 The Benue Trough

The Benue Trough (Fig 1.1) is a linear rift structure whose development has been closely associated with the separation of Africa from South America and the opening of South Atlantic ocean. It is about 250 km wide in its southern portions where it includes the Anambra Basin, Abakaliki Anticlinorium and Afikpo syncline. Towards the Northeast, the width of the trough varies between 80 and 150 km, while its total length is about 1000 km.

The mechanism of the formation of the trough is controversial but most authors suggest that it is as a result of tension resulting in a rift (King, 1950; Cratchley and Jones, 1965) or a graben-like structure (Stonely, 1966). Burke *et al.* (1971) suggested the existence below the Niger delta and lower Benue trough of a spreading ridge active from Albian to Santonian. An unstable RRF triple junction model leading to plate dilation and opening of the Gulf of Guinea was proposed by Grant (1971). As for Burke and Dewey (1974) and Olade (1975), the Benue trough would be the third failed arm or the aulocogen of the three armed rift system related to development of hot spot.

The regional geologic character of the Central African Continent has been compared and correlated with that of Brazil. A number of great zones that intersect the Mid-Atlantic ridge have been mapped almost continuously from Africa to Brazil (Sibuet and Mascle, 1978).

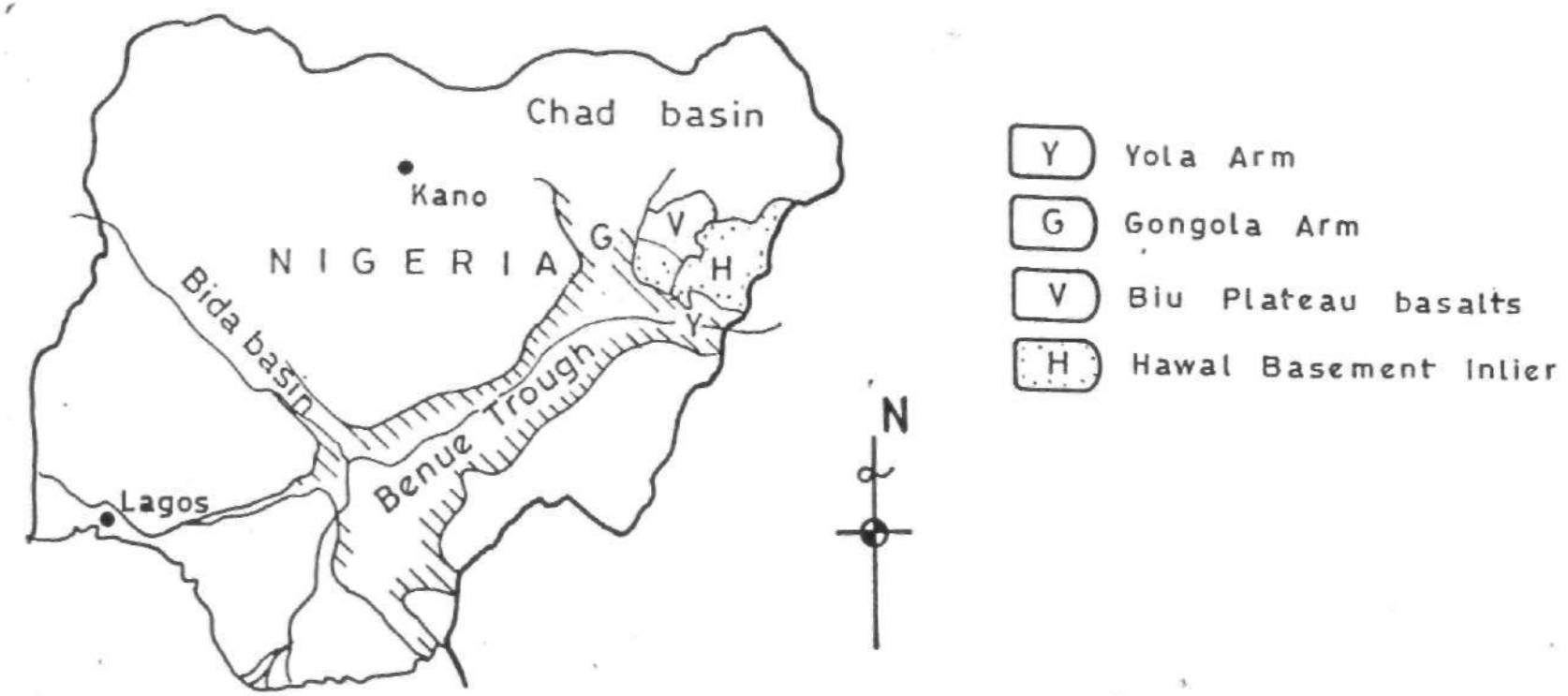


Fig 1.1 Location Map of The Benue Trough of Nigeria

The Benue trough is located along a transform direction extrapolated on to the continent from Charcot fracture zone Benkhelil *et al.* (1989). Ajakaiye *et al.* (1985) concluded from a series of ENE-WSW trending magnetic lineaments, which cut across the Crystalline Basement and Sedimentary cover, were representative of regional structural features. Elements of this system of lineaments correlate well with St. Paul's, Romanche, Chain, and Charcot fracture zones offshore West Africa. This apparent correlation is supported by geophysical studies such as gravity, controlled source seismic survey results and local seismicity data (Ajayi, 1979; Ajakaiye, 1985; Stuart *et al.*, 1985).

A succession of sediments that increases in depth from about 2.5 km in the Northeast to over 7 km in the Southwest (in the Anambra Basin) were deposited in the trough during the Cretaceous (Hoque and Nwajide, 1984). The sediments consist dominantly of mudrocks and sandstone with occurrences of carbonates and coal and were intruded by igneous rocks of intermediate to basic composition at several places.

There exists a widespread igneous activity near the West African craton margin, and most with a pronounced calc-alkaline affinity. Such activity is observed in the Nigerian granitic ring complexes, the Cameroon volcanic chain and the young igneous rocks associated with the Benue trough. Sykes in 1978 suggested that Nigerian basement rocks may reflect an early stage of rifting between Africa and South America that preceded the development of oceanic crust by a few million years. Such an episode of continental rifting according to Sykes (1978) is common prior to the development of oceanic crust in many areas around the world.

On the opposite shore of the Atlantic, there exist young igneous rocks near the continental margin of Brazil (Sykes, 1978). These rocks post-date the separation of South America and Africa near the east coast of Brazil and Uruguay. Marked geologic features occur along the inferred westward extensions of St. Paul's, Romanche, Chain

and Charcot fracture zones. The St. Paul's fracture zone extends beneath the thick sediments of continental shelf close to the mouth of the Amazon. There is a tentative correlation between the Romanche fracture zone and a zone of flexure (horst and grabens) beneath the continental shelf. Alkaline rocks are believed to exist near the end of either the Chain or Charcot fracture zone. There also exist a Complex of extrusive and intrusive rocks found in the Cabo area which are situated approximately in the line with the Cameroon Volcanic line of Africa in a Pangeatic reconstruction.

In a predrift reconstruction of South Africa and Brazil, a number of major structural features appear continuous across their boundaries. For example, a lineament in Brazil (as its counterpart in Africa near Accra) separates Pan-African aged rocks to the north from more than 2000 Ma old rocks to the south. Inferred mineral deposits are localised along these lineaments in both Brazil and Southwest Africa.

Evidently both Africa and South America possesses processes such as volcanism, igneous, and major faulting with intermittent uplift. These can be correlated between Africa and South America and are characteristic of a rift valley setting (Sibuet and Mascle, 1978)

1.2 Scope of the Present Study

The present study covers an area between latitudes' 9^{o} $45^{'}$ N and latitude's 11^{o} 00' N and Longitudes 9^{o} $45^{'}$E to 13^{o} 00' E, extending over an area approximately 49, 000 km^2 (Fig. 1.2).

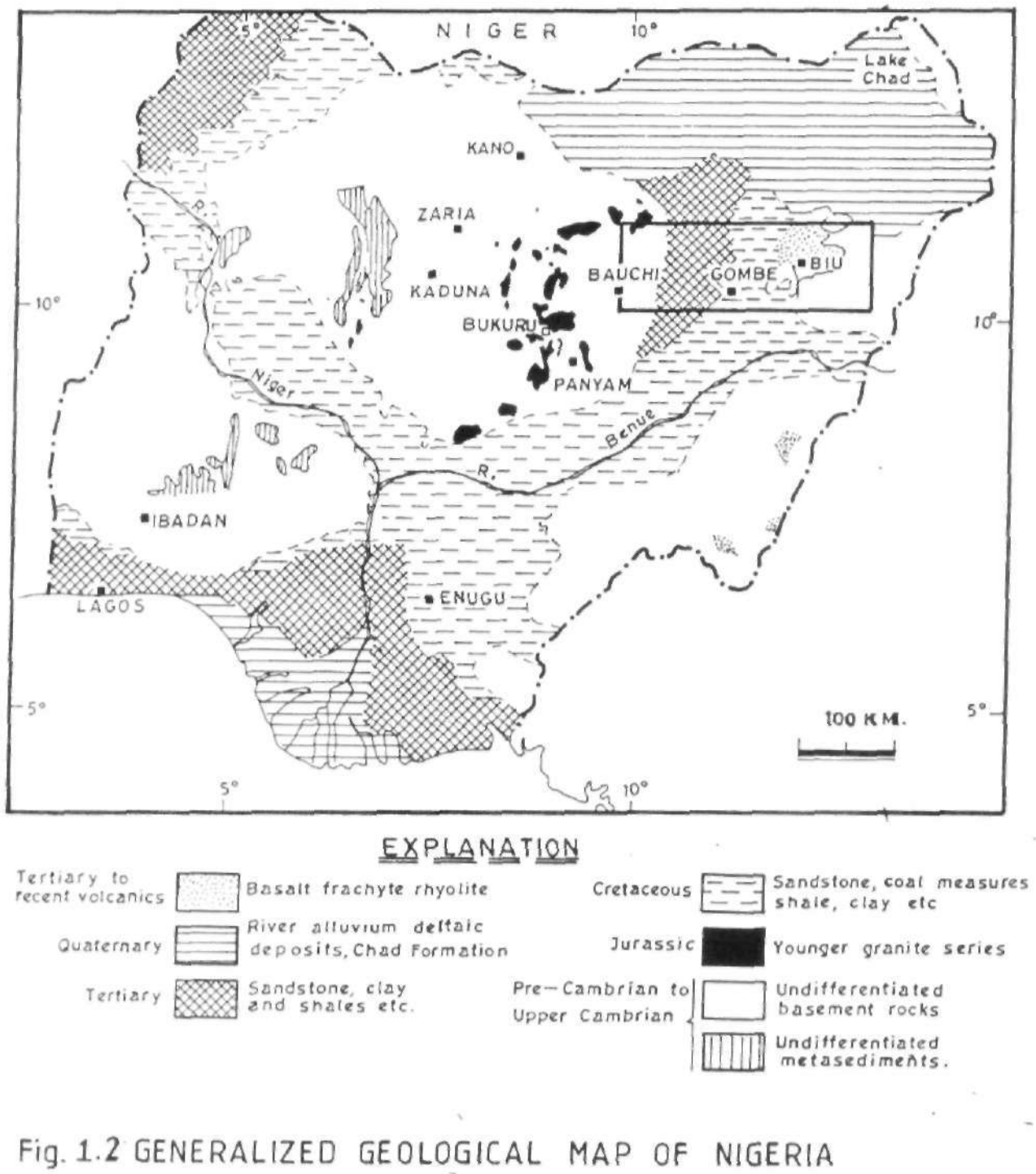


Fig. 1.2 GENERALIZED GEOLOGICAL MAP OF NIGERIA

(Inset rectangle indicates area of study)

Gravity data were collected at 3 km intervals along all major and accessible roads in the area, resulting in 1005 detailed and 95 base gravity data stations. Aeromagnetic maps of the area were also digitised at 3 km intervals for this study. The Geologic map of the area was digitised and analysed for integrated interpretation of the data.

1.3 Aims of the Study

- Defining structures of regional and local interest in the area
- Estimate thickness of sediments in the area.
- Examine the nature and structure of the area of study.
- Examine depths to suspected Igneous intrusive bodies in the area (if any).

CHAPTER 2

REGIONAL GEOLOGY AND STRUCTURE

2.1 Introduction

The Benue Trough contains some of the more interesting and diverse geology in Nigeria. It's Stratigraphy, Volcanism and regional geologic structures combine to form a framework of local and global proportions centred on Nigeria.

References to geologic formations are based primarily on the divisions used in the published 1:2,000,000 scale geologic map by the Geological Survey of Nigeria (GSN) (1984) and other divisions established by researchers in the trough. Large proportions of geologic contacts are approximated or inferred because of poor outcrop exposures in the region (fig. 2.1).

2.2 The Basement Complex

The Basement Complex belongs to the mobile Belt of West Africa, which has undergone intense deformation, including metamorphism and granitisation during the Pan African thermo-tectonic event about 550 ±100 Ma (Benkhelil, 1988). The major rocks of this unit are migmatites, granites and a metasedimentary group (schist belt) located in the Western and North-western part of the Nigerian Shield (McCurry, 1971;

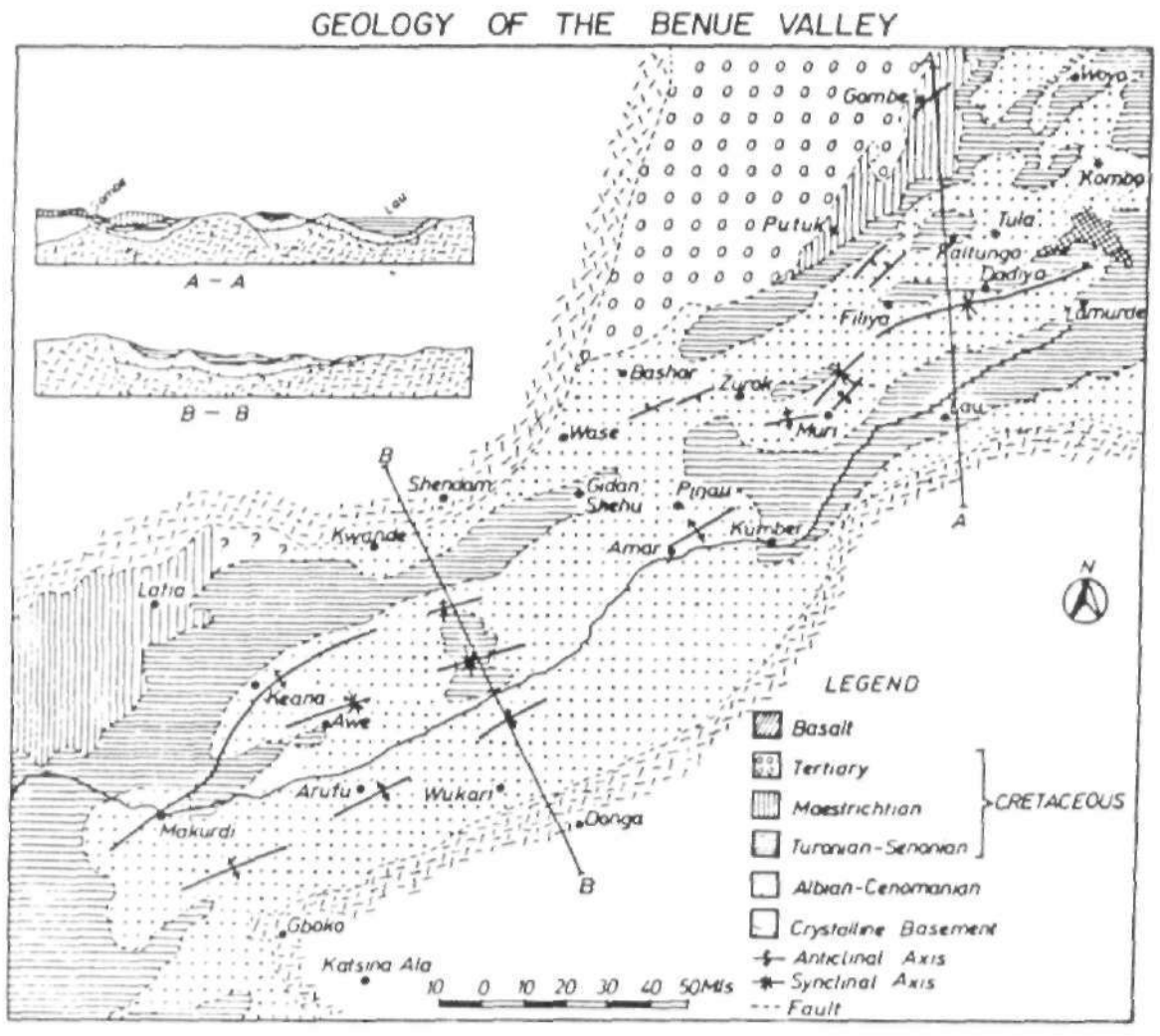


Fig. 2.1 Geological Map of the Benue Valley (after Cratchley and Jones, 1965)

McCurry and Wright, 1971; Burke *et al.*, 1971; Holt *et al.*, 1978). These basement rocks are intruded by granitic ring complexes (Younger Granites) which form a N-S trending belt centred around the Jos Plateau (Fig. 1.2), and continues northwards to the Air region in Niger Republic. These Younger Granites are of Jurassic age (from 141 to 218 Ma) and become younger Southwards (Van Breemen *et al.*, 1975). The granite ring complexes with their associated rhyolites were intruded into uplifted zones and are related to Cauldron Subsidence (Turner and Bowden, 1979).

2.3 The Major Structural Units.

Although the Benue Trough is continuous for more than 800 km, it can be subdivided into different units based on stratigraphic and tectonic considerations (Fig. 2.2). The southern portion (Lower Benue Trough) includes two main units; The Abakaliki Uplift or Anticlinorium and the Anambra basin (Onitsha Basin). The Abakaliki Anticlinorium consists of tightly folded Cretaceous sediments intruded by numerous magmatic rocks (Nwachukwu, 1972). It stretches for about 250 km from the Niger delta to the Gboko-Ogoja area in a N50^{o}E direction (Benkhelil, 1988). It is flanked to the north by the vast synclinorial structure of the Anambra basin, which trends in a N30^{o}E direction.

This basin consists of a thick sequence of undeformed Cretaceous series. The Abakaliki Anticlinorium is flanked southward by the Afikpo syncline and by a narrow strip of undeformed sediments resting on the Basement complex in Ogoja area. On the

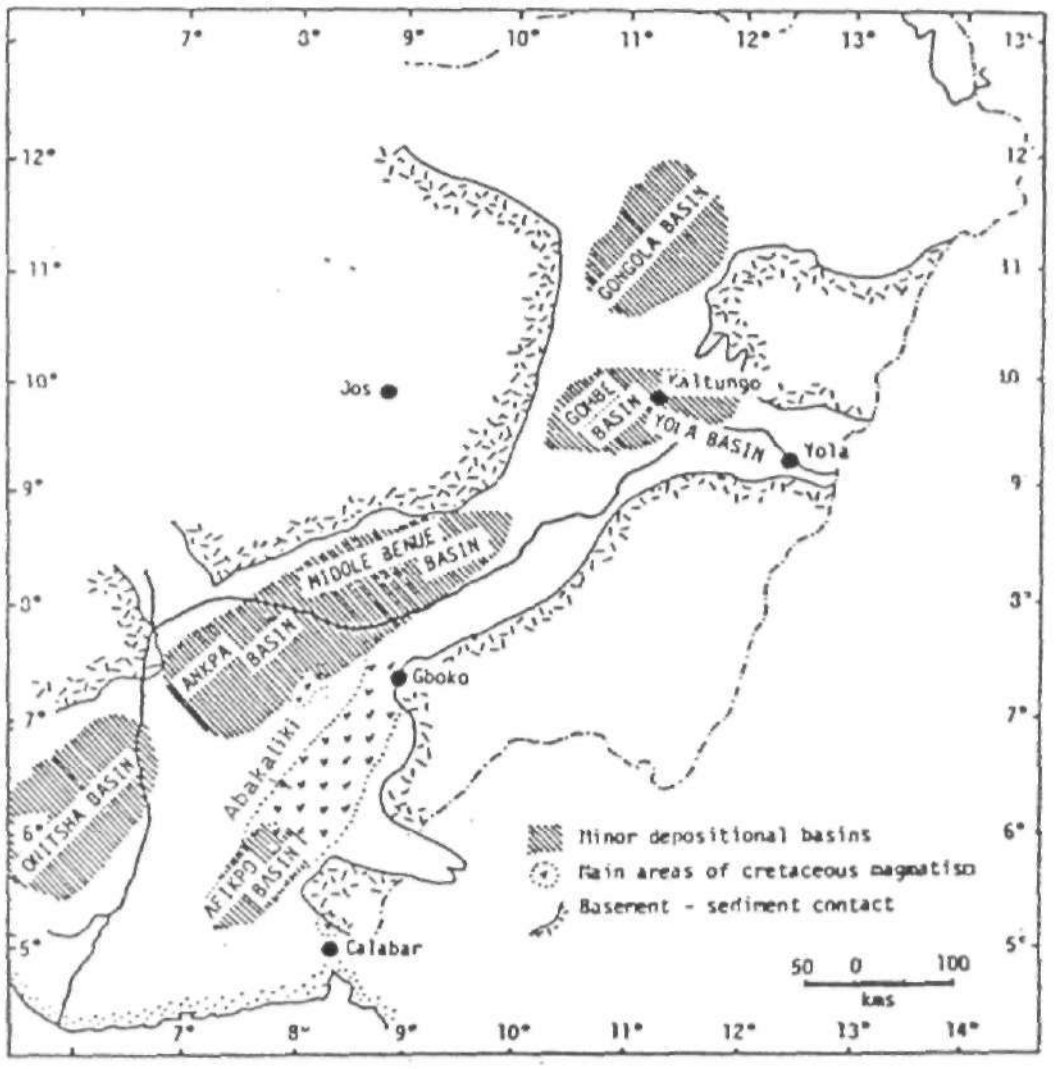


Fig. 2.2 Minor Depositional basins of the Benue Trough (after Adighije 1981)

northern margin of the Anambra Basin we have the Ankpa basin that stretches along a NE-SW trend and consists of Post Santonian flat lying sediments.

The middle Benue Trough occupies the linear portion of the trough. A major Structural element of this part of the Benue trough is the Keana Anticline (fig. 2.1) consisting of Albian rocks. It is flanked to the North by a deep Basin known as the Kadarko basin (Ajayi and Ajakaiye, 1981;1986; Benkhelil, 1986) and southwards by Wukari Basin (Saugy, 1987), both of them showing evidence of slight deformation.

The Upper Benue Trough is much more complex and characterised by cover tectonics (Benkhelil, 1988). It can be subdivided into several smaller units; The Kaltungo Inlier, formed by a Horst of Basement rocks and separates the Dadiya-Lau domain, situated to the south and formed by long gentle folds in the Cretaceous, from Pindiga-Gombe basin (Benkhelil, 1988), which shows evidence of being slightly tectonised. On the north-western side of the Kaltungo Inlier are small basement ridges; Zambuk and Gombe ridge separating small deep basins. The Gongola and Yola arms are digitations of the Benue Trough and present a similar tectonic style. On the north-western margin of the Upper Benue Trough, lies the Palaeocene flat-lying Kerri-Kerri basin that rest unconformably upon the folded Cretaceous rocks.

2.4 The Sedimentary Rocks

The first depression, which was most likely formed about 110 Ma, were probably filled with Continental type deposits that presently lie below several

thousands of meters of Upper Cretaceous rocks. As a result of these rocks being at great depth (of about 3000 m) and not visible at the surface, they are not well documented, and the oldest series presently visible is the upper Aptian/Albian, by which time the trough was already formed.

2.4.1 Lithostratigraphic units.

The sedimentary in filling of the Benue Trough includes a thick sequence that ranges in age from Aptian - Albian to the Maestrichtian (Carter *et al.*, 1963). The Tertiary sediments in the trough are restricted to the Kerri-Kerri Basin. Facies and thickness change rapidly from Southwest to Northwest. Table 2.1 gives the stratigraphic sequence of the Lower-Middle-Upper Benue Trough and their details are as discussed below.

Rocks of Albian and Older Age: The oldest sedimentary rocks recognised in the Benue trough occur in the core of the Lamurde Anticline (fig. 2.1) in the Upper Benue Trough and they constitute the lower part of the Bima Sandstone.

The terranes of Albian age are well developed throughout the trough. They generally outcrop in the core of the main anticline structures (Abakaliki Anticlinorium of the lower Benue Trough), Albian rocks are represented by the Asu River Group, which consists of alternating shales and siltstone with occurrences of sandstone

Age		Anambra basin	Lower Benue-Middle Benue		Upper Benue Basin		
					Dadiya-Numanha	Zambuk-Gulani	Gombe-Pindiga
Palaeocene and Younger		Imo Formation	Volcanics		Lamja sandstones	Numanha sandstones	Kerri-Kerri Fm.
Maastrichtian		Nsukka Formation Ajali Sandstone Mamu Formation Nkporo Formation	Lafia Formation				Pindiga Formation / Gombe sandstones
Senonian	Campanian				Numanha shales Sekule Fm.		
	Santonian						
	Coniacian	Agwu Formation	Awgu Formation				
Turonian Upper Middle Lower		Eze-Aku Formation	Eze-Aku Fm.	Makurdi Fm Keana Fm. Awe Fm	Jessu Formation Dukul Fm.		
Cenomanian		Asu River Group: Okposi Fm. Sandstone and shale	Asu River Group		Yolde Fm. Bima sandstones	Bima sandstones	Yolde Fm Bima sandstones
Mid-Late Albian		Asu River Group: Abakaliki Shales					
Pre-Cambrian		Basement Complex					

..... Unconformity

Table 2.1 Stratigraphic sequence of the Lower-Middle-Upper Benue Basins

(Simpson, 1954). The maximum thickness of this formation is 1500 m (Shell, 1957). In the Middle Benue, the Albian stage is also represented by the Asu River Group and its lateral equivalents and it is overlain by the Awe Formation. The thickness of this Formation was estimated near Keana by Offodile (1976) as 3000 m. The Awe Formation (Offodile and Reyment, 1976) is formed by medium to coarse-grained sandstone alternating with carbonaceous shales. It is about 1000 m thick at the type locality (Offodile, 1976).

In the Upper Benue Trough, the Bima sandstone is a thick, Albian, clastic series subdivided into three main suites. The Lower Bima that is exclusively found in the core of the Lamurde Anticline, comprises 400 m of red purple clays with occurrences of fine to medium-grained feldspathic sandstone. The lower unit contains palymorps which are indicative of an Upper Aptian Age (Allix *et al.*, 1981).

The lowest Marine levels of the overlying Yolde Formation are Lower Turonian in age. The middle Bima comprises of coarse-grained feldspathic sandstone varying in thickness from 300 m to 1200 m. The Upper Bima is widespread and may attain more than 1700 m in thickness (Benkhelil, 1989)

The Cenomanian-Turonian Rocks: Cenomanian rocks in the trough includes the Odukpani Formation on the Calabar Flank, a consequence of fossiliferous shales, sandy shales, sandstone and limestone with a coarse basal sandstone which unconformably overly the basement. In the Middle Benue Trough, the Awe Formations may be partly Cenomanian. Cenomanian rocks on the other hand have not been

formally recognised in the Upper Benue Trough. However they may include the upper most part of the Bima Formation (Benkhelil, 1988).

The Turonian rocks consist of fossiliferous marine series all over the Benue Trough (Dessauvagie, 1975). It is marked by the Ezeaku Formation, which consists of hard grey and black calcareous shale, limestone and siltstone; Makurdi sandstone at Makurdi. This formation varies in thickness up to 1200 m (Dessauvagie, 1975).

In the Upper Benue Trough the Yolde Formation and part of the Pindiga Formation represent the Turonian. The Yolde consists of a variable sequence of thinly bedded sandstone. sandy mudstones and Shelly limestone. The Pindiga formation is a thick shale sequence with intercalation of fossiliferous limestone and some siltstone.

Coniacian, Senonian, Campanian and Maestritchtian rocks: In the Lower Benue Trough, the upper part of the Awgu shale has been identified as Coniacian in age (Hoque and Nwajide, 1984). The Senonian (or Campanian) to Maestritchtian are represented by the Nkporo shale (Enugu shale), a sequence of bluish to dark grey shale and mudstone with local sandy shale with a total thickness estimated to be about 1000 m (Hoque and Nwajide, 1984).

No post-Santonian sediments are known in the Middle Benue Trough, except for the Late-Santonian Lafia formation of coarse to fine-grained sandstone, which is 50 - 1000 m thick (Offodile, 1976). In the Upper Benue Trough, the Senonian stage is entirely represented by the Pindiga Formation. It is a thick shally sequence with basal

limestone overlain by the Gombe Sandstone, a unit that includes sandstone, siltstones with intercalated shale and locally thin coal seams. An Upper Maestritchtian age has been attributed to this formation based on palymorphs (Lawal, 1979).

Tertiary rocks: The Benue Trough was completely emergent at the end of Cretaceous; thus Tertiary sediments are restricted to the Niger delta, the Kerri- Kerri Basin and the south-western Anambra Basin. In the Anambra Basin, a 1000 m thick sequence of shales with sandstone intercalation forms the Imo Shale (Benkhelil, 1989). In the Northeast, the Palaeocene Kerri-Kerri Formation is composed of sandstone, siltstone (locally ferruginous) and clays. The thickness varies from a few meters to 300 m (Adegoke *et al.*, 1978).

2.5 Magmatism

Cretaceous igneous rocks are rare in most parts of the Benue Trough, except in the Abakaliki Trough where they are abundant and varied. During the Tertiary however volcanic rocks (mainly basaltic) were emplaced in the trough with a higher concentration in the Northeast.

2.5.1 Cretaceous magmatic activity

Magmatic activity took place contemporaneously with the opening and in filling of the Benue Trough. Traces of this activity are scarce in the Upper Benue Trough but are particularly abundant in the Workum Hills of Abakaliki area (Benkhelil,

1989). In the Lower Benue Trough, particularly the Workum Hills, various modes of occurrences have been recorded. Intrusive bodies, dykes, lava flows mixed with breccia and tuffs are mainly restricted to the Albian sediments. Fine-grained hypabbysal rocks are dominant but the main occurrence is a 2km circular body of coarse grained nepheline syenite (Wanakande syenite) (Benkhelil, 1989). Basaltic dykes and lava flows are abundant and interbedded with sedimentary rocks. The volcanism also provides micro-conglomerates with basalt pebbles micro-breccia of volcanic rocks and thin bedded tuffs.

Except for the Abakaliki area, few data are available on the nature of the magmatism. Occurrences in the Northeast are mainly lava flows and tuffs interbedded in the Lower Bima near the main fault zones, from where they were extruded (Carter *et al.*, 1963; Popoff *et al.*, 1982). The main rock type is the basalt with transitional affinities (Popoff *et al.*, 1982). A volcanic complex (Burashika Complex) intruding the basement rocks includes rhyolites andesites and some basaltic flows (Popoff *et al.*, 1982).

2.5.2 Tertiary volcanism

Tertiary regional magmatic activity was largely concentrated in eastern Nigeria Abakaliki area). Volcanic activity was particularly intensive in the Upper Benue Trough, where more than 500 necks are reported (Benkhelil, 1986). Extensive lava flows have formed the Biu and Longuda Plateau. Alkali olivine basalt is the dominant rock type while trachytes and phonolites occur locally (Wright, 1976b) The age of

emplacement of these rocks ranges from 22 to 2 Ma with two main periods; 22-11 Ma for the trachyte-phonolite suite, and 7-2 Ma for the basalt. Olivine basalt dated as 41 Ma and 30 Ma occur near Bashar, between the Middle and Upper Benue Trough (Benkhelil, 1986).

The distribution of the volcanic plugs and cones shows some striking relationships with the structural grain of the region (Carter *et al.*, 1963). East of the Gongola River is a clear N-S alignment of volcanic vents (Biu Plateau). This N-S trend is consistent with the Tertiary structures resulting from an E-W extension. On the west of the Gongola River, the Volcanic plugs show alignments following the older structural trends, mainly N60^{0}E and N140^{0}E (Benkhelil, 1989).

2.6 Structure and Tectonics

The dominant structural features of the Benue Trough are remarkably long and narrow fold patterns caused by tectonic activity during the Cretaceous. These features are reflected by the shape and distribution of the depositional basins within the trough (Fig. 2.2). In the Southwest, strata have been folded gently along a predominantly ENE-WSW horizontal axes. These same strata display uplift and intense folding south of the Abakaliki area (fig. 2.2). Cratchley and Jones (1965) identified two episodes of folding of the Cretaceous sediments in the Southeast; one at the end of the Albian, and the other sometimes during the Santonian. Olade (1975) recognised the same two episodes, but places the first in Cenomanian, and the second sometime during the Senonian.

The Late Albian-Cenomanian folding episode coincides with the Cenomanian regression and the end of the first sedimentary cycle. The Santonian is regarded as marking the first major episode of folding (Wright, 1976a; Burke and Dewey, 1974), and probably coincides with the Senonian regression.

A third episode of folding is known to have taken place in the north-eastern part of the Benue (Cratchley and Jones, 1965). The age of this episode is put as post - Maestritchtian, and sometime following extensive Maestritchtian transgression that reached as far as middle Niger delta A notable display of this episodic folding occurs in sediments located in the Northeast (Upper Benue), they are folded once, gently and uniformly (Benkhelil, 1986). The sediments to the Southeast (lower Benue) are folded twice, and more intensely deformed. Carter *et al.*, (1963) reported a localised occurrence of six steeply dipping anticlines that trend north-eastwards *en-echelon* in the Upper Benue valley.

The faults within the Benue trough appear closely related to folding, especially in the Middle Benue (Carter *et al.*, 1963). Faults in this area generally strike N-S but trend *en-echelon* NE-SW in groups. Benkhelil (1986) suggested that this arrangement is due to sinistral lateral movement along a more regional trending NE-SW fault system. The N-S faults presumably made way for subsequent metallic mineralisation via fracture in-filling.

Tensional faulting is present in the sediments flanking the basement (*Carter et al.,* 1963) and within the crystalline rocks. The faults strike approximately at right angles to the basement boundary, and radially around the crystalline rocks. These faults likely represent adjustment to folding stresses.

2.6.1 Transcontinental and Atlantic features

Sibuet and Mascle (1978) identified and traced equatorial fracture zones in the gulf of Guinea using Magnetic, Gravity, and Seismic data. The St. Paul's, Romanche, Chain, Charcot, and the Ascension fracture zone were included among those that may clearly be traced across the Atlantic to offshore Brazil (Fig. 2.3). Major geologic features such as volcanic activity almost invariably occur near the ends of these oceanic fractures as noted by Sykes (1978).

The existence of a major transcontinental shear was described by Neev (1977) and named the Pelusium Line. The Pelusium Line forms an arcuate shear from Anatolia (in Turkey) through the eastern Mediterranean, Africa and the Equatorial fracture zones, to off the coast of northern Brazil and into the Amazon Basin. A more detailed investigation of the Pelusium Line by use of LANSAT images (Neev *et al.,* 1982) determined the existence of lineament swarms associated with the Pelusium Line.

The structural bounds of the trough have been correlated with the onshore extensions of the Charcot oceanic fracture zones by means of Aeromagnetic data

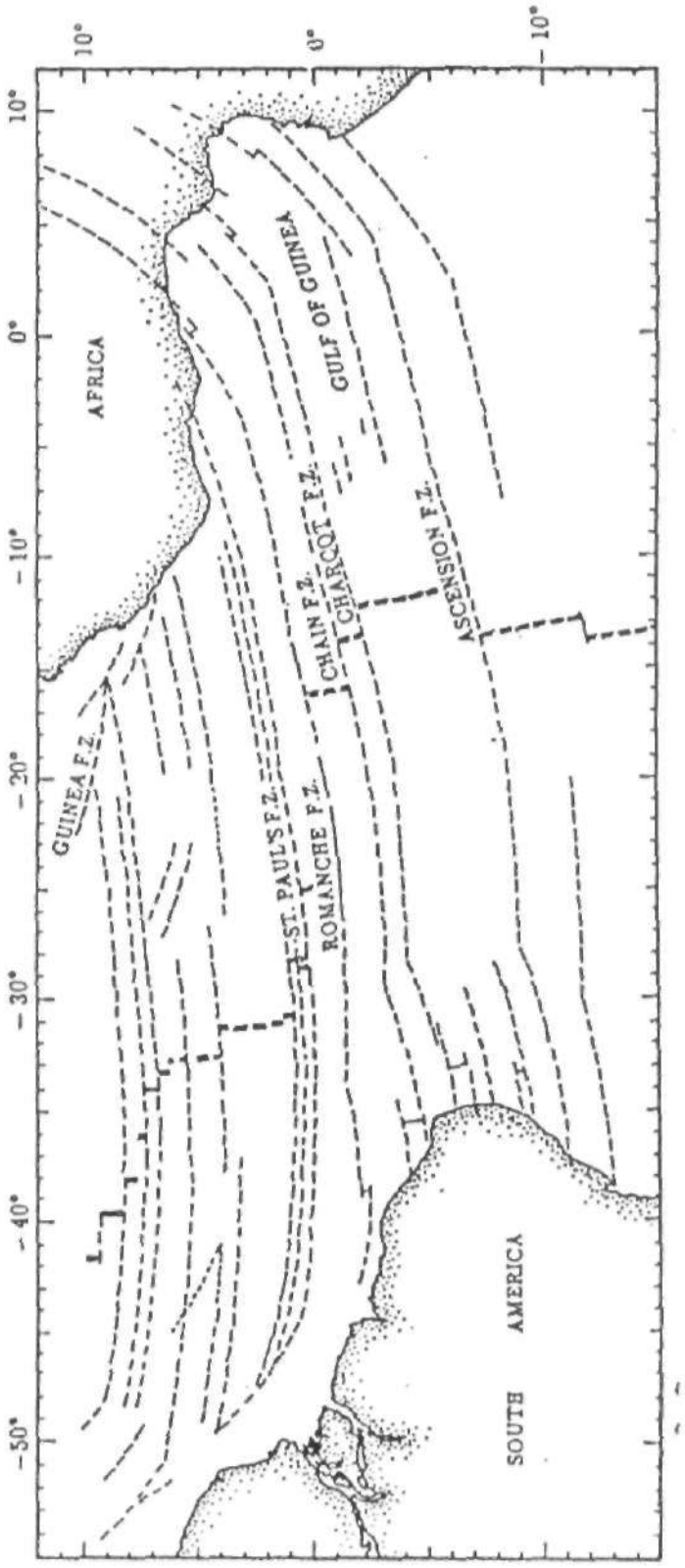


Fig. 2.3 Equitorial fracture zone pattern (dashed lines) for the Atlantic and Mid-Atlantic Ridge is shown as double dashed line (After Sibuet and Mascle 1978)

(Ajakaiye *et al.*, 1986). The St. Paul's and Romanche fracture zones, when extrapolated onto the continent, correlate with other continental features such as NE-SW trending zones of major faulting, extensive Volcanism (Jos Plateau) and metasedimentary belts.

An important point of note is that the Benue Trough and it's associated structures are in some manner linked to the Equatorial fracture zones, and ultimately a portion of the Pelusium line. The Benue trough, therefore, has some importance as a feature of global proportions.

2.7 Economic Geology

The potential of the Benue Trough for sources of mineral raw materials of economic significance is related to it's origin and structure. Deposits of limestone, brick and fire clay, construction stone, laterite and coal, all of commercial importance exist and some are being worked. Lignite is found to occur with the highest rocks of the stratigraphic sequence at the seaward end of the trough. Significant occurrences of base - metal sulphide (lead and zinc with smaller amounts of copper) cadmium and silver, and the associated mineral barytes are known to occur in the Trough. There is a very high potential of finding large quantity low grade base metals, as well as large potential for glass sands and mineral (juvenile water) in the trough. Fig. 2.4 shows the economic mineral occurrences of the Benue Trough.

The mineral resources of the Trough can be broadly classified as follows:

Metalliferous: This group includes detrital ironstone found on the Udi Plateau, west of Enugu, sulphides of zinc and lead found around Ishiagu-Abakaliki-Agbaja in the Abakaliki Anticlinorium, Akwana-Arufu, and from Wase through Zurak to Gwana in the Middle Benue Trough. Other metals include cadmium and silver which generally occurs in association with Pb-Zn. Gold has been recovered in very small amounts during concentration of cassiterite by gravity in the area north of the Middle Benue Trough, and may also occur in the basement rocks to the south and east (Ford, 1981).

Energy Resources: These include coal, lignite, oil and natural gas. Coal is found at Obwetti, Iva, Okpara, Ribadu, Prison Creek, First Hill, Palm Valley and Oyeama all in the Lower Benue Trough. Coal is also found at Okaba Ogbayoga, Orukpa Ezimo also in the lower parts of the trough. In the Middle part of the Trough coal is found in the Lafia-Obi area (Doma coal field). Coal occurs in Gombe area in the Upper Benue Trough.

Lignite deposits are found in a formation of early Tertiary age between the Anambra Basin and the recent Niger delta

Exploration for hydrocarbons is now being intensified in the trough especially in the Upper Part (The Gongola Arm). To date, oil production in exploratory wells is largely limited to the coastal areas in the Gulf of Guinea, especially in and about the Niger delta. Some production wells are located inland around the Calabar, Enugu, and Antui, as well as several dry wells as exploration efforts move up the Benue Trough.

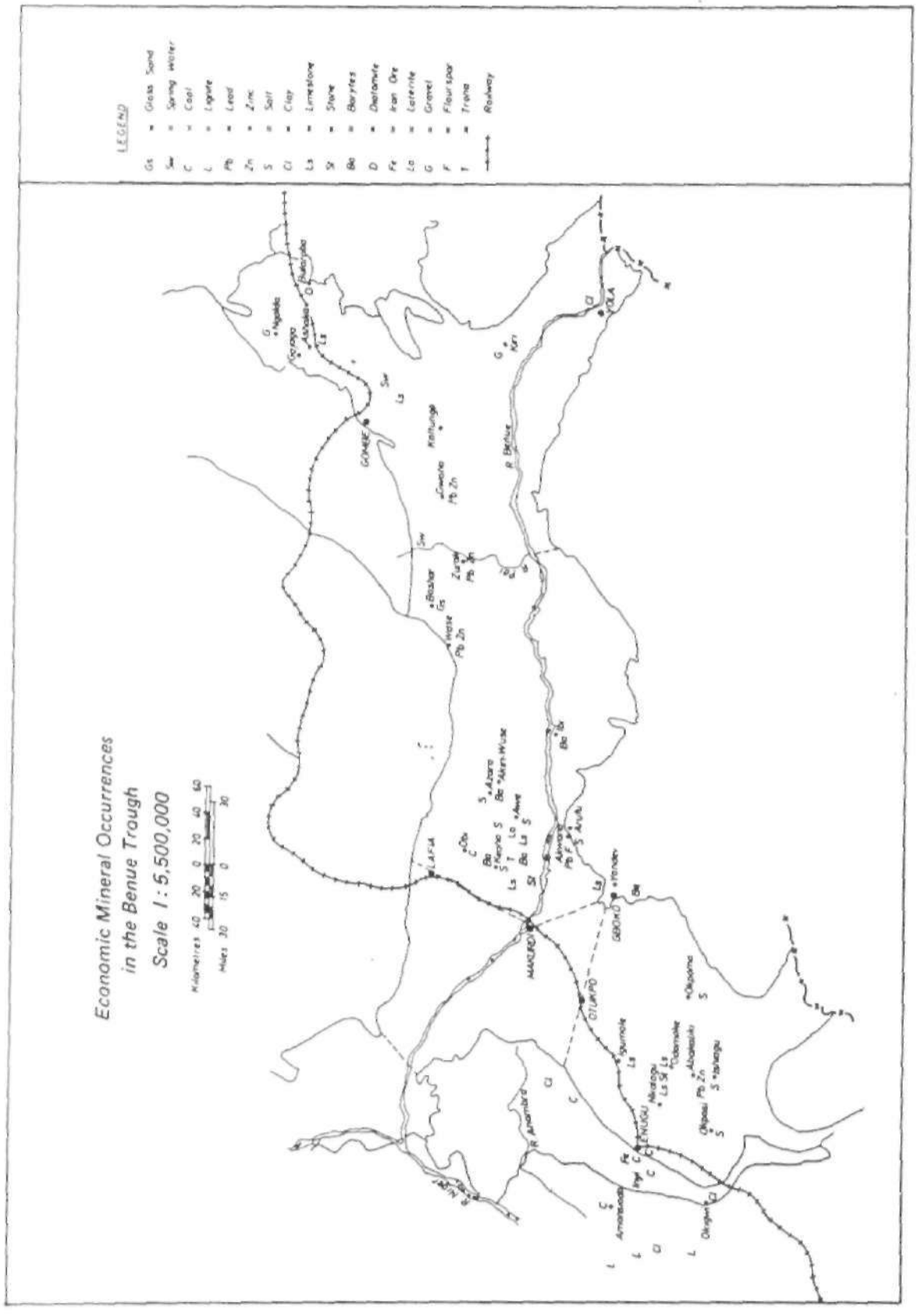


Fig. 2.4 Economic Mineral Occurrences in the Benue Trough (After Ford, 1981)

Industrial Minerals: Bulk raw materials such as stone aggregates, gravel, sand, clay, limestone, and laterite are all found in the trough.

Limestone occurs most abundantly in the Agwu-Ndeaboh shale Group and is the major raw material for the Nkalagu Cement Company. There are also extensive limestone outcrops at Igumale and Yandev near Gboko. The one at Gboko is currently serving the Benue Cement Company (BCC). In the Upper part of the Trough, limestone occurs extensively at and around Ashaka where it is currently used as for the manufacture of cement by Ashaka Cement Company. Other deposits occur elsewhere in the Trough.

Laterite occurrences are extensive in the Trough, and has been used extensively for road and building foundations.

In the central (axial) zone of the Middle Benue trough there are numerous veins and lodes predominantly consisting of barytes. The area encompasses Keana, Azara, Ibi, and Gbande. Fluorspar has been found to occur with galena in the absence of Zinc lodes at Arufu and Akwana.

A massive white sandstone outcrops at Bashar in the Middle Benue. Beds of compact coarse arkosic grit that are locally used for producing grinding and sharpening stones outcrops in the Makurdi Sandstone. Fine clay is found below the coal seams in the Lower Coal Measures at Enugu, this clay appears suitable for several types of ceramic ware. Diatomite occurs at the extreme northern end of the upper Benue in the

form of local lake deposits of Pleistocene age in a small depression in the surface of the Cretaceous Sediments at Bularaba.

Chemical Minerals: These are rock salt, salt water, trona and sulphur.

Numerous springs (freshwater and/or saltsprings) are found along the entire length of the Trough and many of them contain noticeable quantities of dissolved salts of which the highest concentration is sodium chloride. Salt springs have been mapped south of Makurdi, while in the area from Keana to Akiri-Wusi and across the river Benue to Akwana (Fig. 2.4) every village has a thriving salt industry. Salt springs have also been recorded near the western ends of the Lamurde anticline and the Kaltungo inlier.

Trona has been reported from a salt-water spring near the Crest of the Keana anticline, a few km south of Keana.

Sulphur is seen to occur as a constituent of pyrite and marcasite which accompany base metal sulphides.

Water: This is classified as Surface Water, Ground Water of Meteoric Origin and Mineral Water of Juvenile Origin.

Most of the rivers and large streams in the Benue Valley are perennial, but flow is greatly diminished during the dry season. These rivers and streams can supply water for domestic, or industrial needs or for irrigation.

Groundwater wells are widely used in the villages and towns for domestic water supply. These wells generally prove to be adequate for purely local needs. Recent hydrogeological investigations undertaken (by Some State Governments) with the aim of improving water supply to the towns and villages has given encouraging indications in the areas of large sandstone outcrops. Artesian water has also been reported at Oji, between Enugu and Onitsha in the Anambra Basin as early as 1912, and good flows have been obtained by pumping from boreholes in the Kerri-Kerri and Bima Sandstone in recent years.

Water from springs associated with Open fissures and Faults, which is frequently warm is used in many cases as a perennial and reliable source of water supply by the local population. Quite a number of these springs now serve as an acceptable source of mineral water for table use (e.g. Yankari-Diamare Spring water tapped from the Wikki warm spring in the Kerri-Kerri formation).

2.8 Origin and Evolution of The Benue Trough

The origin of the Benue trough has been a subject of discussion and speculation for the past 40 years. When one takes a quick look at the Trough there is the tendency for one to conclude that it is an aborted rift structure, but the interesting

thing is the absence of rift faults at the margins of the trough and a generalised folding of the Cretaceous sediments. Most authors, however do support the rift concept as the mechanism responsible for the evolution of the trough, although they differ as to whether it is an RRR or RRF. Another group of authors (Benkhelil 1982,1986; Benkhelil and Robineau 1983; Popoff *et al.*, 1983; Benkhelil *et al.*, 1988; Maurin *et al.*, 1986;) do propose that the Trough is as a result of strike slip Tectonics.

2.8.1 The Rift concept.

Numerous researchers do support the hypotheses of a rifted origin for the Benue Trough (e.g. King, 1950; Carter *et al.*, 1963; Cratchley and Jones, 1965; Kennedy, 1965; Wright, 1968; Olade, 1975; Fitton, 1980; Ajayi and Ajakaiye 1981; Fitton 1983; Fairhead 1988; Fairhead and Green 1988). For this authors the R-R-R (Ridge-Ridge-Ridge) triple junction is the favoured tectonic origin. They however do not agree on the mechanisms of the rifting. Two general mechanisms are put forward by this authors plate tectonics generated and mantle plume or hot spot originated.

To be able to classify the Benue trough as rift or not there is the need to compare it with some well known rift systems such as the East African, the Rhine Graben, the Baikal rift and the Rio Grande rift. These rift systems are all associated with volcanism and regional uplift. Mareschal (1983), indicated the basic geophysical characteristics of a rift as having a thin crust, a low velocity and density upper mantle and higher than normal heat flow.

Geophysical studies have shown that the crust in the trough is indeed thinned (Cratchley and Jones, 1965; Adighije, 1979; Ajayi and Ajakaiye, 1981; Osazuwa *et al.*, 1981; Stuart *et al.*, 1985; Fairhead and Okereke 1987, 1990;) A low velocity and density upper mantle is inferred from gravity (Fairhead and Okereke 1987). There is the presence of warm springs within the trough thus suggesting the presence of heat flow. Based on these facts the Trough could be said to be a rift.

Gross similarities exist between the Benue trough (depicted as a failed arm or aulocogen structure) and the East African Rift (Red Sea - Gulf of Aden - Afar triple junction) and are quite striking. The patterns of the Gravity field of the Benue trough (a central high flanked on both sides lows) and the central Red Sea are very quite similar. Both areas display contemporaneous magmatism and Lead-Zinc mineralisation, attributable to a triple junction.

Wright (1976a) proposed a model addressing the plate tectonics concepts and outlined the history of the trough as follows:

- The Benue trough formed part of an R-R-R triple junction, the arms of which developed at different rates.

- Limited spreading beneath the Benue arm (no more than a few kilometres) ceased as soon the Northwest arm began, since the first major episode of folding is of Santonian age and is limited to the Southwest of the trough.

- A Maestritchtian transgression spread up the Benue trough and middle Niger valley was a result of further subsidence (perhaps due to renewed tensions in the trough).

- A less - intense Post- Maestritchtian (Santonian) folding affected all the sediments in trough and, as a result, the sediments in the Northeast (upper) portion of the trough are folded gently and uniformly while in the Southwest (lower) Benue the Santonian and the older sediments are folded twice, overlain by less deformed younger sediments, separated by an erosional unconformity.

- Uplift and erosion of the folded sediments in the Palaeocene gave rise to *molasses* accumulations in the northern part of the folded belt (Kerri-Kerri Formation of probable Palaeocene age).

- The Benue trough becomes once again a structural part of the Nigeria - Cameroon dome. Cenozoic alkaline-peralkaline volcanism occurred within and adjacent to the trough, lasting until Recent in some places.

A variation of the triple junction model is the R-R-F (Ridge - Ridge-Fault) triple junction (Wright, 1968; Grant, 1971; Le Pichon and Hayes, 1971; Burke *et al.*, 1971; Emery *et al.*, 1975; Benkhelil and Robineau, 1983).

There are deficiencies in the R-R-F and R-R-R models of lithospheric spreading. Both require approximately 30 Ma of active spreading (Albian through Santonian). Nwachukwu (1972) estimated that this will require about 160 km of new

oceanic crust generated in the Benue trough. Even accounting for the Crustal shortening due to folding, estimates of about 8 km (Wright, 1968) leaves a substantial amount of oceanic crust to be accounted for considering the 100 - 250 km width of the trough. Olade (1975) suggested the non existence of subduction zone beneath the trough due to lack of ophiolites, remnant oceanic crust and extensive calc-alkaline volcanics.

Early researchers (Burke *et al.,* 1971) contended that the different spreading rates between the northern and southern parts of the African continents set up stress patterns responsible for the structural evolution of the trough. During the early stages of separation, the southern portion of Africa would have moved with slightly greater speed, wedging the continent apart in the Benue are with great tensional stress. At a later stage, the two halves of Africa converged on the Gulf of Guinea, producing the compressional stresses required for the present structural patterns in the Benue area. The Cretaceous *quite magnetic zone* which bothers the North Atlantic is absent from the South Atlantic, supporting this two-stage development idea (Wright, 1968; Heirtzler and Hayes, 1967).

Olade (1975), Burke and Dewey (1974) suggested an alternative evolutionary model based on plume generated triple junctions. The sequence of the hypothesise as follows.

The R-R-R triple junction of the Benue trough arose from doming and rifting associated with the rise of a mantle plume beneath the present Niger delta.

- Limited outpouring of alkaline-mafic lava and volcaniclastics associated with the doming and rifting in the Benue trough are expressed in the Abakaliki Pyroclastics.

- Rifting within the Benue would then have soon ceased, followed by rapid subsidence and deposition. A temporary cessation of mantle upwelling could have caused folding of the Albian sediments through a process of subcrustal contraction.

- Upwelling resumed in Turonian times, and rifting occurred along the old lines of weakness

- Lastly, mantle upwelling ceased in the Santonian (or migrated west to beneath the present Cameroon line) and the Subsequent subcrustal contraction would have caused folding of all pre-Santonian rocks within the trough.

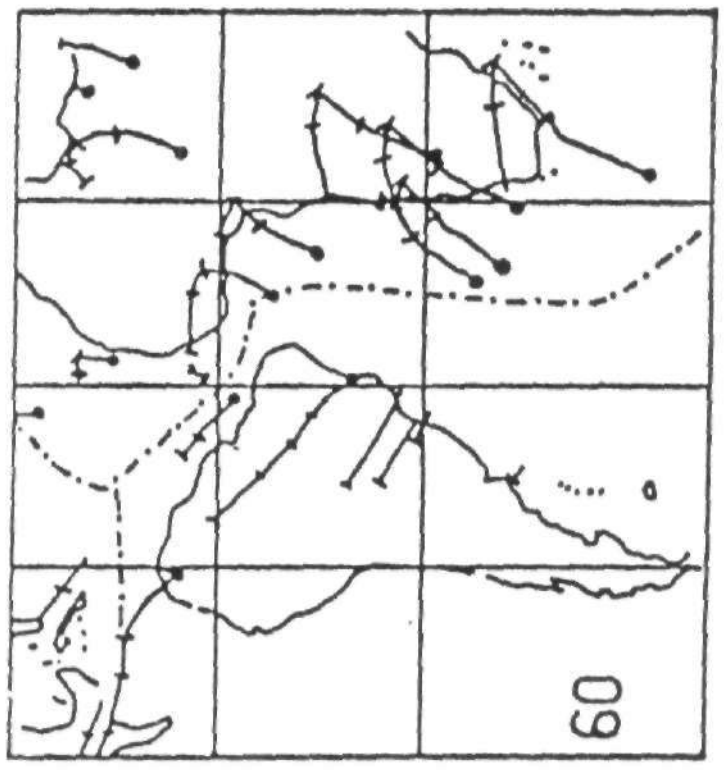
Fitton (1980) suggested that the structure of the Benue trough is due to hot spot activity, presently centred beneath the Cameroon volcanic line. The similarity in shape between the Benue trough and the Cameroon volcanic line may indicate that both owe their cause to a common Y-shaped asthenospheric hot-spot. The sequence and form of volcanic evolution of the Cameroon line and the Benue trough are similar enough in nature to inspire earlier suggestions that they were controlled by the same forces (Wright, 1968).

According to Fitton (1980) If the general CCW (Counter -Clock-Wise) rotation of the African continent (during it's separation from South America) experienced a short lived clockwise shift of only a few degrees c. 80 Ma ago, the Benue trough hot-spot could have migrated west to below the Cameroon volcanic line. Morgan (1983), in his model of early opening of the Atlantic, shows hot spot tracks related to the African continent as requiring a component of CW rotation around this period (fig. 2.5)

Wood (1983) reports continental rift jumps as being common relocating at distances approximately equal to the local lithospheric thickness. This stage of the geologic history (c. 80 Ma; Santonian - Campanian) also coincides with the widespread plate reorganisations, magnetic pole reversals (anomaly 33) and the Santonian deformational phase in the Benue trough.

2.8.2 Strike-slip Tectonics.

Benkhelil and Guiraud (1980); Benkhelil and Robineau (1980); Benkhelil (1982,1986); Allix (1983); Popoff *et al.* (1983); Maurin *et al.* (1986) observed that it is not possible to explain fully the origin of the Benue Trough without a correct understanding of its tectonics framework and history. They suggested constraints on the origin such as tectonic framework, thermal history and other geological and geophysical considerations. These authors went ahead to suggest that the strike-slip tectonics along the deep-seated faults within the trough produced NE-SW trending



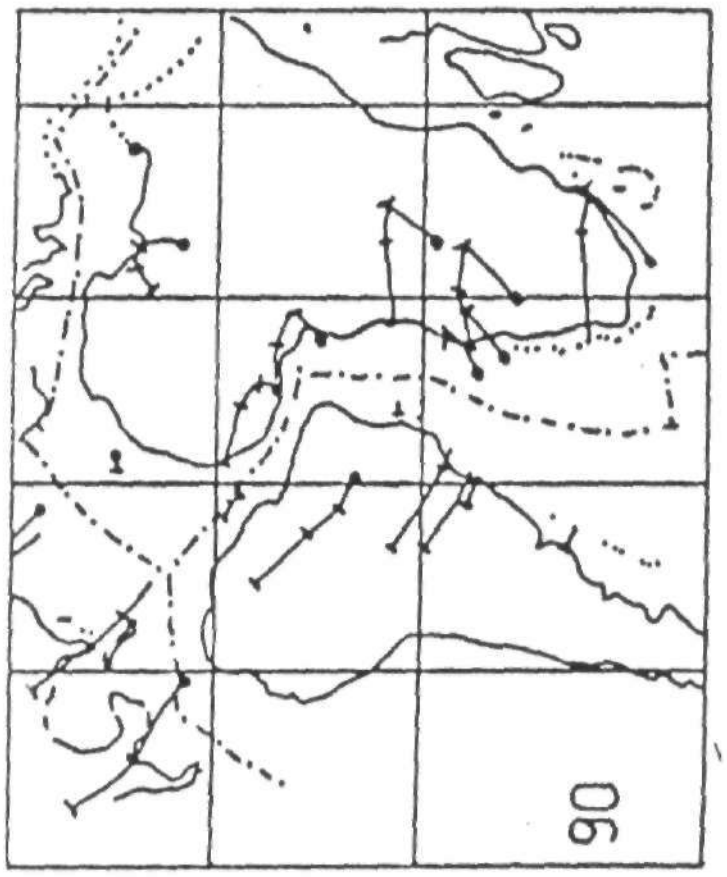


Fig. 2.5 Opening of the Atlantic at 90 Ma and at 60 Ma before present. An element of clockwise rotation is suggested for this interval (After Morgan, 1983)

long and narrow depressions in the form of pull-apart basins (fig. 2.6). They contended the extension of the Chain and Charcot fracture zones onto the continent, corresponding with the major axial fracture system beneath the Cretaceous cover of the trough. In such a manner, the sediments were folded and faulted by horizontal compression coupled with sinistral shear along the axis of the trough. This would have been preceded by an extensional phase due to the divergent strike- slip motion, which originated a chain of pull-apart basins and other extensional features. Cratchley *et al.* (1984) pointed out that this theory does not reconcile with known marine regressive and transgressive sequences. Nonetheless, the widespread occurrence of NE-SW trending structures and lineaments (e.g., the Pelusium Line) probably do contribute to the observed structure within the Trough.

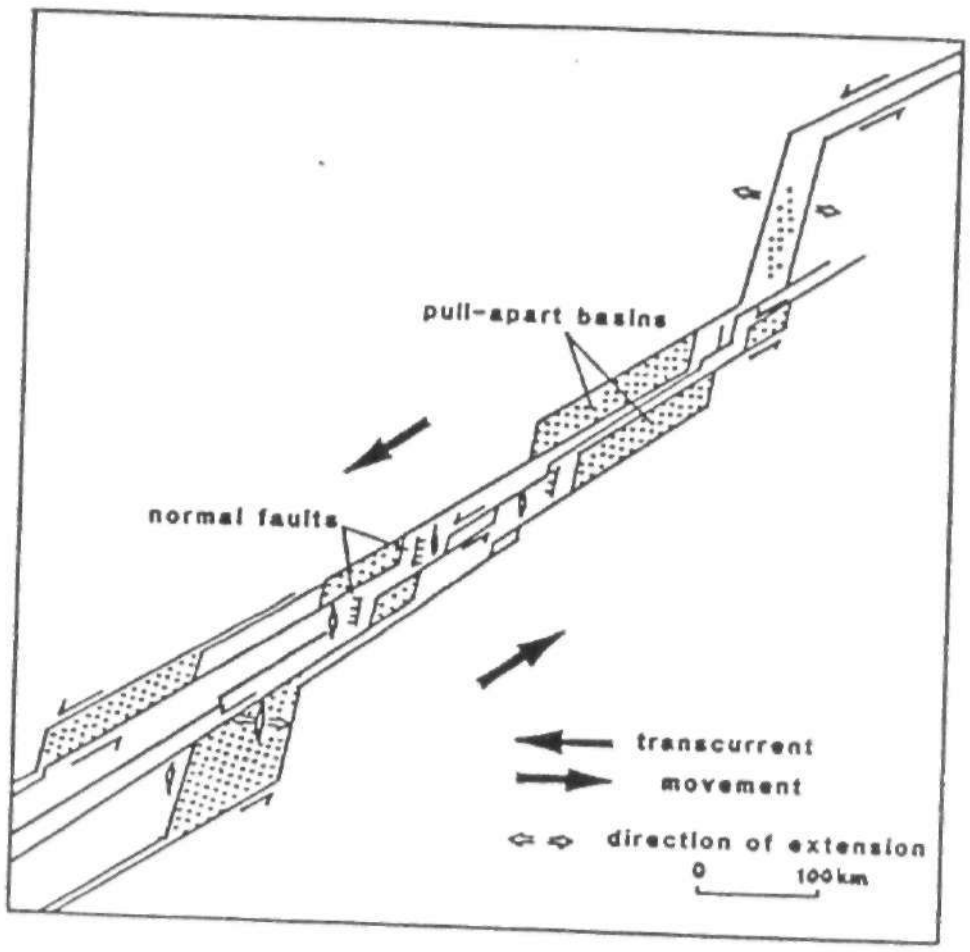
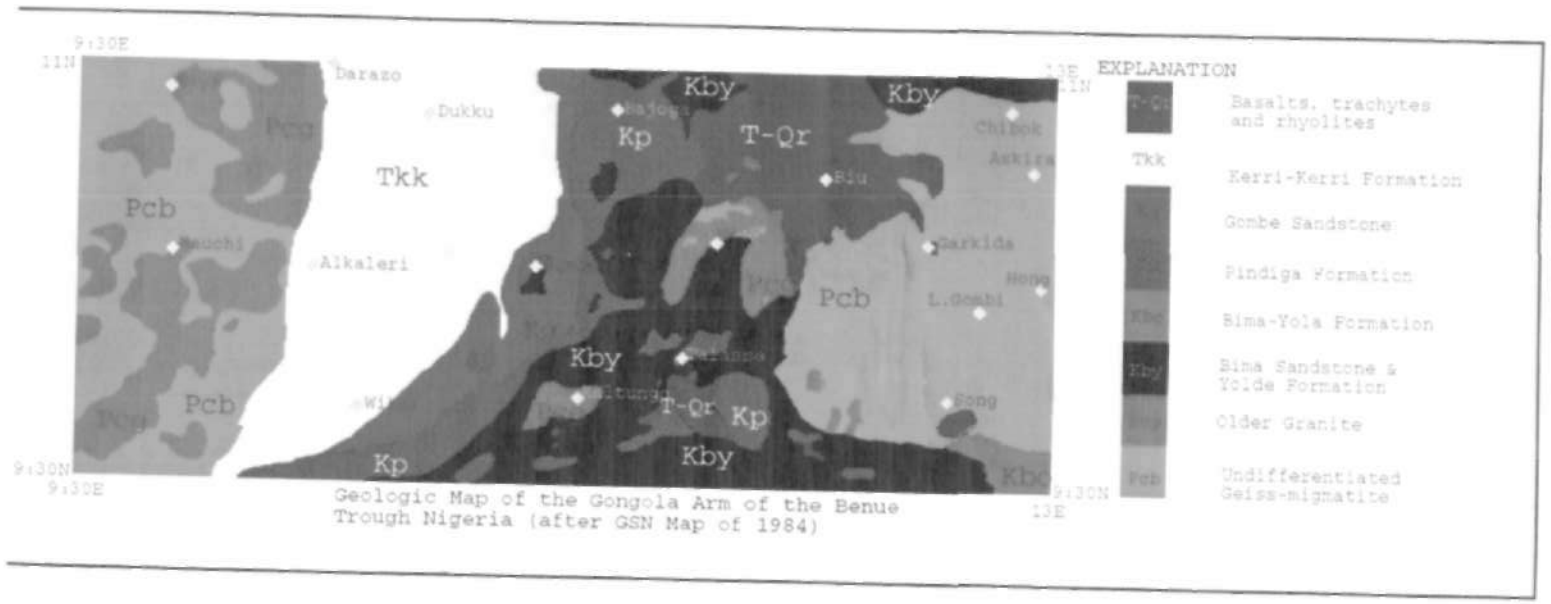


Fig 2.6 Sketch of extensional features associated with a zone of transcurrent movement (After Benkhelil, 1982)



Geologic Map of the Gongola Arm of the Benue Trough Nigeria (after GSN Map of 1984)

Fig. 3.1 Geology Map of the Area of Study (After Geological Survey of Nigeria, 1984)

3.2 The Crystalline Basement

The crystalline basement consists of scattered remnants of highly metamorphosed sedimentary rocks and diverse predominantly granitic, plutonic masses collectively known as the Older Granite (Carter *et al.*, 1963). They outcrop extensively in the east near Pieta and cover a wide area south of the Benue Basin (fig. 3.1). Basement rocks also outcrop as an inlier around Kaltungo.

3.2.1 The Metasediments.

There is little that remains of the metasediments in the crystalline basement in this area. Granitisation has almost completely transformed those rocks to anatectic migmatite and granite relics of the metasediments are found only as xenoliths and small pendants in the granitic rocks(Carter *et al.*, 1963). The metasediments include quartzo-feldspathic biotite- and hornblende-gneisses, quartzite, marbles, and calc-silicate rocks. Biotite-and hornblende-gneisses are amongst the most frequently occurring types (Carter *et al.*, 1963). Mineral assemblages correspond to those of the amphibolite Facies. Feldspathization of the Metasediments is reflected by the presence of late microcline; and transitions from metasediments to granite frequently occur (Cater *et al.*, 1963).

3.2.2 The Older Granites.

These granites (fig. 3.1) represent a cycle of granite evolution in which anatexis and stages of granitisation and magmatic activity are displayed. They vary in structure, texture and mineralogy and show diverse contact relationships with the metasediments. The granitic members of the Older Granites are characteristically rich in potash. Three major divisions of Older Granites are recognised (Carter *et al.*, 1963).

Syntectonic granites

Fine-grained granites

Basic and intermediate plutonic rocks (Oldest).

Basic and intermediate plutonic rocks which include gabbro and quartz diorite are widespread but individual occurrences are small (Carter *et al.*, 1963). These rocks occur in places like Bauchi, Kwaya Tera, etc.

The fine-grained granites, which were intruded prior to the emplacement of the syntectonic granites, are a group of minor, discordant intrusions of small total area extent. The length of the time interval separating the emplacement of the syntectonic and fine-grained granites is not known though no intervening episode has been recognised between them.

The syntectonic granite division embraces more than half of the total area of the basement. It includes anatectic migmatites and diverse range of equigranular and porphyritic, semi-concordant granites.

3.3 The Cretaceous Rocks

The Upper Cretaceous marine transgression is believed to have been preceded by the deposition of great thickness of continental sands and clays, the Bima Sandstone. The Bima Sandstone is succeeded by transitional beds which pass upwards into a predominantly marine sequence of Turonian to Senonian age. Continental conditions are believed to have been re-established in the Maestrichtian that resulted in the deposition of the Gombe Sandstone(Carter *et al.*, 1963). A period of folding that followed and a further continental sequence, the Kerri-Kerri Formation, unconformably overlies the continental Maestrichtian along the Southern margin of the Chad Basin was deposited.

3.3.1 The Bima Sandstone

The Bima Sandstone is found at the base of the sedimentary secession in the cores of great anticlines and directly overlying the crystalline basement floor (Carter *et al.*, 1963). The thickness of the formation ranges from about 100 m to at least 3500 m. The Top of the formation ranges in age from Upper Cenomanian to Lower Turonian, while the base may be as old as Upper Albian. The variation in thickness is believed to be partly due to the irregular relief of the Crystalline floor on which the sediments accumulated in the basins of deposition. Table 3.2 gives the stratigraphic succession of

<table>
<tr><td></td><td></td><td></td><td>Benue Basin</td><td colspan="2">Zambuk Ridge</td></tr>
<tr><td>Pliestocene</td><td></td><td></td><td></td><td>Gulani Area</td><td>Gombe Area</td></tr>
<tr><td>Paleocene</td><td></td><td></td><td></td><td></td><td>Kerri-kerri Fm</td></tr>
<tr><td rowspan="6">Upper Cretaceous</td><td>Maestrichtian</td><td></td><td>Lamja sandstone
Numanha shales</td><td></td><td>Gombe sandstone</td></tr>
<tr><td rowspan="3">Senonian</td><td>Campanian</td><td rowspan="3">Sekule Formation

Jessu Formation

Dukul Formation</td><td rowspan="3">Gulani sandstone</td><td rowspan="3"></td></tr>
<tr><td>Santonian</td></tr>
<tr><td>Conician</td></tr>
<tr><td rowspan="2">Turonian</td><td>Upper</td><td colspan="2" rowspan="2">Pindiga Formation</td></tr>
<tr><td>Lower</td></tr>
<tr><td>Cenomanian</td><td></td><td colspan="2">Yolde Formation

upper
middle
lower</td><td>Bima Sandstone</td></tr>
<tr><td>L.Palaeozoic to Pre-cambrian</td><td colspan="5">Crystalline Basement</td></tr>
</table>

..... Unconformity

Table 3. 2 Stratigraphic succession of the Upper Benue Trough
(After Carter *et. al.*, 1963)

the area. The Bima Sandstone is believed to have been derived from granitic terrain. The lower beds are invariably feldspathic but the higher beds, which accumulated as the basin subsided and at greater distances from the granitic highlands, generally contain less feldspar (Carter *et al.*, 1963). The diverse Lithology of the Bima Sandstone indicates accumulation under widely varying conditions. Evidence of fluviatile and/or deltaic conditions is seen in the ubiquitous cross-bedding structures of the Sandstone whilst the massive, white and purple clays are probably lacustrine sediments. The shaly beds of the Lamurde anticline are believed to represent the marginal deposits of an Albian marine invasion.

3.3.2 The Yolde Formation

The Yolde Formation is a variable sequence of sandstone and shales which marks the transition from continental to marine Sedimentation (Carter *et al.*, 1963). The base of the formation is defined by the first appearance of marine shales and the top by the disappearance of sandstone and the commencement of limestone-shale deposition. The Yolde formation is almost certainly diachronous and shows lateral variations in thickness (Carter *et al.*, 1963). The type section occurs in the Dadiya syncline and is exposed in the stream at Yolde where about 380 m of sediments are present (Carter *et al.*, 1963).

On the Zambuk ridge the formation is more arenaceous . The formation is often poorly exposed and it's presence over much of the area can be inferred only from rock

debris, changes in soil type and topography (Carter *et al.*, 1963). At Hinna, where it reaches it's maximum thickness of 450 m, the formation consists of medium- to fine grained, calcareous sandstone interbedded with shales and occasional Shelly limestone. The lower members of the sandy horizons often contain a small amount feldspar.

The Yolde formation is dated on the basis of fossil record as Lower Turonian, pre-Salmurian (Upper Cenomanian?) by Carter *et al.* (1963).

3.3.3 The Pindiga Formation

The Pindiga Formation is a sequence of marine shales which include a number of limestone beds towards the base. These rocks occur from Pindiga to Gombe and do continue as far north as Bularaba and Ligda (Carter *et al.*, 1963). The Upper part of this Formation consists of about 120 m of blue-black shale which is termed the shale member. In the upper part of this sequence, a calcareous sandstone and a band of Shelly limestone are present and the top of the member is marked by a bed of oolitic phosphatic ironstone (Carter *et al.*, 1963). At Gombe, boreholes drilled have penetrated about 190 m of Pindiga Formation.

The Formation is characterised by faunas in the limestone-shale member, and this faunas have been used to date the Formation as Lower Turonian (Salmurian) to Maestritchtian (Carter *et al.*, 1963).

3.3.4 The Gombe Sandstone

The Gombe sandstone is a sequence of estuarine and deltaic Sandstone, siltstones shales and ironstones. It has a restricted outcrop (fig. 3.1), thus suggesting that these rocks were deposited in a basin which lay to the west of the Zambuk ridge in the Late Cretaceous times (Carter *et al.*, 1963).

Siltstones and flaggy Sandstone form the greater part of the Gombe Sandstone. These rocks are soft and light grey in colour when fresh, but on exposure give rise to a dark red, flaggy debris which are found on top of the Gombe Sandstone hills. The Gombe Sandstone is the top member of a folded and eroded sedimentary sequence and it has not been possible to determine its' original thickness. Carter *et al.* (1963), however, suggested that this formation is at least 300 m thick. This Formation is believed to be Maestritchtian in age (Carter *et al.*, 1963).

3.4 The Tertiary Kerri-Kerri Formation

The Kerri - Kerri Formation was first recognised by Falconer (1911) who named it the 'Kerri-Kerri Sandstone', and believed it to be Eocene in age. The Tertiary Kerri-Kerri Formation, as it is now being called, consists of a sequence of flat-lying grits, sandstone and clays. This formation rests unconformably upon the folded Cretaceous and is Palaeocene in age (Carter *et al.*, 1963).

The Kerri-Kerri Formation is unaffected by folding but dips gently to the north and Northeast below the Chad Formation (Carter *et al.*, 1963) Drilling at Dukku has revealed that this formation is at least 200 m thick in that area.

The Kerri-Kerri Formation is a continental sequence which was deposited under a wide range of conditions. Lacustrine- and deltaic-type sediments form the most frequently recurring strata. There is a similarity in lithology and sedimentary structures between Kerri-Kerri formation and the Bima Sandstone, though the latter is characterised by its feldspathic sediments and the very much coarser grade of the sandstone. The Kerri-Kerri Formation appears to have been derived from a terrain of Cretaceous sedimentary rocks, whose relief was much more subdued than Topography of Bima Sandstone times (Carter *et al.*, 1963).

The Kerri-Kerri Formation which is at least 200 m thick is separated from the Maestrichtian beds of the Pindiga Formation by 300 m of Gombe sandstone strata and an angular unconformity (Carter *et al.*, 1963).

3.5 The Biu Plateau Basalt

The Biu Plateau extends for over 1250 km^2 of which the western margin of about 250 km^2 lies in the area of study (Fig. 3.1). It is capped by sheets of olivine-basalt that gives rise to impressive topography. The Biu basalt are believed to be Neogene in age.

In the area of study, these basalt have not been seen to be more than 30 m thick, though du Preez (1949) estimated that elsewhere in the Biu plateau that the basalt attain thickness of up to 244 m.

In parts of the plateau, a number of well preserved volcanic vents form prominent features. They have well defined craters with breached rims and steep Conical sides. The vents are composed of basaltic agglomerate, ash, lava, and tuffs. Small flows resting on the Plateau lava have been issued from craters.

The basalt are fine-grained, dense, olivine bearing rocks. The various flows show little variation in appearance or composition, and this factor, coupled with the rather poor scree-covered exposures render the correlation of flows uncertain.

There is no satisfactory evidence concerning the mode of eruption of the lava. No parent vents have been identified and there is no indication that they were extruded from central vents of the Hawaiian or Strombolian type.

CHAPTER 4

PREVIOUS GEOPHYSICAL INVESTIGATION IN THE TROUGH

4.0 Introduction

Until recently, geophysical investigations in most parts of the Benue Trough has centred on the measurement and interpretation of the gravity and magnetic fields of the Trough. The occurrences of Lead-Zinc mineralisation, salt deposits, and bright prospects of finding oil and uranium deposits in the Trough have turned the area into one of great economic importance to the country. This has resulted in more extensive and intensive geological and geophysical studies in the Trough in the past few years, such as the seismic activities presently going on in the Gongola Arm of the Trough to asses its potential for hydrocarbon deposits. Some of these activities are reviewed here below.

4.1 Gravity Studies

A gravity studies in the Trough was pioneered by Cratchley and Jones in 1965 with the aim of resolving the nature of the trough in terms of two contradicting hypotheses at that time; namely that the trough was either a buried Cretaceous rift valley or it was a minor geosynclinal furrow formed as a result of compression. The resulting work (Cratchley and Jones, 1965) remains one of the most frequently cited gravity research in the Benue Trough.

Subsequently numerous gravity surveys have been carried out over the years (Ajakaiye and Burke, 1972; Artsebashev and Kogbe, 1974; Osazuwa, 1978; Adighije, 1979, 1981a, b; Ajayi, 1979, 1987a; Ekine, 1979; Ajayi and Ajakaiye, 1981; Osazuwa *et al.*, 1981; Cracthley *et al.*, 1984; Elf, 1985; Fairhead, 1988; Fairhead and Okereke, 1987, 1990).

Analyses of the Bouguer anomaly data in the Trough indicate a general linear relationship between the Bouguer anomalies and elevation (Cratchley and Jones, 1965; Ajayi, 1979; Adighije, 1981a, b), thus suggesting that the entire Benue region is approximately isostatically compensated. This being the case, the free- air anomalies approximately reflect the isostatic anomalies. The mean free- air anomaly within the confines of the trough is about 20 mGal (Cratchley and Jones, 1965), and the basement immediately outside the trough bound shows a mean anomaly close to zero.

The most striking characteristic of the Bouguer anomaly pattern is a central axial positive belt of about 20 - 40 mGal approximately centred on the Trough (Crtahley and Jones, 1965; Elf, 1985). According to Elf Nig. Ltd (1985) this axial positive zone is flanked on both sides by elongated long wavelength gravity lows of values in the range of -20 to -50 mGal (fig. 4.1) The axial positive is seemingly restricted to those zones of the trough where known uplift, erosion, mineralisation, or tectonic activity has taken place. A portion of this axial high (from Ishiagu to Gboko) coincides extremely well with the core of the Abakaliki uplift (Fig. 2.2).

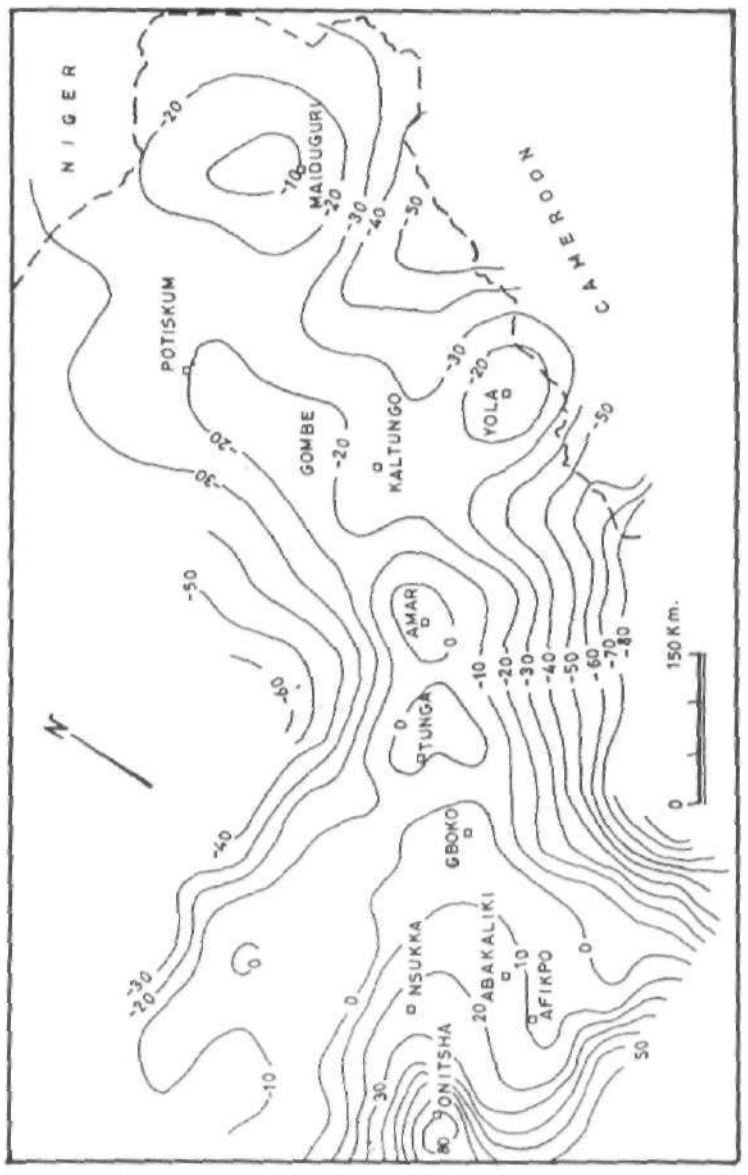


Fig. 4.1 Bouguer Anomaly map of the Benue Trough (after Elf, 1985).

In general, however, the Bouguer anomalies observed in the Trough range from 60 mGal to about 40 mGal (Ajakaiye, 1981), while the Free-Air Anomaly values are close to zero except for the local attainment of values about 30 mGal (Adighije, 1981a; Ajakaiye, 1981). There exists a pronounced regional positive anomaly which is superimposed on the anomalies in the Trough. This regional positive anomaly has been independently interpreted in terms of mantle uplift and thinning of the crust underneath the trough (Cratchley and Jones, 1965; Artsybashev and Kogbe, 1974; Ajayi 1979; Adighije, 1981a; Ajayi and Ajakaiye, 1981; Osazuwa *et al.,* 1981; Fairhead and Okereke, 1987, 1990).

Early workers in the Trough (Cratchley and Jones, 1965; Artsybashev and Kogbe, 1974) suggested an uplifted mantle of between 10 - 20 km having a width of 190 - 220 km based on an assumed density contrast of 0.17×10^3 kg/m^3 between the crust and mantle. Adighije (1981a) modelled the regional positive gravity over the Trough in terms of an uplifted mantle of 1.5 - 3 km, based on a density contrast of 0.57×10^3 kg/m^3. Adighije suggested that the width of this uplift is in the range of about 70 - 170 km representing an increase from north to south.

Osazuwa *et al.* (1981) interpreted the regional field in the Upper Benue trough in terms of up-arching of the mantle - crust interface. They estimated an uplift between 2 km and 5 km using a density contrast of 0.31×10^3 kg/m^3. Fairhead and Okereke (1987) interpreted the regional anomaly in terms of an uplift between 1.5 to 15 km based on a density contrast of 0.17×10^3 kg/m^3 Cratchley *et al.* (1984) suggested a

thinning of the crust of between 2 and 8 km based on an assumed density contrast of 0.37×10^3 kg/m^3 .

Regional analyses of the Bouguer anomalies in the Trough has led to estimation of Crustal thickness in the range of 22 - 37 (Artsybashev and Kogbe, 1974), 22 - 27 km (Adighije, 1981a); 25 - 28 km (Osazuwa *et al.*, 1981). Elf Nig Ltd (1985) in a recent detailed analyses of the regional gravity field over the Trough, showed that the Crustal thickness varies between 22 and 32 km.

There has been attempts at interpreting the Bouguer anomaly in terms of its different components (regional and Residual), the first attempt being that of Cratchley and Jones (1965). They interpreted these anomalies in terms of the combined effect of a zone of intermediate to basic intrusions about 19 - 30 km wide, which either occurs within the basement or within the Sedimentary basin and having a density in the range of between 2.65 - 2.69 $\times 10^3$ kg/m^3.

Other researchers in the Trough presented interpretations similar to those of Cratchley and Jones (1965). Ajayi (1979); Ajayi and Ajakaiye (1981) assumed a density a density of between 2.63 $\times 10^3$ kg/m^3 and 2.67 $\times 10^3$ kg/m^3 for the near surface rocks and a density of 2.82 $\times 10^3$ kg/m^3 for the basic intrusives. Osazuwa *et al.* (1981) working in the Upper Benue trough accounted for this residual positive anomaly in terms of near -surface basement rocks at a depth between 0.9 - 2.2 km and intermediate to basic intrusives at a shallow depth of 2 km or less.

Adighije (1979, 1981a) interpreted the axial positive anomalies over the Benue trough in terms of a mantle diapir, which he suggested might have been the source of the Pyroclastics reported around Abakaliki (Hoque 1984; Uzuakpunwa, 1974; Okeke *et al.*, 1988). Adighije also suggested that this diapir has a density of about 2.9×10^3 kg/m^3, with an average width of 30 km and extends from a depth of about 10 km to the Moho, and stretches for over 350 km from Abakaliki.

Cratchley and Jones (1965) reported that local positive residual anomalies in the Benue Trough appear to correlate well with some outcrops of Cretaceous rocks and concentrations of ironstones of density approximately 3.60×10^3 kg/m^3 occurring at shallow depths of between 50 - 200 m (Myada 1979).

Benkhelil *et al.* (1988) interpreted the residual anomalies in the trough in terms of basement depths playing the major role in determining the magnitude and trend of the residual anomalies. They used average densities of 2.30×10^3 kg/m^3 for the Cenozoic and 2.55×10^3 kg/m^3 for the Cretaceous sediments; 2.95×10^3 kg/m^3 for the basic intrusives and 2.70×10^3 kg/m^3 for the Crystalline basement.

The lateral elongate negative gravity anomalies that flank the axial positive anomalies on both sides have been attributed to sediment thickness that vary from 1.5 km to a maximum of 7 km (Cratchley and Jones, 1965; Adighije, 1979, 1981a, b; Ajayi, 1979; Ajayi and Ajakaiye, 1981; Osazuwa *et al.*, 1981; Fairhead and Okereke, 1987, 1990,). These sediment are believed to attain their maximum thickness in Lower

and Middle Trough and decrease in thickness towards the northern parts of the trough where their thickness are about 2 km or less.

There are locally occurring negative anomalies whose values hardly exceed 10 mGal and have been interpreted in terms of brine springs occurring at different depths of 300 - 800 m (Ajakaiye, 1981). Ajayi (1987a) identified similar brine springs in the middle Benue Trough occurring at moderate depths of between 0.56-1.64 km.

Estimates of Crustal extension that occurred perpendicular to the strike of the Trough have been made (Fairhead and Okereke, 1987). They obtained estimates of about 65, 55 and 95 km for the Gongola and Yola arms of the Benue trough and the Middle Benue Trough respectively.

4.2 Magnetic Studies

The magnetic anomalies over the Benue trough has been reported by several authors to be made up of contributions from short, medium and long wavelength anomalies. Ofoegbu (1984c) reported that the Basement Complex bordering the Benue Trough and outcropping in some places within it, is characterised by short wavelength anomalies which arise either from susceptibility changes within the basement, near surface intrusives or a combined effect of both. In contrast to the short wavelength anomalies there are medium to long wavelength anomalies which characterised the sedimentary sections of the trough. These anomalies are of the order of ±20 nT to

±150 nT and an average width of 30 - 40 km and they exist as belts of magnetic highs and lows. The belts are not continuous but appear as several elongate lobes over varying distances (Ofoegbu, 1984a, c, 1988; Ajakaiye *et al.*, 1985, 1986) before being interrupted by occasional occurrence of short wavelength anomalies which may be due to near surface intrusive, volcanic plugs, basement rocks and/or thin basalt flows.

According to Ofoegbu (1984a, c) and Ajakaiye *et al.* (1985), these belts of magnetic lows correspond remarkably well with the basin- basement contact as picked up from geological studies and the belt of negative gravity anomalies observed over the contact (Cratchley and Jones, 1965; Adighije, 1979, 1981a, b) though these contacts generally suggest shifts of about 15 km southwards.

Analyses of Aeromagnetic data over the Benue trough by several authors (Osazuwa *et al.*, 1981; Ajakaiye, 1981; Ofoegbu, 1984a, 1985, 1988) have shown extensive block faulting in the Trough, with the faults attaining considerable lengths at places and marking out several basinal structures in the Trough.

Ajakaiye (1981); Ofoegbu (1984c); Elf (1985) and Saugy 1987 identified some of these basinal structures as Anambra basin which has a sediment thickness of about 3 - 7 km; Afikpo basin with sediment thickness of 2 - 5 km; Gombe basin with sediment thickness possibly up to 6 km (Fig. 4.2)

Sediment thickness estimated in the Benue Trough from interpretation of magnetic anomalies agree to some extent with those obtained through the analyses of

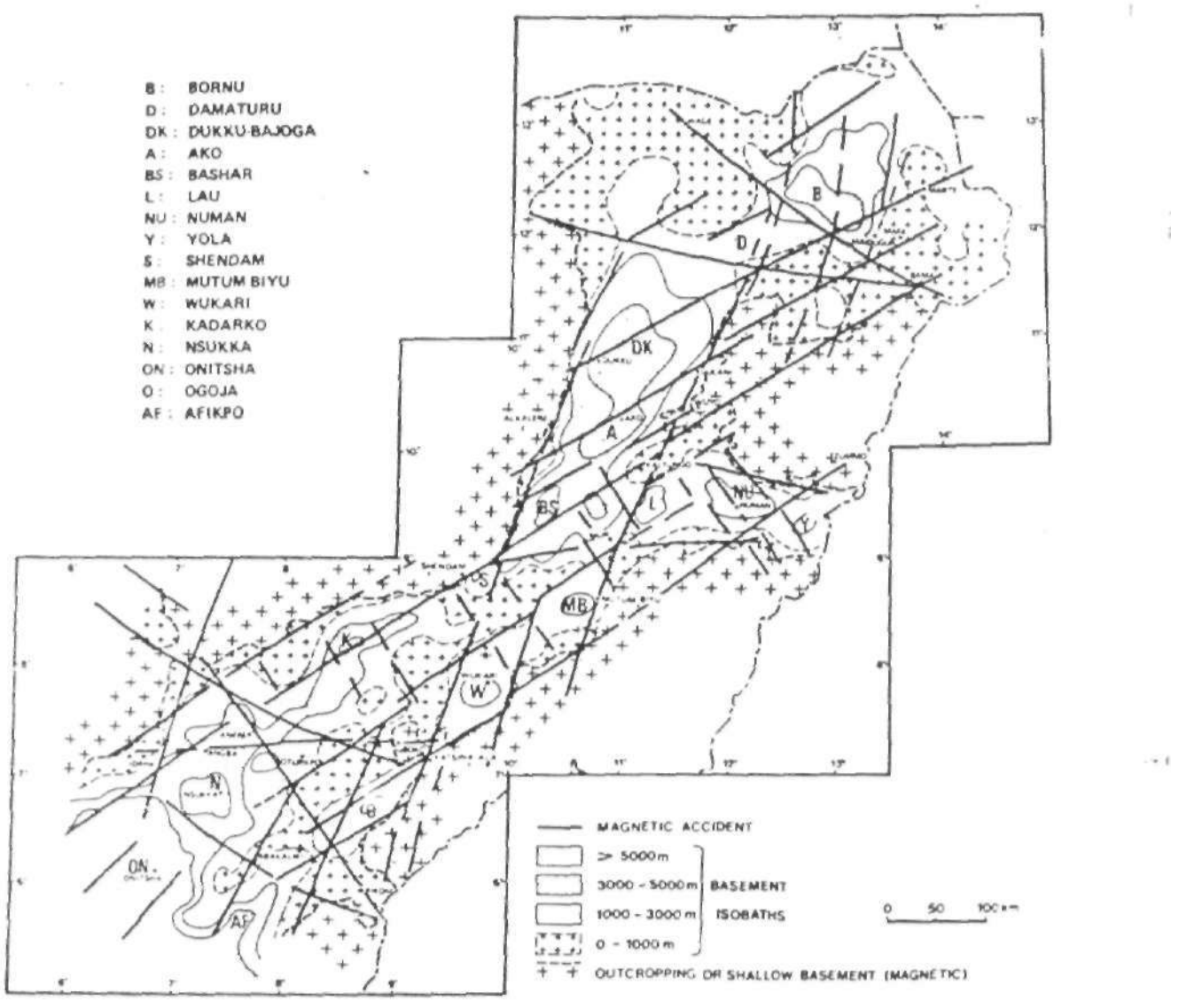


Fig. 4.2 Basement Isobaths of the Benue Trough (After Saugy 1987)

gravity field. Osazuwa *et al.* (1981) estimated thickness of sedimentary rocks of between 0.9 and 4.8 km for the Yola Arm of the Trough. Ofoegbu (1988) working in the Upper part of the Trough estimated thickness of sediments of between 0.5 to 4.6 km. In the Lower and Middle Benue Trough Ofoegbu (1984c) estimated the thickness of the sedimentary rocks between 0.5 and 7 km.

Ajakaiye (1981); Ofoegbu (1984a, 1984c); Osazuwa *et al.* (1981) analysed the rather small amplitude, medium wavelength anomalies of general and regular shape and gentle gradients on which are superimposed several locally occurring high frequency anomalies that characterised the Benue Trough in terms of a combined effect of susceptibility variations within a deep lying basement, topography of the basement or both. These authors modelled the intrusive bodies using magnetisation in the range of 1.0 A m to about 4.0 A m and an average width of about 10 km and a depth of existence of this bodies of about 1 km and beyond. these bodies, on the account of their magnetisation values of between 1.0 to 4.0 A m range in composition from basic to intermediate and are probably gabbroic.

According to Ofoegbu (1984b) these bodies have variable thickness and directions of magnetisation, suggesting that although they are derived from the same mantle material, the intrusives were probably emplaced at different polarity epochs.

In addition to the medium and short wavelength anomalies, Ajakaiye (1981), Ofoegbu (1984a) identified several minor magnetic features scattered over the area.

They reported that some of these anomalies could be traced as long as 60 km, and they interpreted them in terms of dykes and volcanic plugs.

Ofoegbu (1985) used the power spectrum analysis in an effort to eliminate anomaly components due to shallow sources. He then inverted the resultant long wavelength anomalies in terms of a magnetised crust layer whose bottom surface coincides with the Curie isotherm in the area. He then found out that the Curie isotherm underneath the part of the trough analysed was found to vary from 18 km - 27 km, suggesting lateral and vertical variations in composition of the crust in the area. He therefore concluded that the long wavelength anomalies are due essentially to variable curie isotherm or morphological variations at the top of a magnetised crust.

Ofoegbu (1986) also performed pseudogravimetric transformation of several Aeromagnetic profiles in the Upper part of the Trough using the Equivalent layer method. A joint analysis of the magnetic, gravity and pseudogravimetric anomaly profiles showed that:

The short wavelength anomalies observed on the Aeromagnetic profiles are most likely caused variations of magnetisation due to the existence of thin intrusions occurring at shallow depths or minor near surface variation in the magnetisation of the basement underlying the trough.

Medium and longer wavelength anomalies are probably due to intermediate to very large lateral variations in magnetisation arising from susceptibility changes within

the basement and the possible existence of deeply seated intrusive bodies of asthenospheric origin.

4.3 Seismic Studies.

With the exception of seismic surveys carried out by oil companies in the Lower part of the trough and currently in the Gongola Arm of the Trough, Seismic coverage in the trough remains limited to one reverse profile across the Yola rift at the Garoua in Cameroon (Stuart *et al.*, 1985). The result of this seismic profile places an abnormally thin crust beneath the Yola arm, compared with a *normal* Crustal thickness of about 33 km as beneath the Adamawa plateau. Crustal thinning of the order of about 10 km seemingly occurs in this region (Stuart *et al.*, 1985).

4.4 Other Geophysical Studies in the Trough.

Techniques such as electromagnetic, electrical and radiometric have been applied in the Trough mostly directed at investigating the economic mineral resources of the trough. Most of the results of these investigations have not been published.

Ajakaiye (1981) reported a background radioactivity of 100-300 cps. over the Benue Trough with Cretaceous sediments having values between 50 and 150 cps. Locally values reach as high as 500-20 000 cps. These values have been interpreted by Ajakaiye (1981) as indicative of occurrences of rocks rich in uranium, potash and thorium.

CHAPTER 5

DATA ACQUISITION AND PROCESSING

5.1 Gravity Measurement and Data Reduction

Gravity prospecting involves the measurement of variation in the gravitational field of the earth that is neither generated by the observer nor influenced by the things that he does. In most gravity surveys the quantity observe is not the earth's true gravitational attraction but it's variation from one point to another on the earth's surface. This lateral variation can be more easily measured than the total gravitational field.

5.1.1 Fundamental principles of gravity prospecting.

The principle of gravitational prospecting is based on Newton's Law of universal gravitation which states that two particles of masses m_1 and m_2, each with dimensions very small compared with the separation r of their centres, will be attracted to another with a force.

$$F = G \frac{m_1 m_2}{r^2} \quad \ldots(5.1)$$

where G is the universal gravitational constant.

5.1.2 Gravitational acceleration.

The acceleration of a point mass m_2 due to the attraction of a point mass m_1 at a distance r away can be simply obtained by dividing the force F by the mass m_2 (since force is mass x acceleration), where upon

$$a = \frac{F}{m_2} = G \frac{m_1}{r^2} \quad \ldots(5.2)$$

Because the acceleration is independent of the mass on which it acts it is the conventional quantity used to measure the gravitational field acting at any point. Thus the attraction of the earth may be considered as a force per unit mass.

5.1.3 Application of the Newton's law to gravity exploration.

Consider the attraction of an irregular laminar body in the x z plane at an external point also in the x z plane (fig. 5.1)

First determine the x (horizontal) and z (vertical) components of acceleration at p associated with it's attraction. To achieve this, we first divide the plate into N small elements of mass, each of area Δs as shown. If the density (mass per unit area) σ_n is uniform within the n^{th} element, we can express the x component of acceleration at a point P due to the attraction of this element as

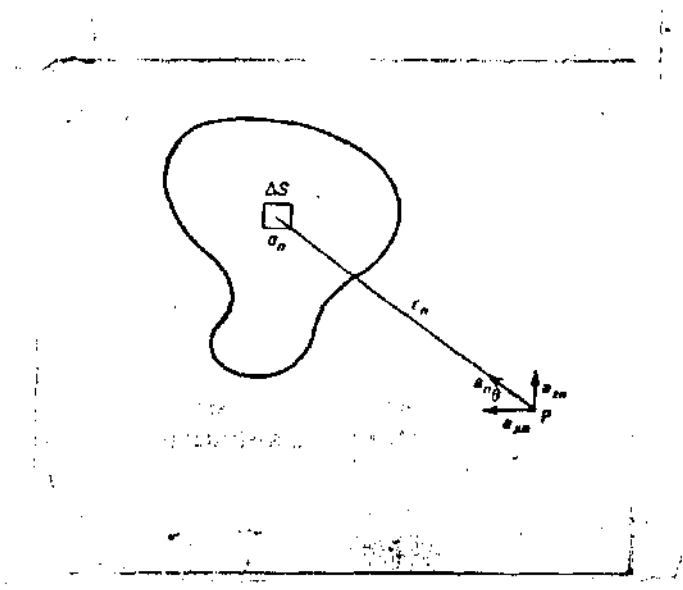


Fig. 5.1 Determination of gravitational acceleration caused by irregular two-dimensional sheet. ΔS is the element of area (after Dobrin and Savit, 1988)

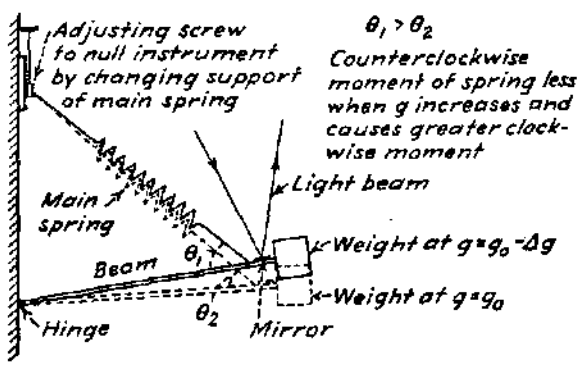


Fig. 5.2 Schematic Representation of the operation of the Lacoste and Romberg gravimeter (after Dobrin and Savit, 1988)

$$a_{x_n} = \gamma \frac{\sigma_n \Delta_s}{r_n^2} \cos\theta = \gamma \frac{\sigma_n \Delta_s}{r_n^2} \frac{x}{r_n^2} = \gamma \frac{x}{r_n^3} \sigma_n \Delta_s \ldots (5.3)$$

and the Z component as

$$a_{z_n} = \gamma \frac{\sigma_n \Delta_s}{r_n^2} \sin\theta = \gamma \frac{\sigma_n \Delta_s}{r_n^2} \frac{z}{r_n^2} = \gamma \frac{z}{r_n^3} \sigma_n \Delta_s \ldots (5.4)$$

Summing the acceleration for these elements, we obtain the respective accelerations

$$a_x = \sum_0^N \gamma \frac{x\sigma_n}{r_n^3} \Delta s \quad \ldots (5.5)$$

and

$$a_z = \sum_0^N \gamma \frac{z\sigma_n}{r_n^3} \Delta s \quad \ldots (5.6)$$

as the element of area get smaller and smaller , Δs approaches the limit ds and one express two components of acceleration at P by the respective integrals.

$$a_x = \int_S \gamma \frac{\sigma_x}{r^3} ds \quad \ldots (5.7)$$

and

$$a_z = \int_S \gamma \frac{\sigma_z}{r^3} ds \quad \ldots (5.8)$$

where s is the area of the body and is the mass per unit area.

Applying the same approach to a three-dimensional body with a density (mass per unit vol.) of ρ. Extending the reasoning for a two-dimensional body to one of three dimensions it is easy to show that the components of acceleration in the x, y, z directions respectively, become

$$a_x = \int_v \gamma \frac{\rho_x}{r^3} dv \quad \ldots.(5.9)$$

$$a_y = \int_v \gamma \frac{\rho_y}{r^3} dv \quad \ldots.(5.10)$$

$$a_z = \int_v \gamma \frac{\rho_z}{r^3} dv \quad \ldots.(5.11)$$

where V is the volume of the body.

In gravity exploration only a_z, the vertical force is measured and the measurements show only differences in gravity from one place to another, the attraction of the earth itself is significant only insofar as it varies laterally over the earth's surface. Such variation must be taken into account in evaluating the gravity effect of buried bodies having any geological or exploration significance.

If the earth were a homogenous body and did not rotate the, attraction of the surface of the earth would be the same everywhere and would not affect the reading of gravity meters, which measure only differences in acceleration between one place and another. However, the earth does rotate (so that the centrifugal forces are

superimposed on gravitational attractions) and it is spheroidal (being flattened at the poles, and has lateral irregularities in density; (Garland, 1965; Heisken and Moritz, 1967). The observed value of gravity depends on latitude, elevation, tidal movements as well as lateral changes in density and to some extent on topography (Dobrin and Savit, 1988).

5.1.4 Global variations of gravity field.

In order to be able to predict the gravitational field of the earth precisely at any point, we must know the shape and density distribution of that point with the greatest possible accuracy. Because of the earth's rotation, its shape is not actually spherical. It's shape can be approximated as an oblate spheroid with an eccentricity of approximately 1/298. Both its departure from sphericity and it's rotation causes the earth's gravitational acceleration to have a maximum value at the poles and a minimum at the equator. As a result of this balance the equatorial radius, R_E is about 21 km greater than the polar radius R_P (Sharma, 1986). Also as a result of this flattening, gravity (g) is distinctly less at the equator than at the poles, the actual difference being about 5200 mGal.

The analysis of gravity data over the earth's surface has played an important role in describing the shape of the earth in terms of an ideal reference surface. Although the most accurate reference surface appears to be a spheroid rather than an ellipsoid of revolution (Sharma, 1986), the latter is more convenient to use, since

fewer constants are involved. The variation of gravity with latitude over the surface of an ellipsoidal earth can be expressed in the form

$$g = g_0(1 + C_1 \sin^2\phi - C_2 \sin^2\phi) \quad \ldots(5.12)$$

where g_0 is the value of the gravity on the equator and ϕ is the latitude. C_1 and C_2 are constants depending on the earth's shape, the numerical values of which are adjusted to give best fit to the measured variation of the gravity of the earth's surface.

Until the 1960's, the International Gravity Formula of (1930) was the accepted standard for the reduction of gravity data. According to this formula the normal sea level gravity at any latitude is given by

$$\mathbf{g_\phi\,(1930)=9.78049(1+0.0052884\sin^2\phi-0.0000059\sin^2 2\phi)\ mGals\ \ldots.(5.13)}$$

Studies on the orbits of artificial satellites provide more precise values for constants c_1 and c_2 and in 1967 the International Association of Geodesy adopted new values of earth parameters: $R_E = 6378.16$, $R_p = 6356.78$ and ellipticity = $(R_E - R_p)/ R_E$ = 1/298.25

Based on the parameters a new International Gravity Formula was determined as

$$\mathbf{g\phi(1967)=9.780318(1+0.0053024\ \sin^2\phi-0.0000059\ \sin^2 2\phi)\ mGals\ \ldots.(5.14)}$$

Equation 5.14 gives the gravity value at any latitude on the earth's surface with reference to mean sea level.

5.1.5 Instrumentation.

Gravity measurements for exploration purposes have been carried out with three kinds of instruments that differ from one another. These instruments are the torsion balance, the pendulum, and the gravimeter with the first two no longer in use.

The requirements for precision in gravity exploration are so demanding that few measuring instruments of any kind have specifications which are more difficult to meet. The earth's gravitational field is about 10^4 mGal (Dobrin and Savit, 1988), yet many anomalies of interest in exploration have maximum values of about 1 mGal or less. The identification of such anomalies with the accuracy needed for the meaningful interpretation requires readings that are valid to at least 0.05 mGal.

Modern land meters have a nominal precision of as great as 0.01 mGal when readings are taken with extreme care; i.e. they are responsive to very small magnitude changes in the earth's gravitational field.

There are two basic types of gravity meters; the stable and unstable. A **stable meter** contains a responsive element (such as a spring) with a change in displacement proportional or approximately proportional to the change in gravity. This displacements are always extremely small, they therefore must be greatly magnified by optical mechanical, or electrical means. Stable gravimeters have a single element to balance the force of gravity with another force measurable by displacement (linear,

angular, or electrical) which can be magnified and read directly. Any change in gravity is accompanied by a corresponding change in this displacement.

For a simple spring this change would be in it's length and the formula of restoring the length of the spring would be

$$F = k(x - x_0) = mg \quad \text{....(5.15)}$$

where x = length of spring

x_0 = original length before weight was applied

k = spring constant

Since the mass m is a constant, any change in g causes a proportional change in elongation.

Unstable gravimeters, sometimes referred to as *labilized* or *astitized*, the force of gravity is kept in unstable equilibrium with the restoring force. The instability is provided by a third force which intensifies the effect of any in gravity field, the force called into play by a departure from equilibrium is proportional to the magnitude of change and acts, off course in the same direction (Dobrin and Savit, 1988).

A vertical spring that is elongated by the gravitational pull mg of a mass m will oscillate with a period

$$T = 2\pi \sqrt{\left(\frac{m}{k}\right)} \quad \text{....(5.16)}$$

where k is the spring constant

From equation (5.15), it is evident that

$$x - x_0 = \frac{mg}{k} = \frac{T^2}{4\pi^2} g \quad \text{....(5.17)}$$

It follows therefore that the elongation is proportional to g, and a change in gravity g will result in an elongation Δx which is dependent on it according to the formula

$$\Delta x = \frac{T^2}{4\pi^2} \Delta g \quad \text{....(5.18)}$$

From equation (5.18) it follows that any oscillating system can be adapted by proper damping for use as a gravity meter.

5.2 The LaCoste and Romberg Gravity meter

The LaCoste and Romberg instrument has a design typical of unstable gravity meters in general. Any change in the force of gravity acting on a weight at the end of a nearby horizontal beam supported by an inclined spring (Fig. 5.2) causes a motion which changes the angle between the beam and the spring (and hence the movement of the spring's pull on the beam), thereby accentuating the movement associated with the gravity increment or decrement, whichever it may be. This reinforcement provides the necessary instability to magnify the effect of the gravity variation.

In practice the motion is nulled by an adjustable screw which varies the at point which the mainspring is supported. The angle through which this screw must be turned to restore a light beam, reflected by a mirror on the arm, to it's null position is used as a measure of the change in gravity.

The Lacoste and Romberg instrument uses the principle of the *zero-length spring*. With this spring the displacement of the spring from equilibrium caused by the weight of the beam in zero position is effectively concentrated by an opposing tension put into the spring when it is wound. It is only with this arrangement that the elongation of the spring caused by any given increment in gravity will be actually proportional to the increment itself. In addition, the deflection will be symmetrical about the equilibrium position; i.e., the positive reading for an increase in gravity over it's equilibrium value will be equal to the negative reading for a gravity decrease of the same magnitude (Dobrin and Savit, 1988).

The LaCoste and Romberg instrument requires heating elements, a thermostatic regulator, and an insulated case to maintain the temperature sufficiently uniform to avoid significant errors in the gravity readings caused by thermal effects. A change of temperature of 0.002 ^{0}c will result in a deflection equivalent to a gravity change of 0.02 mGal, which represents the limit of precision for most surveys. To keep the temperature constant, the meter is enclosed in an insulated housing, and a small electric oven powered by a storage battery is regulated by a highly sensitive thermostat.

5.2.1 Drift of Gravimeters.

If a gravimeter is left undisturbed for an hour or so after a reading and a second observation is taken, the gravity value will apparently have changed by an amount as great as several hundredths of a mgal. If additional readings are taken over a period of hours and the observed gravity is plotted against time, the points tend to fall on a smooth curve. This continual change of gravity readings with time is known as drift and has a number of causes. One is the fact that the gravimeter springs or torsion fibres are not perfectly elastic but are subject to a show of creep over long periods. Another cause is the earth tides, and still another is related to uncompensated temperature effects. Fig. 5.3 is a plot of a drift curve obtained over period of 24 hrs during the planning stages of the data collection.

5.3 Gravity Data Collection

The gravity survey was carried out during the periods of June - July 1992 and June - July 1994 using the Lacoste and Romberg No. 446 obtained from the Dept of Physics, Ahmadu Bello University Zaria, Nigeria. The instrument was carried by a Landrover over roads and tracks and stations were established at 3 km intervals using the Speedometer of the Landrover. The study area was adequately covered, but one would have wished that there were more stations established. This was however not achieyable because of the limited periods for which the gravimeter could be loaned, the limited funds available for the field work and partly because of the lack of access roads in certain sections of the study area. Prior to the field work, the instrumental drift was

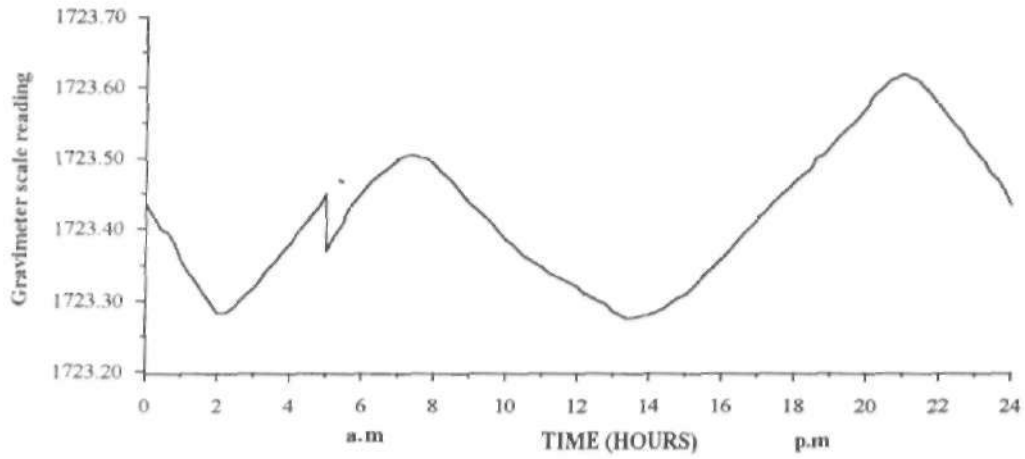


Fig 5.3a Plot of Gravimeter drift curve obtained for a period of 24 hrs on July 22nd 1992

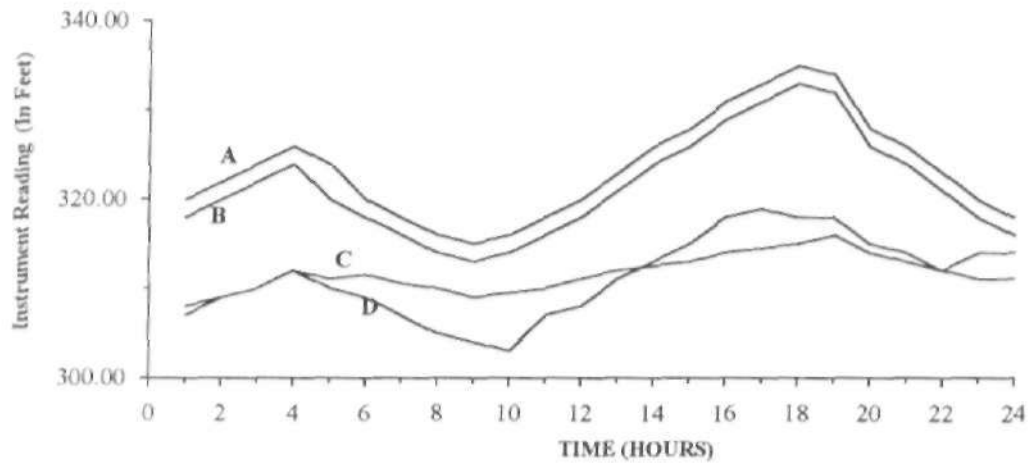


Fig 5.3b Drift Curve for the four Atimeters for a 24 Hours Period(on 22 July 1992)

observed over a period of 2 days at the department of Physics A.B.U Zaria for the June-July 1992 data collection and for 2 days at the Department of Geological Sciences, ATBU Bauchi Nigeria for the June - July 1994 collection. Fig. 5.3 shows the plot of the drift of the instrument obtained over a period of 24 hrs. It is evident from the curve that linear regions of drift of instrument with time exist and hence data collection was restricted to the periods where a linear relationship exist between time and gravimeter reading, and ties between base stations made within this time periods.

All together 1005 gravity stations and 95 base stations were established on all available roads and tracks in the area (fig. 5.4) using a LaCoste and Romberg gravimeter (model no. 446). Two Wallace and Tiernan altimeters were used to determine elevations of stations. Base stations were established using the ABABCBCD ... 'looping' technique. During the outward A - B journey, intermediate stations were established at approximately 3 km intervals, with station position fixed by the Landrover speedometer. Readings of both the gravimeter and two altimeters were taken at each of the stations irrespective of whether or not such a station was sited on a bench mark. The altimeter readings were 'looped' along with the gravimeter readings in order to obtain fairly reliable height differences between the base stations, thereby guaranteeing reasonably accurate elevation values for the intermediate stations.

Temperature readings were also taken by whirling wet-and-dry bulb thermometers and the wet and dry temperatures taken at all the gravity stations. These temperature readings were used to correct the altimeter readings for air temperature, relative humidity variation and diurnal variations.

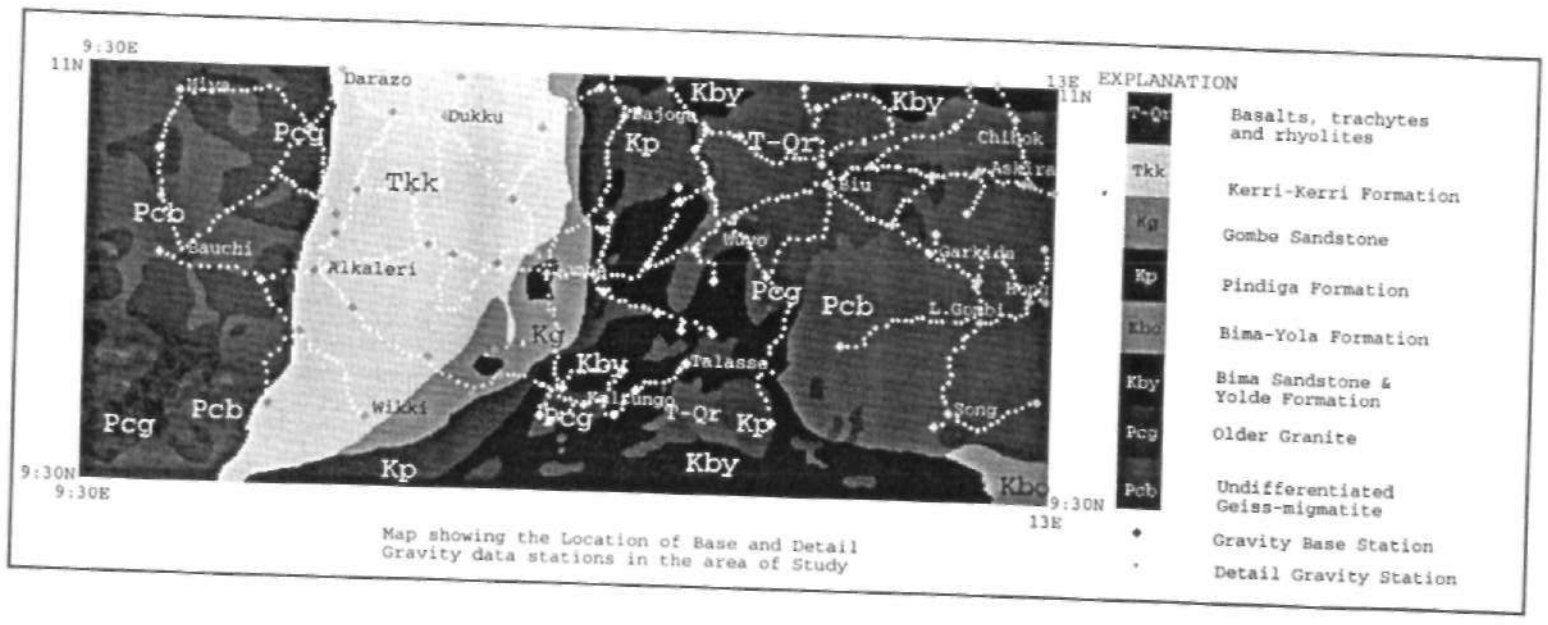


Fig. 5.4 Map showing the Location of detailed gravity and base gravity station of the area of study (White dots represent detail gravity stations while grey diamond blocks are base stations)

The regional base-network established in this work was tied to 3 bases earlier established by Osazuwa (1985) in the area; at Bauchi (porch of the old post office building), Gombe (porch of post office building) and Biu (Veranda of the reception of the catering rest house).

5.3.1 Adjustment for drift.

The instrument reading as made in the field required correction for the drift of the gravimeter (including earth-tide effects) , and this was essentially achieved using the base tie plot technique. Plots of base station gravity values obtained when the stations were continuously re-occupied, were plotted against time (Fig. 5.5 shows a base tie plot for Gombe Post Office and Deba junction which are adjacent base stations). The difference in reading with time when the two stations were re-occupied ΔR_{12} was calculated for this base plot to be 1.258 mGals and was distributed over the detail stations with time (the difference with time was subtracted from the detail stations because the drift of the instrument was positive). The difference in reading with time when the stations were re-occupied ΔR_{12} was computed for all the base stations established. The resulted difference in reading that is attributed to instrument drift and tidal effects was distributed over the detailed stations with time, and was added or subtracted depending on whether there is an increase or decrease in gravity reading within the time the two base stations were re-occupied, and hence correct for instrument drift and tidal effects for all the gravity stations established in the area of study.

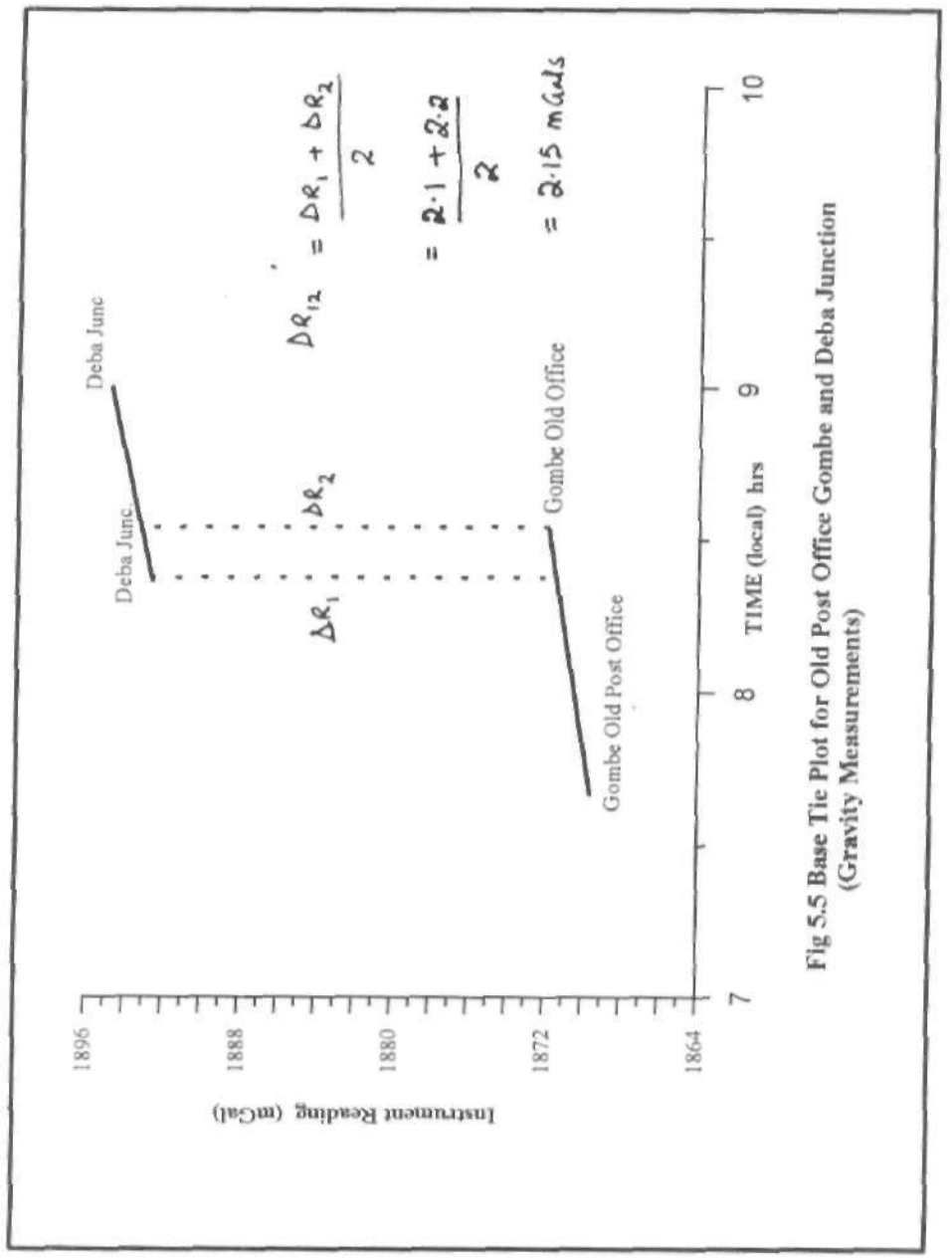


Fig 5.5 Base Tie Plot for Old Post Office Gombe and Deba Junction (Gravity Measurements)

5.4 Determination of Elevation of Stations

Altimeter readings were converted to elevations and barometric corrections carried out. In order to verify the elevations obtained from the altimeters, the altimeter readings were tied to 5 stations, with bench marks. The heights obtained for these stations from the readings of altimeters agreed with the benchmark values within 3 m. Fig. 5.6 is plot of the heights above mean sea level determined for the area of study.

The overall accuracy of the survey was limited by the barometric height determination method used and by uncertainties in the location of the data point on the map.

5.5 Gravity Data Correction

The observed gravity differences between an arbitrary reference point and a series of stations are subject to various extraneous effects that are unrelated to the subsurface geology. For instance, effects due to the oblateness of the earth, and to changes in elevation and topography must be carefully removed from the observed data before geophysical interpretation can be seriously attempted.

The necessary corrections include:

(i) Latitude correction

(ii) Free-air correction

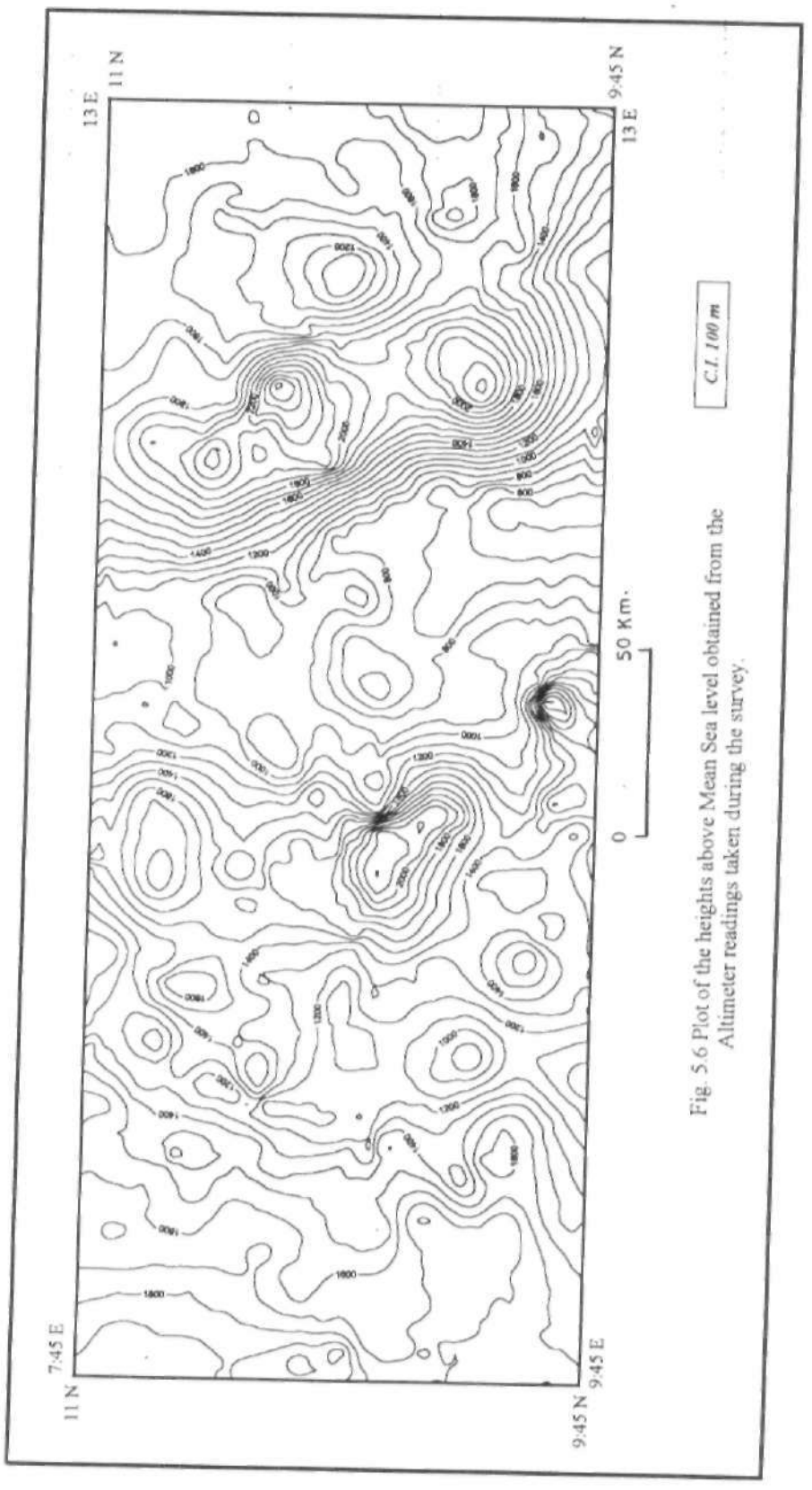


Fig. 5.6 Plot of the heights above Mean Sea level obtained from the Altimeter readings taken during the survey.

(iii) Bouguer correction

(iv) Terrain correction (sometimes carried out)

The first three corrections were carried out on the data collected using the procedures outlined below.

5.5.1 Latitude correction

The latitude correction takes into account the increase of gravity from equator to pole. The basis of the correction is the I.U.G.G. (1967) Gravity formula (eq. 5.14). The Formula gives the variation in normal gravity g in mGals as a function of latitude on the surface of the reference ellipsoid. Latitude corrections are nearly always based on the gravity difference derived directly from the gravity formula of 1967.

Since the base network was tied to some stations that had absolute gravity value already determine, the station gravity values for the middle stations (for middle latitudes) were determined by computing the theoretical gravity value at each latitude using the 1967 gravity formula. Subtracting the value of the theoretical gravity on the international ellipsoid from the value obtained from the base network adjustment gave the corrected gravity value at that latitude.

5.5.2 Elevation correction

The correction of gravity values which must be made on account of differences in elevation take care of the following two effects which are discussed below:

(i) The free-air Correction.

(ii) The Bouguer Effect.

Free -Air Correction: This correction is based on the fact that the attraction of the earth as a whole can be considered to be same as if its mass were concentrated at its centre. During the course of gravity data collection, there is elevation change between stations, which corresponds to change in distance from the centre of the earth. The inverse square law (equation 5.1) enables us to predict how much the acceleration of gravity will change as a result of change of the latter.

If the radius of the earth (at sea level) is R, the height above the sea level is h, and the value of gravity at sea level is g_0 ,then the gravity value g at height h, can be expressed as

$$g = g_0 \frac{R^2}{(R+h)^2} = g_0 \frac{1}{(1+\frac{h}{R})^2}$$

$$g = \frac{1}{1+\frac{2h}{R}+\frac{h^2}{R^2}} \quad \ldots(5.19)$$

stopping the binomial expansion of equation (5.19) at the first term only as $\frac{h^2}{R^2} \langle\langle \frac{2h}{R}$

$$g \cong g_0\left[\frac{1}{1+\frac{2h}{R}}\right] \ldots (5.20)$$

$$\Rightarrow g = g_0\left[1-\frac{2h}{R}\right] \ldots (5.21)$$

$$\text{i.e. } g-g_0 \cong \Delta g \cong -\frac{2hg_0}{R} \ldots (5.22)$$

This variation has a magnitude of 0.3086 mGal /m

The corrections for this data was made with reference to the mean sea level, using elevations determined by the altimeters. From equation (5.22), it can be seen that stations with relative high elevations (above mean sea level) have lower gravity values because they are farther from the centre of the earth. The corrections determined from equation (5.22) were added to the observed values for stations higher than the reference level (elevation) but were subtracted from observed values for stations with elevation lower than the reference elevation.

The Bouguer Correction: The expected increase in gravitational attraction due to the rock between the station and the sea level is often simply modelled (approximated) by a horizontal infinite slab of uniform density with a bottom surface at the sea level and a top surface at the elevation of the station. If the material in this slab has a density of the attraction of the slab is given by

$$2\pi\rho Gh = 0.04193h\rho \text{ mGals/m} \ldots (5.23)$$

where h = slab thickness

ρ= density of material

G= 6.6732×10^{-3}

If a given station is higher than the reference elevation, its gravity value is increased because of the attraction of the slab material between it and the reference level and the correction is negative. If the station is lower than the elevation, its gravity value is decreased because of lack of attraction of the absent material between it and the reference level and the correction is positive.

Since Bouguer correction requires a good knowledge of the density of the rocks in the area, a total of 150 rock samples were collected for laboratory determination of densities of the different rock formations. Table 5.3 is a summary of representative densities of rocks in the study area, while table 5.4 gives a values obtained by previous workers (such as Cratchley and Jones, 1965; Ajayi, 1979 and Adighije, 1981) in the trough.

5.5.3 Terrain Correction.

In many gravity surveys, the terrain in the vicinity of a station is sufficiently flat for the elevation correction to provide adequate compensation for topographic effects.

However, in areas with rugged topography the presence of hills in the vicinity of the gravity station gives the upward component of gravitation attraction that contracts a part of the downward pull exerted by the rest of the earth. Also the presence of valleys in the vicinity of the station corresponds to holes in the slab between the gravity station and the datum level which are responsible for smaller downward pull at the station than is accounted for by the Bouguer correction. Therefore, it is necessary to compensate for such effects if the topographic features are causing distortions in the observed gravity large enough to affect the accurate interpretation of anomalies from buried features of interest.

Terrain corrections are usually obtained by dividing the region around a gravity station into segments bounded by concentric rings at suitable angular intervals (ϕ). The difference in mean sea elevation (Δh) between each segment and the gravity is determined from a topographic map, without regard to sign. The terrain correction due to the attraction of the material in such segment is ,

$$C_T = G\rho\phi\ (r_2 - r_1)\ + \sqrt{[r_1^2 + (\Delta h)^2]}\ - \sqrt{[r_2^2 + (\Delta h)^2]}\ \text{....(5.24)}$$

where r_1, r_2 are the radii of the inner and outer rings bounding the segment and ρ is the density of the terrain.

Rocktype	no. of samples	range (x 10^{-3} kg m^{-3})	dry	wet	mean	SD
Biu basalt	10	2.58 - 2.78	2.77	2.79	2.78	±0.012
Kerri - Kerri Fm	15	2.30 - 2.52	2.38	2.39	2.40	±0.035
Gombe Fm	20	2.25 - 2.90	2.37	2.43	2.40	±0.100
Pindiga Fm	15	2.30 - 2.85	2.47	2.57	2.52	±0.025
Bima and Yolde Fm	40	2.40 - 2.80	2.46	2.48	2.47	±0.053
O l d e r granite	20	2.40 - 2.76	2.59	2.60	2.62	±0.0112
Migmatite - Gneiss	30	2.65 - 2.77	2.69	2.70	2.70	±0.0710

Table 5. 3: Density Values of rocks in the Gongola Arm of the Benue Trough

Rock Type	Cratchley and Jones 1965	Ajayi 1979	Adighije 1981
Basement	2.65	2.64 ±0.034	2.70± .07
Shale (Albian)	2.65	2.65± 0.04	2.62
Sandstone (Bima)	2.45 - 2.5	2.48± 0.05	-
Sandstone (Turonian Senonian)	2.40 - 2.5	2.45 ± 0.05	2.40± 0.161
Shale (Turonian Senonian)	2.50 - 2.55	2.53± .02	2.60
Sandstone (Tertiary)	1.90 - 1.94	2.30± 0.09	
basic intrusions	2.75 - 3.00	-0.26	

Table 5. 4: Generalised rock densities obtained in the Benue Trough

Due to the non availability of good topographic maps and the fact that there were no rapid changes in topography in the vicinity of most gravity stations, terrain corrections were not carried out on the gravity data. The non application of this correction is not expected to introduce errors greater than 0.2 mGals in the Bouguer anomaly value at any station.

5.6 Gravity Anomalies.

When the observed gravity has been corrected for the effects of the environmental factors discussed above, two basic gravity anomalies are recognised and these are distinguished by the gravity reductions which has been applied to the observed gravity g_{obs}. These are

(i) The Free-air anomaly obtained when the Free-air correction has been applied to the observed gravity and this is defined as

$$\Delta g_F = \left(g_{obs} + \delta_F\right) - g_\phi \quad \ldots(5.25)$$

where Δg_F is the Free-air anomaly

g_{obs} is the observed gravity

δ_F is the Free-air correction

g_ϕ is the theoretical gravity value at latitude ϕ

(ii) The Bouguer anomaly - obtained when the Bouguer correction combined with the Free-air correction and terrain correction (where possible) are applied. This is defined as

$$\Delta g_{Bs} = \left\{ g_{obs} + \delta_F - \left(\delta_{Bs} + B \right) \right\} - g_{\phi} \quad \ldots (5.26)$$

where Δg_{Bs} is the Bouguer anomaly

δ_{Bs} is the Bouguer correction applied

B is the bullard's term.

A third anomaly, isostatic anomaly, is also distinguished mainly in large scale surveys when isostatic correction has been applied to account for large scale density variations within the crust. For this research this correction was not carried out because of the relative small area covered by the survey and the lack of topographic maps for parts of the survey area.

The gravity anomalies (equations 5.25 and 5.26) resulting from the data reduction exercise are usually presented as maps of gravity isoanomalies. The production of isoanomaly maps can be either through manual preparation or graphical processing of geophysical data by means of computer.

For this work maps were produced using a computer software package (that carries out gridding contouring of the data on an IBM 486 PC) from the Golden

Software Inc. of the United states of America (1994). Figures 6.1 and 6.2 are the Bouguer and Free air anomaly maps of the study area.

5.6.1 Accuracy of the Bouguer gravity anomaly

In an attempt at analysing the accuracy of the gravity anomalies g, it is always necessary to evaluate the accuracy of the method used for this computation. The neglect of some terms as a result of simplification of formulae used in computations and erroneous values of constants may cause systematic errors in the computed anomalies- Δg. Systematic errors in Bouguer anomalies can be created by neglecting the correction for irregularities in the terrain, or by omitting Bullard's term. Other sources of errors include, instrument and operator precision, non-linear drift of the instrument and errors in the calibration of the gravimeter.

It is also a necessity that the effect of random and systematic errors of parameters of the formulae, the values of which are determined separately for each point of gravity. These include the observed value of gravity, g, the latitude of the station and the elevation of the station h. Also considered are the variable parameters of the model of topographic, or compensating masses , such as, the mean elevation of the terrain in the individual sectors into which the neighbourhood around the point of gravity has been divided for computing the terrain correction.

The total mean square error (Milos *et al.*, 1973) $M_{\Delta g}$ of the gravity anomaly Δg is defined by

$$M^2_{\Delta g} = m^2_{\Delta g} + C^2_{\Delta g} \ldots\ldots (5.27)$$

where $m_{\Delta g}$ is the mean square random error and $C_{\Delta g}$ is the mean square systematic error. The latter error is always very difficult to discern.

In practical gravimetry, the law of propagation of errors applies to the mean square random error (Milos *et al.*, 1973)

Therefore

$$m^2 \Delta g = mg^2 + \left(\partial \Delta g / \partial \phi\right)^2 m^2 \phi + \left(\partial \Delta g / \partial h\right)^2 + m^2 h \ + m^2 T \ \ldots.(5.28)$$

where

m_g, m_ϕ and m_h are mean square random errors in determining the gravity g, the latitude ϕ and the elevation h of the point of gravity respectively; m_T is the mean square error of the terrain correction. Thus the equation can be used for computing the mean square error of the Bouguer Anomaly.

The value m_g is determined by checking the gravity measurements. At a gravity checkpoint, n independent measurements of gravity (g) were made. The mean value of ***g*** and of the deviation ***d*** is determined at each control point for that observation with respect to the former. Thus

$$mg^2 = \Sigma d^2 / n-1 \ \ldots.(5.29)$$

Latitudes ϕ in most cases are usually taken from map, the error $m\phi$ therefore depends largely on the graphical accuracy with which the point of gravity is plotted. According to Milos *et al.*, (1973), a graphical accuracy of ± 0.50 mm on a map of scale 1:100,000 represents an error of ± 50 m and error in Bouguer anomaly of 0.08 mGal for $\phi = 45^0$.

Errors in elevation measurements m_h determined with altimeters can be up to 3 m (Ojo, 1974; Verheijen and Ajakaiye, 1980 and Umego, 1990). This result in $(\partial\Delta_g/\partial h) = 0.6$ mGal in the Bouguer anomaly. The mean square error m_T in the terrain corrections depends on the accuracy of the elevation in the individual sectors. In mountainous regions the error amount to several tenths of a milligal. Terrain corrections were not carried out in this work because of the lack of reasonably accurate topographic maps of the area. For areas of low - to - moderate relief (as is mostly the case in the area of study),these corrections rarely exceed a very few gravity units (Grant and west, 1965). Ojo (1974) in his attempt to compute the terrain correction of a station surrounded by hills as high as 300 m returned a value of about 0.2 mGal . This means that the maximum error introduced by not carrying out the terrain correction in the study area amounts to a maximum value of 0.2 mGal as none of the stations was seen to be surrounded by rocks that up to 300 m high.

Working under normal atmospheric and instrument conditions, errors in bouguer anomaly coming form repeated measurements of gravity at a point are negligible. Thus the main errors in bouguer anomaly always comes from inaccurate determination of the Latitude and elevation of stations. A graphical accuracy of ± 0.5

mm on a base map has a maximum error in Bouguer anomaly of 0.08 mGal. Elevation error in Bouguer anomaly for the error in altimetric levelling of 3 m is 0.6 mGal, and error resulting from non carrying out of terrain correction is 0.2 mGal. Thus the error in Bouguer anomaly coming from these sources is less than 1 mGal.

5.7 Magnetic Data

5.7.1 Data sources

The Geological Survey of Nigeria (GSN) through it's contractors ; carried out an Aeromagnetic survey of parts of the Country of which flying was completed in 1975. Contour maps of the total magnetic intensity, on a scale of 1:100,000 i.e. in half degree by half degree sheets were produced for the areas flown which included the area of study area of study.

Twenty one of these maps covering the entire study bounded area by Latitudes 9^0 10' and 11^0 N and Longitudes 9^0 30' to 13^0 E were digitised and utilised for this work. As indicated on the maps the nominal flight altitude used to acquire the data was 500 ft (152.4 m) above terrain, while the data were acquired on flight lines spaced 2 km apart. Tie lines were established at 20 km apart over the study area, the flight line direction was generally $150^0/330^0$ while the tie line direction was $60^0/240^0$. Regional correction was based on the IGRF (epoch date of 1st January 1974). The general direction of orientation of the flight lines is approximately perpendicular to the NE -

SW strike of the Benue Trough. Thus it is expected that the maps would give very accurate and useful pictures of the magnetic anomalies over the region.

5.7.2 Digitisation.

The Aeromagnetic maps were digitised at an interval on a grid of 3 km. In accordance with the Nyquist criterion , the smallest identifiable magnetic structure is at most 6 km wide. This is considerably smaller than the size of the targeted magnetic features of the current study , which are of the order of 20 to 200 km. Anomalies of this wavelength are of interest for the characterisation of the subsurface and Crustal structure.

The 21 sheets were digitised separately and the data stored according to grids.

5.7.3 Interpolation.

The data from each sheet was transformed into a regular grid using a computer program MINC (Webring ,1987), which iteratively carries out interpolation of data minimising the sum of the second horizontal derivatives. The solution honours data when it is available, and tends to extrapolate smoothly when not available. A search radius of 0.1^0 latitude degree (11 km) was used, and the resulting grid size was 0.009 latitude degree (1 km x 1 km) thus creating a 57 rows x 57 columns grid of 3249 grid positions for each sheet.

In order to ensure that the data at the adjacent sheet are compatible, it was necessary to include part of data from all surrounding maps in interpolating near sheet boundaries. An extra margin of 0.20^0 latitude (21 km) was included from adjacent sheets at each boundary. This was to ensure that the last row/column in a sheet is identical to the first row/column of adjacent sheet at all boundaries.

5.7.4 Merging.

The gridded data for the individual sheets were then imported into GRASS (Geographic Resources Analysis Support Systems) GIS and then converted into raster images. The raster images were then combined together into a master image for the entire area of study using the Subroutine r.patch available in the GRASS GIS Package.

The raster image represents a plot of the total intensity magnetic anomaly field over the project area for this work. The image was produced using the GRASS GIS Package and a black and white image plotted using a Canon (model LBP 430) printer at a scale of 1:2,400,000 to give fig 5.7. The raster image is a variable density plot. The format was chosen because such image have immediate visual appeal and do not require close examination that contours do.

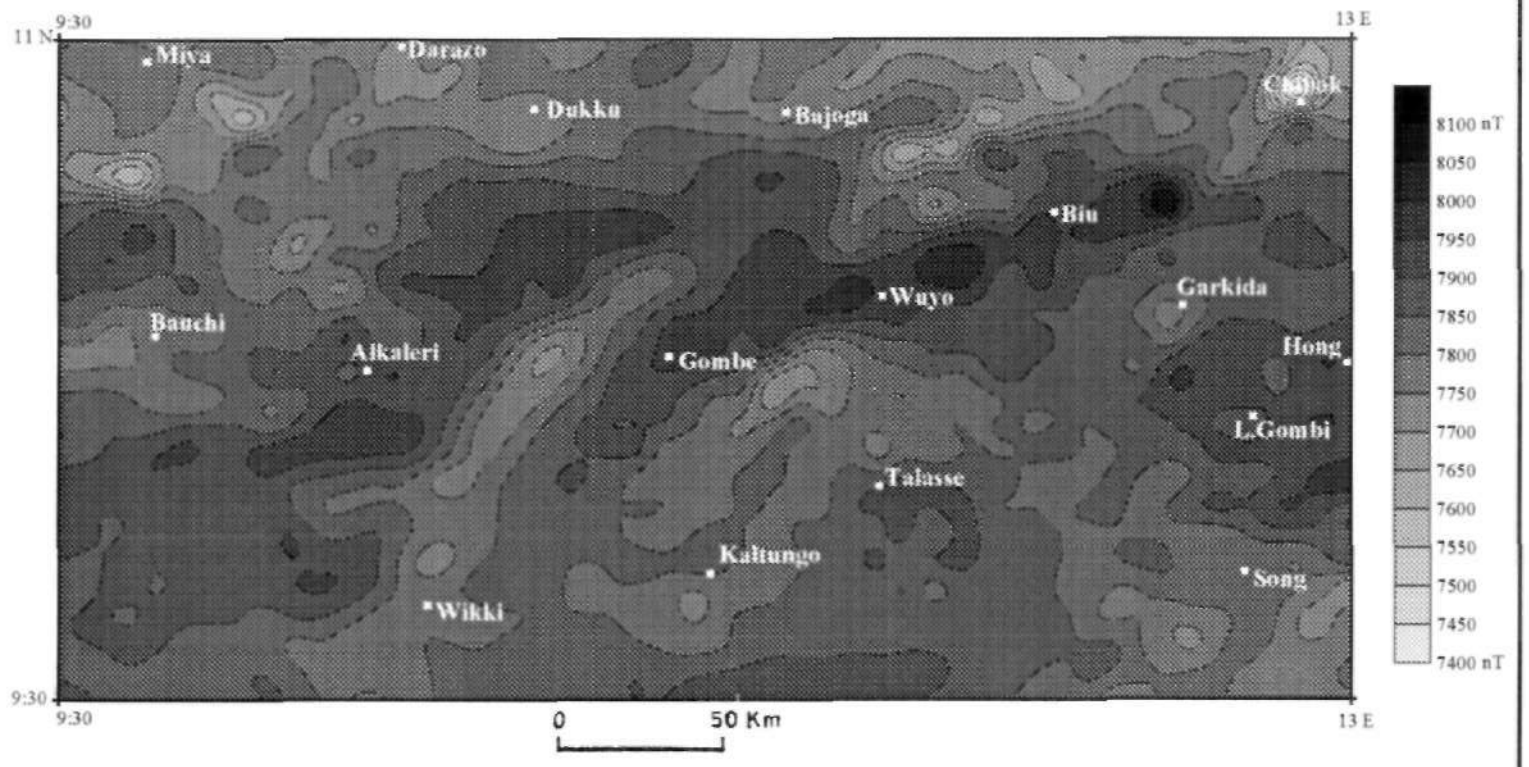


Fig. 5.7 COMPOSITE MAGNETIC-ANOMALY MAP OF THE GONGOLA ARM OF THE BENUE TROUGH OF NIGERIA

CHAPTER 6

INTERPRETATION OF GRAVITY DATA

6.1 Introduction.

According to Skeels (1967) two major problems are identifiable in gravity interpretations and can be summarised as follows:

(i) Separating the effects associated with geological features of interest from those that are not of interest from the Bouguer anomaly map and

(ii) Interpreting the anomalies of interest once they have been separated from others.

The first problem, commonly termed "regional - residual separation", is intimately related to the second whereby the anomalies of interest are first isolated before they can be interpreted. The second problem is that of having to choose from a large pool of possible geophysical models (sources) those which are most compatible with the geology of the area based on the other information at the interpreter's disposal.

6.2 The Bouguer Anomaly map and its Qualitative Interpretation

The Bouguer anomaly map (figure 6.1a&b) shows that the Gongola Arm of the Benue trough and it's environs is characterised by a negative Bouguer anomaly of the order of -75 to -10 mGals, with an average value of -42 mGals. A close examination of the Bouguer map reveals apparent trend of anomalies (numbered A -

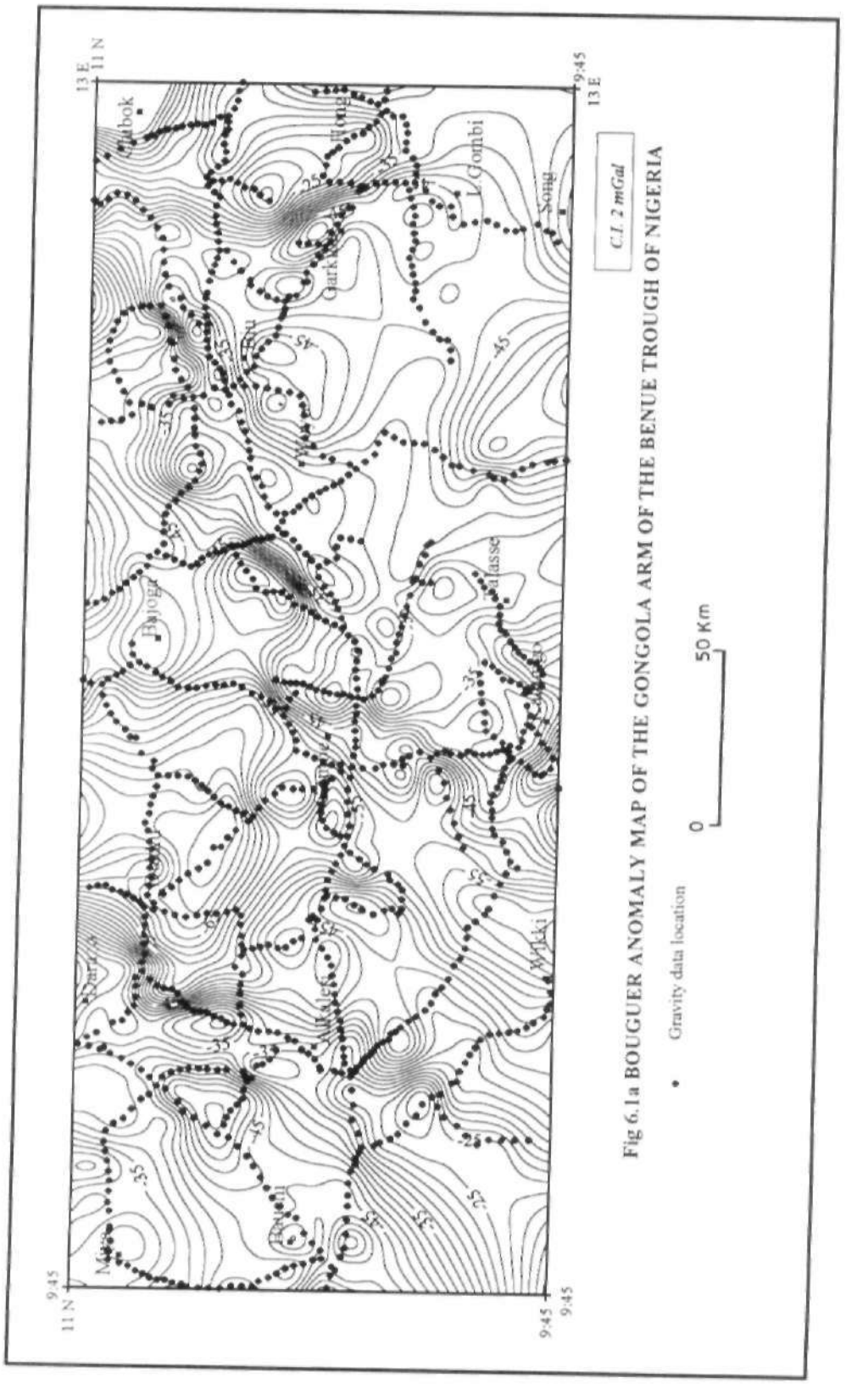


Fig 6.1a BOUGUER ANOMALY MAP OF THE GONGOLA ARM OF THE BENUE TROUGH OF NIGERIA

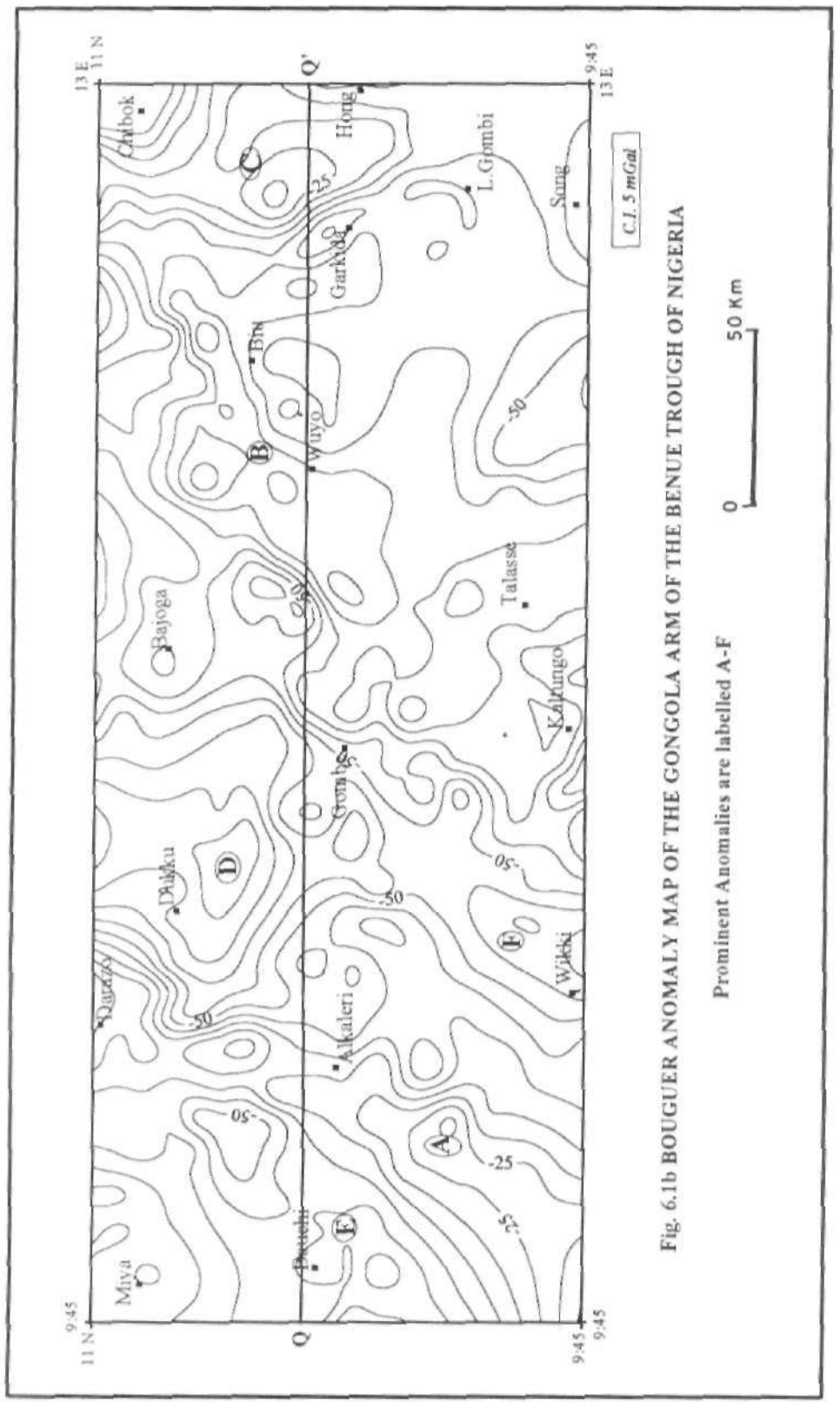


Fig. 6.1b BOUGUER ANOMALY MAP OF THE GONGOLA ARM OF THE BENUE TROUGH OF NIGERIA

Prominent Anomalies are labelled A-F

F, Fig 6.1b) along a NE-SW direction, which is most likely due to the fact that trend of the Benue Trough, of which the area of study is part, is in the NE-SW direction.

The area (figure 6.1b) reveals a number of anomalies characterised by relative high gravity values, one striking almost NE-SW and stretching from Darazo through Alkaleri (anomaly A) to the south-western part of the mapped area. Another anomalous area strikes NE-SW and stretches from Kaltungo through Wuyo to Biu and beyond (anomaly B). There is yet another anomalous area that stretches from Chibok to Hong (anomaly C) on the Eastern margin of the map, which trends in a NW - SE direction. The prominent relatively low gravity anomalies in the area are mostly centred on the Cretaceous Sediments in the Trough. The most prominent of these low gravity anomalies occurs to the Southeast of Dukku town (anomaly D) and appears to trend in the NW-SE direction. Another relatively low gravity anomaly area is centred around Bauchi town having a NE-SW trend (anomaly E), the one around Wikki (anomaly F) also has a NE-SW trend.

The gravity lows within the Basin, especially close to Dukku, (anomaly E) and Wikki (anomaly F) could all be due to low density materials (sedimentary rocks) of considerable thickness at basement depressions. The low gravity anomaly area around Bauchi (anomaly E) is ascribed to low density Older granites found within the area. The gravity high that occurs to the west of the Bouguer anomaly map (anomaly A, fig 6.1a&b) coincides with the contact between the basement rocks and the Tertiary Kerri-Kerri Formation and most probably indicates this

boundary. The other anomaly that stretches from Kaltungo through Wuyo to Biu and beyond (anomaly B) is attributed to basement rocks (which are seen to outcrop at Kaltungo and Wuyo) with associated basic intrusions at depth, the basaltic rocks that outcrop around Biu are also seen to give to high Bouguer anomaly. The Chibok to Hong gravity high anomaly(anomaly C) on the other hand could be said to result from density variations and associated intrusions within the undifferentiated gneiss-migmatite rocks.

Fig. 6.2 is a free-air anomaly map of the area of study. Since the calculation of free-air anomalies takes no account of the attraction of material above sea level, these anomalies will tend toward large positive values at higher stations (Garland, 1965). Garland also observed that the Bouguer anomalies have the tendency to go into large negative values for higher stations, this he attributed to the fact that there is a deficiency in mass below sea level, with the deficiency increasing as the land surface rises. A close examination of the free-air anomaly map reveals that the western part of the map (Fig. 6.2) is characterised by low free-air anomaly values (between -10 to 30 mGals) while the eastern part is characterised by higher free-air anomaly values (between 0 to 45 mGals).This implies that the western part of the map is at lower elevations and eastern part is at higher elevations. A comparison between the Bouguer and the free-air anomalies of the area of study reveals that although the free-air anomalies on the eastern part of the study area are high (Fig 6.2, between 0 to 45 mGals) as result of high elevations; the Bouguer anomalies (Fig 6.1a&b) do not go into large negative values as expected from the free-air anomalies values in the area, thus suggesting that the area is isostatically

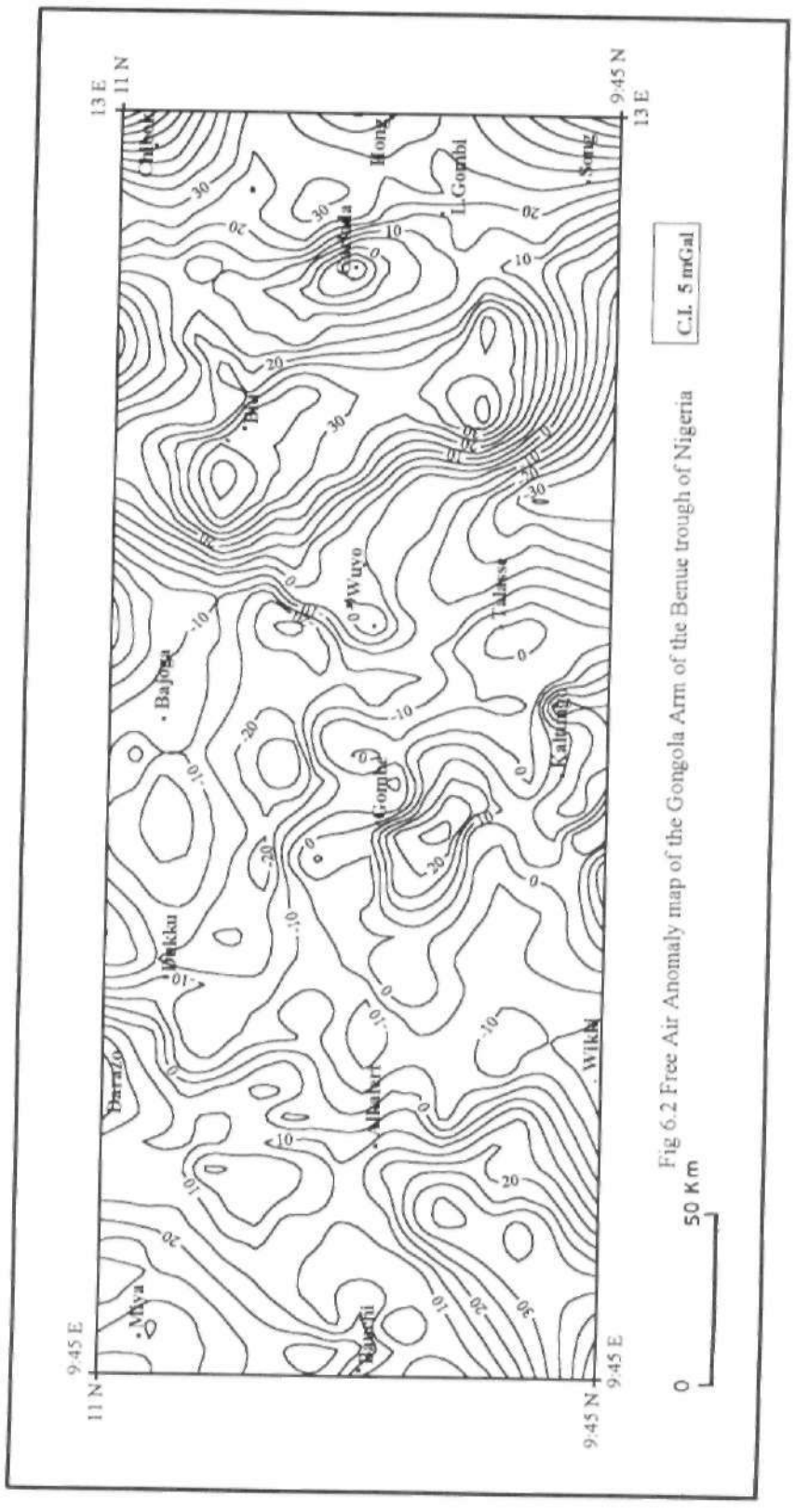


Fig 6.2 Free Air Anomaly map of the Gongola Arm of the Benue trough of Nigeria

compensated.

6.3 Regional Residual Separation

The observed gravity anomalies in an area usually represents the contributions from all anomalous masses within a given volume from the crust to the core beneath the area. It is always desirable to separate attractions caused by regional features from that caused by pertinent local structures. As a result, the observed anomaly can be subdivided into a regional anomaly representing the effects of broad and deeper structures; and the residual anomaly, which represents the effects of local relatively narrow geological features with shallow origin and which are often the object of gravimetric prospecting surveys.

The residual anomaly Δg_{res} is expressed as

$$\Delta g_{res} = \Delta g_B - \Delta g \quad .....(6.1)$$

where Δg_B is the (simple) Bouguer anomaly

and Δg is the regional effect.

Of critical importance in gravity interpretation is the estimation of regional effect, in that it determines what is left for further analyses after the subtraction from the observed Bouguer anomaly. There are two principal groups of techniques of removing the regional trend, one approach is entirely graphical while the other is

analytical. The graphical or smoothing techniques are highly flexible since they allow the interpreter to incorporate personal judgement of rightness about the forms of the residuals and hence do not have legitimate bearing on solution of some problems. If the regional trend is very strong the residual anomalies will be very difficult to discern. The same problem is encountered over rugged terrain and surface material of considerable inhomogeneity (Grant and West, 1965).

The analytical approach of regional- residual separation is purely numerical. The second derivative technique resolves directly the harmonic equation to which gravity fields are subjected to (Grant and West, 1965). Since the technique is a measure of curvature of the fields, enhancement of near- surface structures is often the object of interest. The main problem with this technique is the apparent lack of interpretational basis to which fields are to be subjected to. This is mainly due to the imperfection in the data with each level of differentiation which is an inherent problem of numerical differentiation (Grant and West, 1965). Thus the chief functions of second derivative method is to indicate the presence of anomalies under difficult circumstances (Grant and West, 1965).

One of the most widely used technique for regional - residual separation is polynomial fitting. This technique has many applications in geology especially in fields as stratigraphic studies. The basis of fitting polynomial to observed data is to compute mathematical surface giving the closest fit to the data that can be obtained within a specified degree of details. This surface is considered to approximate the effect of deep-seated or regional structures if it is of low degree (Zeng, 1989).

The polynomial fitting is based on statistical theory which assumes the residuals to be random errors whose sum is zero (Telford *et al.*; 1976). The fitting surface, which represents the regional, is a surface which will have both positive and negative flanks from the observed data points with the residual balanced between positive and negative areas (Nettleton, 1973).

Polynomial fitting yield results similar with second derivative maps because of the negative as well as positive flanks of residual anomalies (Nettleton, 1973). For this reason, the residual anomalies from surface fitting techniques cannot generally be said to represent the local geologic effects of any degree of surface. Therefore, not all results for surface fits can be used directly for quantitative geological interpretations by calculating the gravity effects to compare with the observed anomaly. The system is however very effective in picking out local anomalies (Nettleton, 1953 and 1973). Choice of appropriate order of residual, makes it possible to isolate or emphasise anomalies of almost any magnitude desired within limits of the definition by the spacing of the original data. For any quantitative evaluation of particular anomalies by calculation from geological interpretation or assumptions to be carried out, the regional Bouguer gravity map must be referred to.

All of the methods highlighted above can be applied to removal of the regional component from the gravity field. Alli (1988) compared results of obtained by several of these methods: Upward continuation, wavelength filtering, 2D wave

number filtering, graphical smoothing and polynomial trend analysis. He concluded that in his case the arbitrary graphical smoothing method gave the best results.

For the present work, however, the first order polynomial surface fit was found to be adequate and was therefore adopted because of the fact that it was found very effective in picking out local anomalies and also for reasons highlighted above. The basis of the method is discussed here below.

6.3.1 Concept of Polynomial fit

The objective of most trend surface analysis is to obtain a polynomial of sufficiently high order to give a surface of "best fit" to the map data. This is achieved by fitting a trend function to a set of data values. According to Simpson (1954), for a trend surface of degree n, the trend function F is

$$F(x,y) = \sum_{i=0}^{n} \sum_{j=0}^{n-1} a_{ij} x^i y^j \quad \ldots\ldots(6.2)$$

where a_{ij} are coefficients to be determined by adjustment using the least squares methods; x, y are co-ordinates of the point at which the function is evaluated. In regional gravity prospecting, the x, y co-ordinates of a point represent the longitude and the latitudes respectively and n is the degree of the polynomial.

When measurements are taken on a regular grid, the co-ordinates x and y in the latter series are replaced by orthogonal polynomials F(x) and F(y) (Milos *et al.*, 1973). However, non orthogonal polynomial analyses are used to estimate trends for observations not made on a grid pattern (Krumbein, 1959). Thus F(x, y) is the estimated regional field at point x, y for polynomial of any degree. If (g(x, y) is the observed Bouguer gravity value at that point, then residual anomaly R(x, y) will be

$$R(x,y) = G(x,y) - \sum_{i=0}^{N}\sum_{j=0}^{n-1} aij\, x^i y^j \ldots.(6.3)$$

R represents the random components plus some small scale fluctuations (Krumbein, 1959). A problem in fitting trends involves selection of the terms that are to be included in the trend, after which the remaining terms are combined in the residual. It can be seen from equation (6.3) that once the coefficients a_{ij} are known, the regional values and hence the residual or deviation values will be completely evaluated. Since the coefficients depend on the co-ordinates (which are accurately known) and on a fixed term, they remain constant for any degree of fit (Harbourg and Merriam, 1968) The least square criterion to be satisfied by (equation 6.3) is that of determining the position of the surface so that the sum of the squared deviation R is a minimum.

Therefore

$$\sum_k R^2(x,y) = \sum_k \left(G(x,y) - \sum_i^n \sum_j^{n-1} aij\, x^i y^j \right)^2 \ldots.(6.4)$$

is a minimum.

The computation of the coefficients is in Appendix I

A computer programme SURFIT developed by the USGS, and made available by the Department of Geological Sciences, University of Manitoba, Canada was used to estimate the regional effect in the area of study using the above outlined technique.

6.4 The Regional Anomaly Map

The regional gravity field derived by fitting a first degree polynomial to the Bouguer anomaly data is shown in Figure (6.3). The regional field is represented by a first degree surface, which was chosen out of various degrees of polynomial fits that were tried. It was chosen because it is the best reflecting the regional character of the gravity which correlates well with the known geology of the area. The first degree surface for the area is a plane dipping NNW-SSE at a rate of 0.04 mGal/km. The first degree trend appears to follow the general trend of the Bouguer anomalies in the area (Fig 6.1).

The decrease in regional Bouguer values from -35 to the East to -46 mGals in the West (Fig. 6.3), suggests that the lithosphere thins in the same direction since first degree fit emphasises deepest disturbing sources (Zeng, 1989). Also these values are close, to the -48 mGal obtained by Brown and Girdler (1980) in their interpretation of African gravity and it's implication on the break-up of the

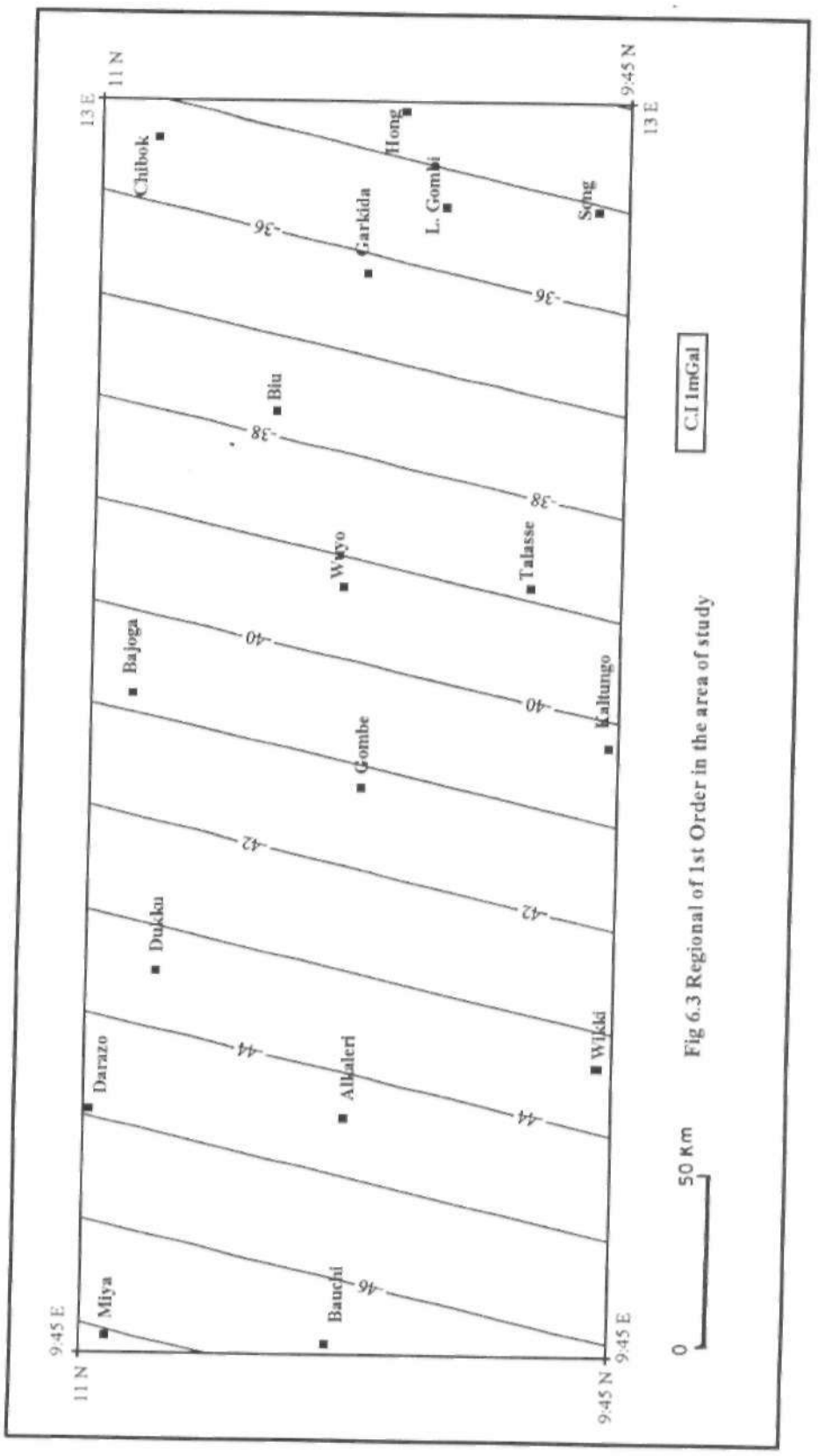


Fig 6.3 Regional of 1st Order in the area of study

continents, which they associated to deep seated structures of lithospheric origin. Thus the regional gravity in the area of study could be attributed to lithospheric structures.

The gentle nature of the slope of the regional in the area shows that the lithospheric thickness in the area of study is to some extent uniform, with only small variations in thickness occurring in the area. Therefore, the crust in the area of study could be said to experience some thinning.

As a result of the limited areal extent of the study area, the regional obtained from this polynomial surface fitting cannot be said to be free of the influence of shallow structures in the area.

6.5 The Residual Anomaly Map and its Qualitative Interpretation.

The residual anomaly map (fig. 6.4) shows several prominent closures (anomalies) within the study area and these have been numbered 1 -11 on the residual anomaly map. A comparison between this map and the geologic map of the area of study (Fig. 6.5) indicates that Anomaly 1 which is a positive gravity anomaly lies to the SE of Bauchi. The anomaly trends in NE-SW direction, and stretches for about 100 km having a width of about 30 km. It stretches from beyond

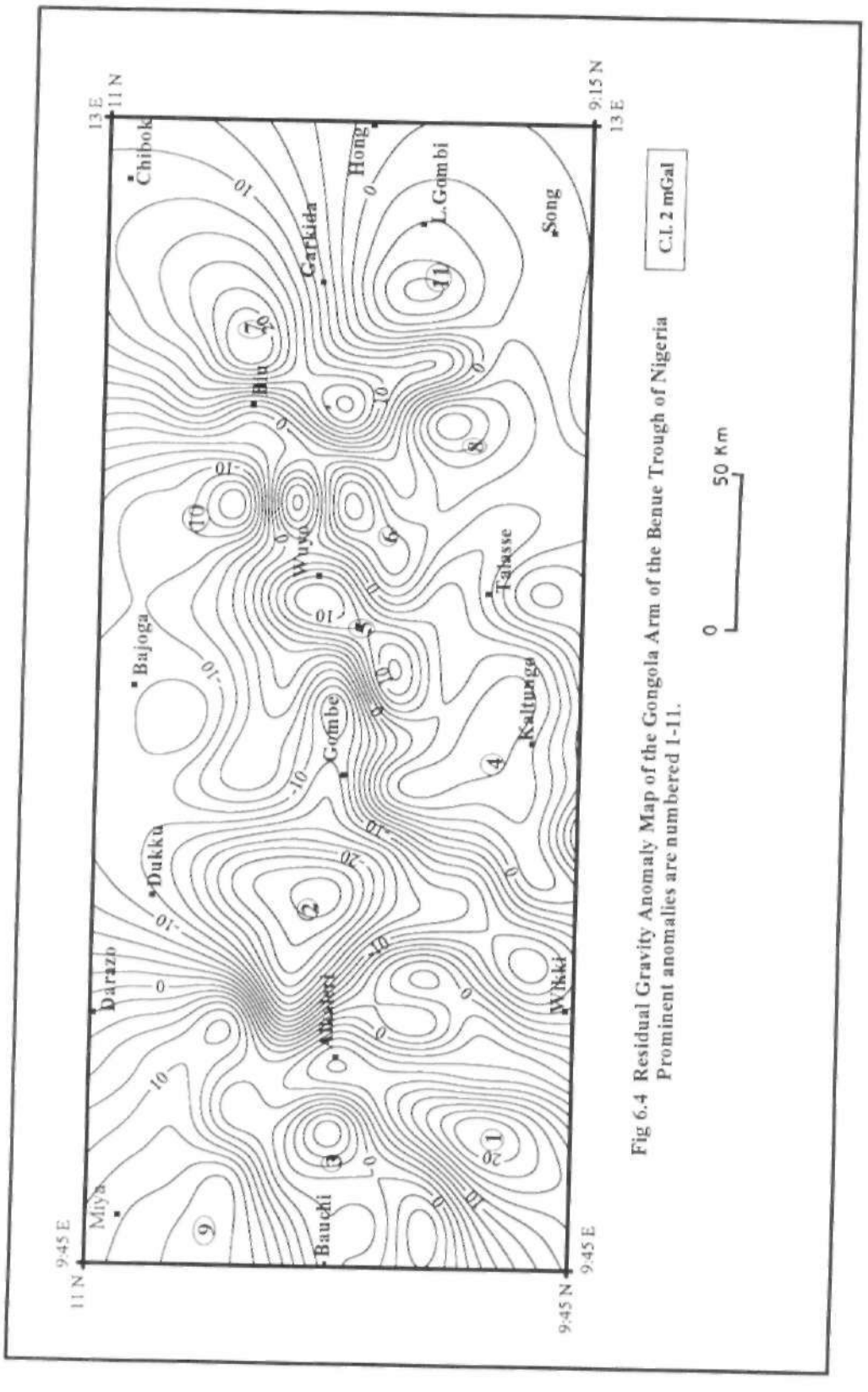


Fig 6.4 Residual Gravity Anomaly Map of the Gongola Arm of the Benue Trough of Nigeria
Prominent anomalies are numbered 1-11.

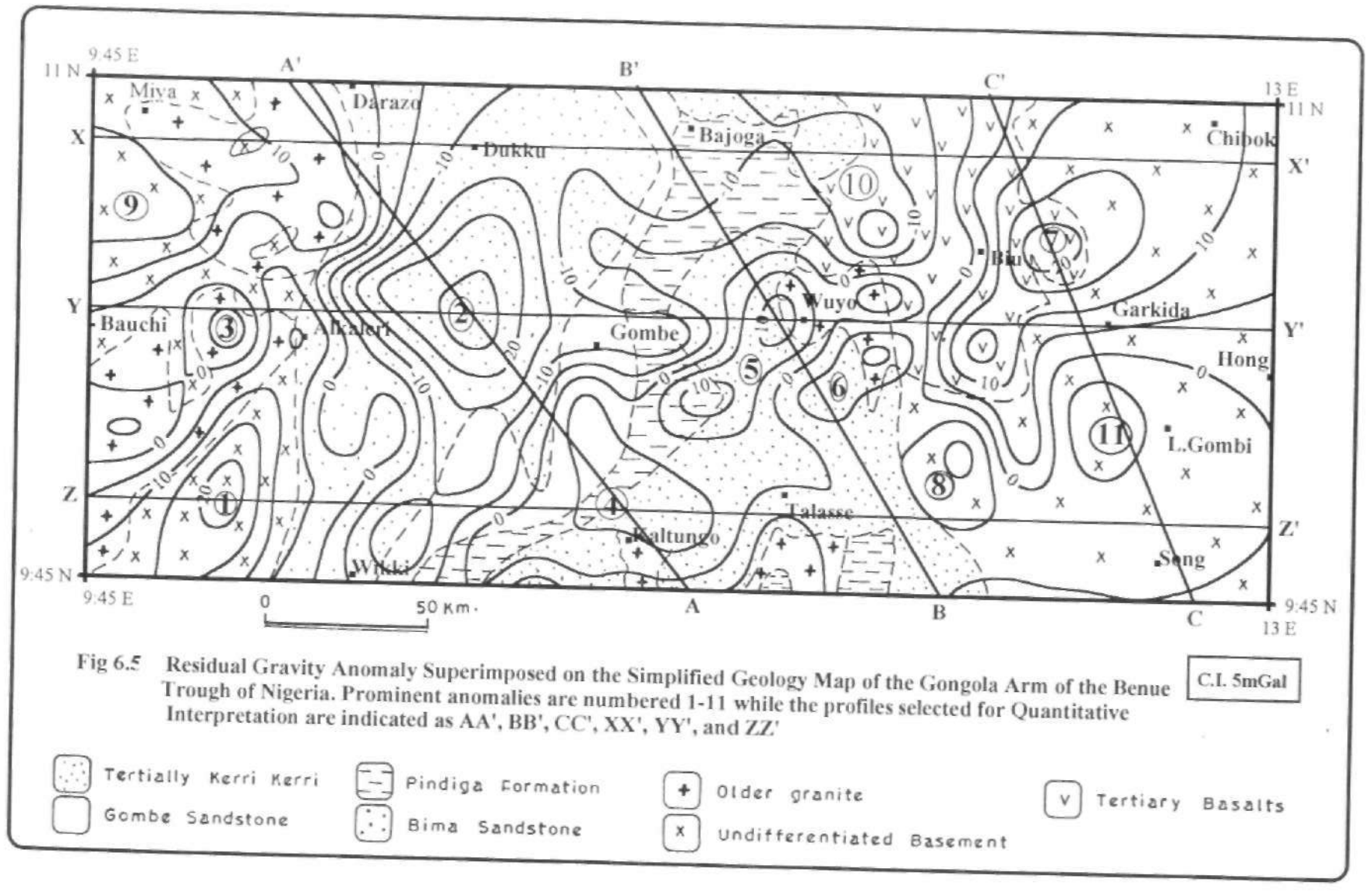


Fig 6.5 Residual Gravity Anomaly Superimposed on the Simplified Geology Map of the Gongola Arm of the Benue Trough of Nigeria. Prominent anomalies are numbered 1-11 while the profiles selected for Quantitative Interpretation are indicated as AA', BB', CC', XX', YY', and ZZ'

Alkaleri to the south western end of the map and is located at the western margin of the basin where the Tertiary Kerri-Kerri Formation is in contact with outcrops of the basement complex and where the thickness of the sediments is thought to be very small. This anomaly coincides with the outcrop of the undifferentiated gneiss-migmatite. Field observations during the data collection confirm that the undifferentiated migmatite, which includes high grade metasediments (amphibolite schist, garnet mica-schist, quartzite etc.) with density of about 2.78 kg m^{-3}. outcrops extensively on the western side of the map and has a contact with the tertiary Kerri-Kerri Formation, and is therefore thought to be the cause of the anomaly seen in the area.

This anomaly (anomaly 1, Fig. 6.4) coincides with the axial anomaly identified by Fairhead and Okereke (1987) at the margin between the sediments and basement on the western side of the study area. This anomaly could be attributed to the marginal volcanic intrusives occurring at the edges of basement horsts associated with major ENE-WSW, NW-SE, N-S and E-W in the Upper Benue trough (Wilson and Guirauld, 1992) of which the present study area is part. Though these volcanics have however not been mapped in that part of the trough, but their presence cannot be ruled out as they are seen to occur in other parts of the area especially around Bashar in the middle Benue Trough, and Biu area, which is located at the eastern part of the study area (Fig 6.5).

Anomaly 2 is a negative anomaly located between Gombe, Alkaleri and Dukku with a minimum (maximum negative) value of about -25 mGal. The

anomaly is located on the Kerri-Kerri Formation and is therefore believed to have resulted from increase in sediment thickness at a basement depression or block faulted area within the trough. The close and sharp (of 25 mGals) nature of the contours at the margin with the basement suggests that some faulting (block faulting) could have taken place in the area and this block faulting resulted in the formation of a depression which has been subsequently filled by low density materials (the Cretaceous sediments below and the Tertiary Kerri-Kerri on top) giving rise to the observed negative anomaly in the area.

The presence of the highly sheared/fractured basement rock (the Gombe inlier) in Gombe suggests that the inlier around Gombe must have been brought about by some tectonic movements such as faulting (block faulting) that resulted in movement of the basement blocks relative to one another. This tectonic movements probably resulted in the formation of horst and graben in the Gombe area and environs thus giving rise to the inlier in Gombe in form of a horst and the graben created by this movement is thought to have been filled by thick sediments which give rise to anomaly **2**

Anomalies **3**,**6**,**8** and **11** which occur around Bauchi and Wuyo respectively correlates well with the Older granites (fig. 6.5) that have been mapped around this areas. These older granites consist of fine grained granites and syntectonic granites that are rich in potash and are acidic in nature (Carter *et al.*, 1963). The acidic nature of these granites is supported by their low residual anomaly values (between 0 to -5 mGals).

6.6 Quantitative Interpretation of the Residual Anomalies

6.6.1 Introduction.

In quantitative interpretation of gravity data, an attempt is made at determining the position, size and shape of the source whose gravitational effect matches, as closely as possible, the measured gravity field at the surface of measurement, through an analysis of it's potential field. This task is always made difficult by the problem of non-uniqueness, in that same anomalous field on the surface, could result from different combinations of the spatial distributions of the anomalous subsurface masses and their densities. This shortcoming is partly overcome by making some basic assumptions which must be justifiable within the context of what is known or can be reasonably inferred about the geologic environment. Thus, constraints in the form of simplification of geometry, limits to size and shape of causative bodies and range limits on density are imposed.

Two routes by which the source distribution is determined are "forward modelling" and "inversion" (Paterson and Reeves, 1985). In this work the forward modelling approach is used and it comprises the following steps:

i) estimation of an initial model, compatible with the known geology,

ii) computing the exact theoretical anomaly for this model,

iii) comparison of the observed and computed anomalies for this model,

iv) fine-tuning of the model by human interaction within acceptable geologic limits, with the hope of improving the fit of the computed data to the observed points.

Once an acceptable fit is found the process is stopped.

6.6.2 Method of interpretation

Two and Three-dimensional interpretation of the prominent anomalies was carried out with the aim of determining the nature, source and type of the anomalies in the area of study. The results of the 2-Dimensional modelling gave an insight into the structure of the area under study. The results of these interpretations are hereby presented.

6.6.3 3-Dimensional interpretation

The three-dimensional (3-D) method of Talwani and Ewing (1960) was used to interpret the anomalies on the residual map. The method uses a computer program GRAVPOLY (Godson, 1983a) that calculates the gravity effect of three-dimensional models that consist of elements that form polygons in plain view (Plouff, 1975a,1976). The elements of the models are bounded by two horizontal planes and a series of intersecting vertical planes. The calculation uses exact formula rather than the numerical integration approach of previous Talwani (1960) programs. Thus, values can be obtained on or inside the model. A least-squares comparison between the calculated anomalies and the observed field was used to determine the best density contrast for the assemblage.

Three profiles (AA', BB' and CC' of Fig. 6.5) representing vertical cross-section through the assumed bodies, were chosen in order to investigate the properties of the residual anomalies identified such as the nature, depth of occurrence and density of causative bodies.

Model Fitting Procedure: The first step of the modelling exercise was that irregularly shaped polygons, representing contours were fitted as closely as possible to the assumed shape of the causative bodies at different - pre-selected depth points (fig. 6.6). The next step was to determine the longitudes and latitudes (x and y co-ordinates) of each point on the profile as two mutually perpendicular axes in a horizontal plane The Z axis (depth) was taken vertical upwards.

The input for the computerised interpretation consists of the following

i) the co-ordinates of all fields points as well as the observed residual anomaly at these points along the profile of interest

ii) the co-ordinates of the corners of the polygon and the depth of the polygon as well as density contrast associated with it (polygon).

The output from the computerised interpretation is as follows:

i) a plot of the polygonal bodies used (on screen) to ensure that polygon co-ordinates are correct,

ii) a listing of all the input data which acts as a check

iii) the contribution of each polygon at each field point (optional)

iv) the computed total anomaly, the difference between the computed and observed anomalies (residuals) the standard deviation and the average difference between the two values.

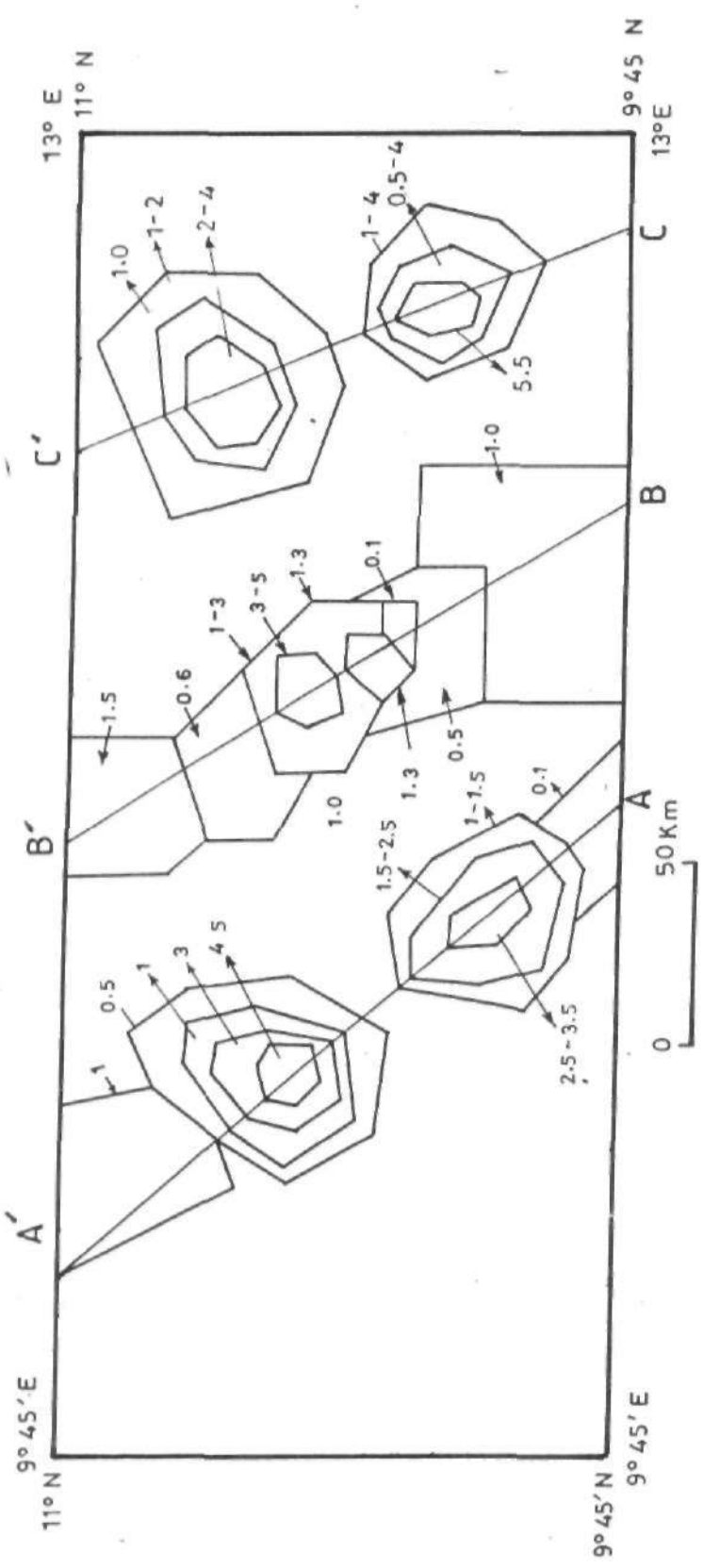


Fig. 6.6 Plan of Three-Dimensional model of Bodies used to interprete four major gravity anomalies in the area (depth values are in Km),

v) a plot of the observed and computed anomalies at each field point along a chosen profile (optional)

6.6.4 Three - dimensional interpretation of the residual anomalies

The 3-dimensional interpretation of the selected profiles (profiles AA', BB' and CC' using the program Gravpoly (Godson, 1983a) is hereby presented below.

Profile AA': This profile runs NW-SE through the basement rocks (close to Darazo), the sedimentary sequence, and again intersects the basement rocks near Kaltungo (inlier). It is centred on Anomaly 2 and covers a distance of over 180 km (fig. 6.5). Figure 6.7 shows the observed and computed anomalies together with the vertical cross-section for the interpreted model of the profile. For this model a density of 2670 kg m^{-3} which is the average value determined for the basement rocks in the area (table 3)was used for the basement rocks, 2780 kg m^{-3} for the high density basement of schist composition and a statistically determined average of 2450 kg m^{-3} was used for the sediments. The model reveals that a high density basement rock probably, of schist composition, underlies the basement rocks at the south-eastern boundary of the area of study, at a depth of about 1 km. This high density basement is seen from the model to outcrop at the north-western margin of the profile. The model also reveals that the Cretaceous sediments (average density 2450 kg m^{-3}) attain a maximum thickness of 4.5 km towards the centre of the profile (Fig. 6.7).

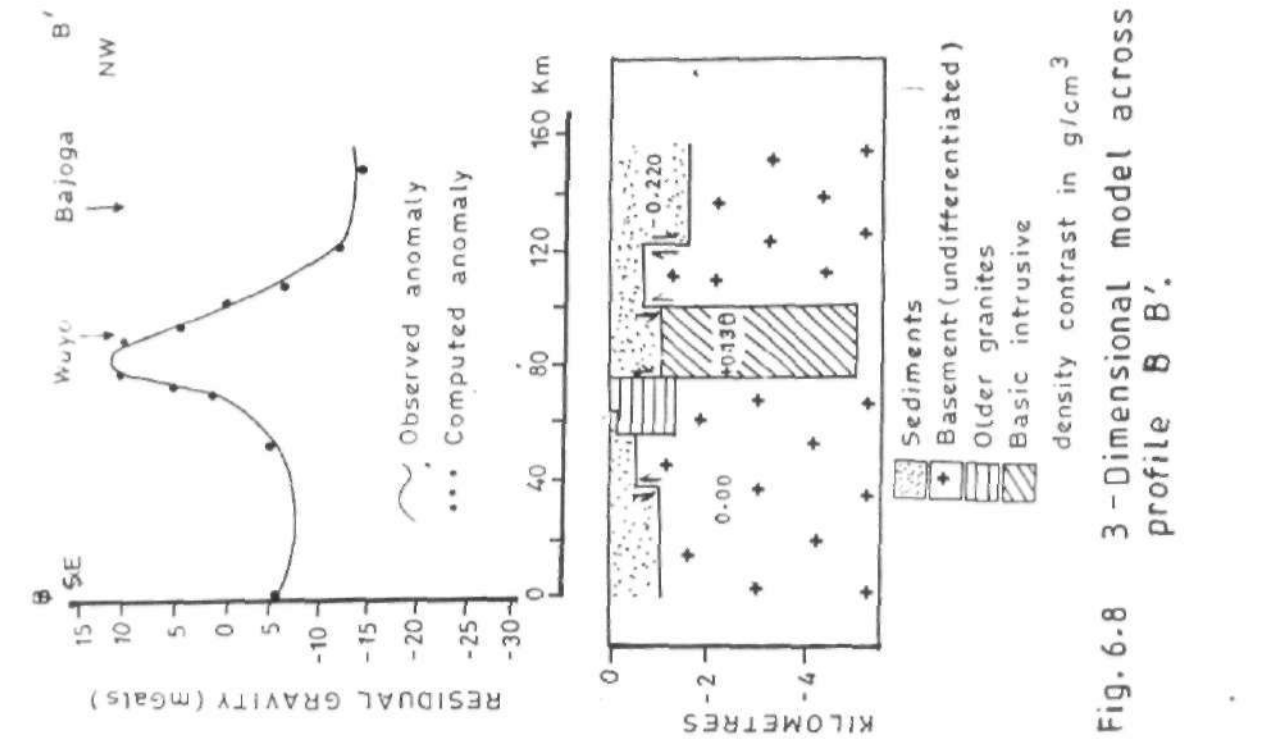


Fig. 6.8 3-Dimensional model across profile B B'.

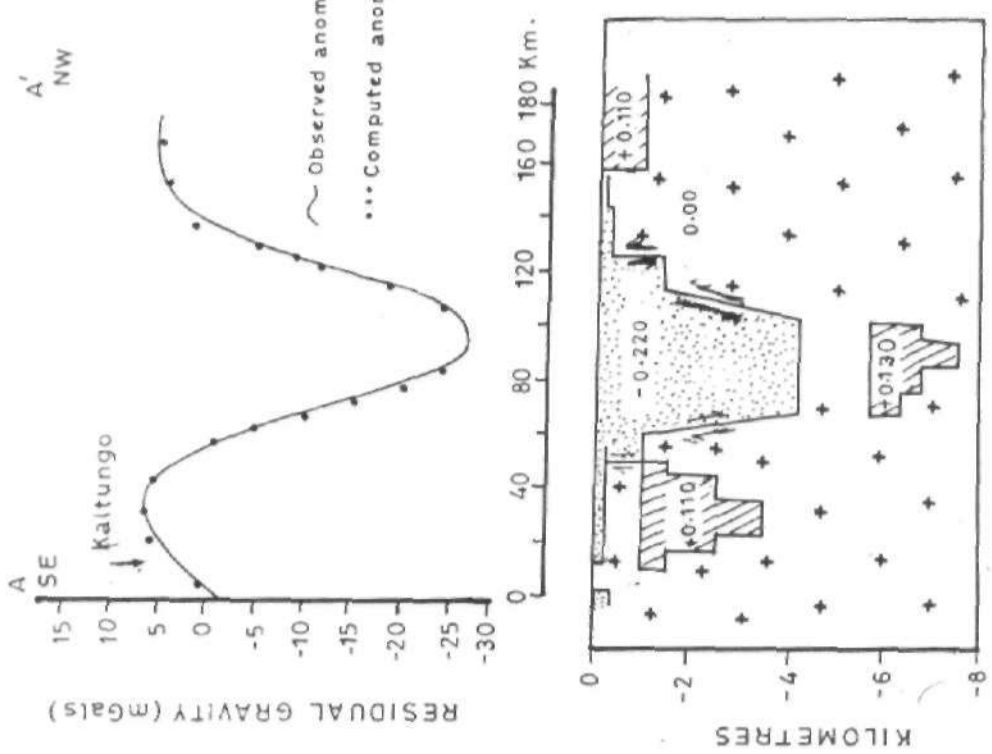


Fig. 6.7 3-Dimensional model across profile A A'.

The computed anomalies are seen to have fitted the observed anomalies fairly well (fig. 6.7). The deduction that could be made from the model is that it suggests that block faulting probably took place in the area giving rise to the graben structure (depression) which was rapidly filled by sediments.

Adegoke *et al.* (1986), in their study on the New stratigraphic, Sedimentologic and structural data on the Kerri-Kerri Formation (which covers the western margin of the study area), suggested the existence of a series of faults along the contact with the basement and concluded that this contact is faulted. This view is supported by the results of this model which suggests that faulting most probably took place in the area resulting in the graben structure seen in the model shown in fig 6.7. Also, a close examination of the contours in Figure 6.5 suggests faulting along the contact of the sediments with the basement. The existence of such faults at the basement/sediment boundary (western part of the study area) could result in the formation of a graben that is now filled by sediments thus giving rise to the sediment thickness of about 4.5 km.

Profile BB'; This profile strikes in the NW -SE direction and crosses anomalies **5** and **6** (Fig 6.5). Anomaly **5** on this profile is a positive anomaly that has a sharp nature, and the sharp nature of the anomaly, suggests that the anomaly most probably results from basement uplift or shallow basement and the presence of basic intrusive at depth. Fig 6.8 shows the possible model accounting especially for the large positive anomaly (Anomaly 5). Thus the source of the positive anomaly is attributed to basement uplift and the existence of high density basic intrusive

(probably of gabbroic composition) at depth in the area. A density of (about 2800 kg m^{-3} was assumed for the basic intrusive. The model (Fig. 6.8) reveals that this basic intrusive occurs at depths between 1 km and 5 km. The older granite unit seen to outcrop on the surface (of density 2620 kg m^{-3}) is also modelled to occur in the area (anomaly 6 around Wuyo), from the surface to depths of about 1.4 km.

The Cretaceous sediments (of density 2450 kg m^{-3}) along this profile are seen from the model to have a maximum thickness of about 1.5 km towards the NW end of the profile, while the undifferentiated gneiss-metasediments unit were modelled to have a density of about 2670 kg m^{-3}.

Profile CC': The profile was chosen to cut across anomalies 7 and 11 on the North-western edge of the map (fig 6.5). It extends for a distance of about 140 km and trends in the NW-SE direction. Figure 6.9 shows the possible model accounting especially for the large positive anomaly. The source of the large positive anomaly is modelled in terms of a basic intrusion of high density (of density about 2800 kg m^{-3}). The basic intrusive because of it's density (2800 kg m^{-3}) is believed to be of gabbroic composition. The denser body is thought to be the source of the basaltic magma seen to outcrop on the surface in the form of basaltic flows, as seen on the Biu plateau. Many craters exist on the Biu plateau (Carter *et al.*, 1963) and these craters are believed to source the materials for these flows from these basic materials that give rise to the strong positive anomaly seen on this profile. These craters are believed to have their root as deep as 4 km as suggested by figure 6.9.

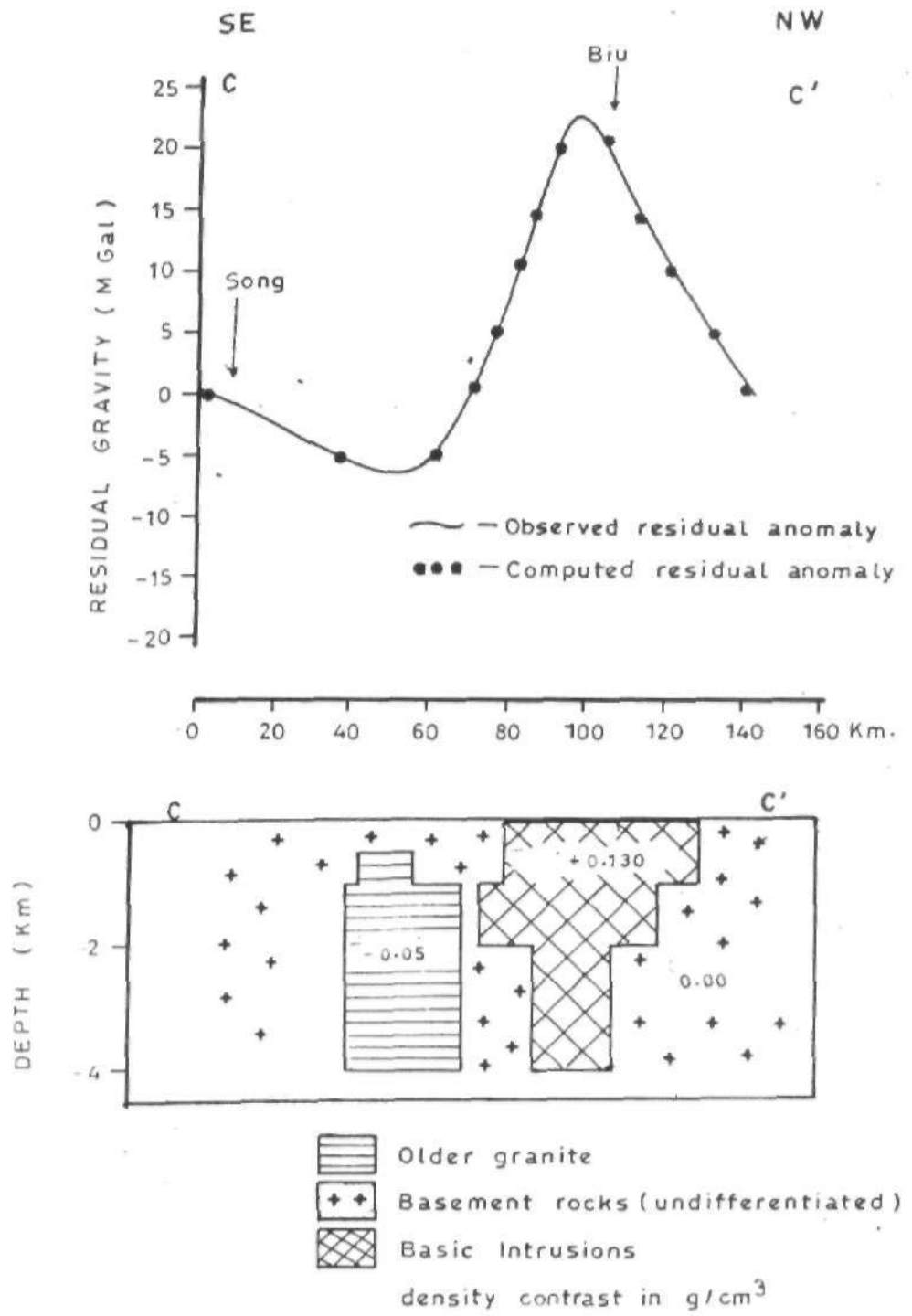


Fig. 6.9 X — section of 3 - dimensional model across profile C - C'.

These basalts could have found their way to the surface around the Biu plateau in form of flows through cracks and fractures in the earth's crust, while some of the lava remained the craters at depth, giving rise to the positve anomaly seen in the area.

An older granite suite(of density 2620 kg m^{-3}) was modelled to intrude the basement rocks in the area and occurs at depths between 0.5 and 4 km.

6.6.5 Two-dimensional interpretation of anomalies.

Three profiles labelled XX', YY' and ZZ' (fig. 6.5) were taken across the axis of the trough in an E-W direction, from basement to basement. These profiles were chosen with the sole aim of taking a look at the structure of the trough in the area of study. The profiles were interpreted using a Two-Dimensional approach because the length of the trough is much larger that it's width. Theoretical models of the assumed model were thus calculated, for various points on each profile, using the line integral method (Talwani *et al.*, 1959, Quereshi and Mula, 1971; Jin, 1974) for a two dimensional body. The computer program used for the calculating the theoretical residuals of the model was based on the algorithm of Talwani (1973).

During the interpretation, several models using different thickness of strata and density contrasts were employed. The models with the best fit for each profile using all available geological information are discussed here below.

Profile XX': The profile runs in an E-W direction and stretches for about 357 km through the northern edge of the study area (fig 6.5). It runs through the basement area on the western flank into the Sediments and terminates in the basement on the eastern flank.

The residual gravity along the profile has a broad minimum centred around 90 - 260 km (fig 6.10), with a gravity relief of -16 mGal. The two ends of the profile (i.e. the western end and the eastern end) are characterised by a maxima. The residual gravity low is seen to coincide with the sediments outcrop in the area while the maxima coincides with the basement outcrop. The interpreted model for this profile (fig. 6.10a&b) suggest that the profile is over a basement complex of density 2670 kg m^{-3}, that has been intruded at depth by some high density rock material of density 2780 kg m^{-3} on the western margin. The eastern margin of this profile is also suggested by this model to have been intruded by high density basic intrusive of density 2800 kg m^{-3}.

The interpreted model suggest that the Cretaceous sediments in the area have attained a maximum thickness of 1.5 km and overlie the graben and horst structures that exist in the area (Fig. 6.10a&b). The interpreted models suggest the existence of two grabens in the area. The first one is about 100 km wide (occurs between 100 and 200 km along the profile Fig. 6.10) and a smaller one of about 35 km wide (occurs between 220 - 255 km) (Fig. 6.10a&b). The two grabens are separated by a

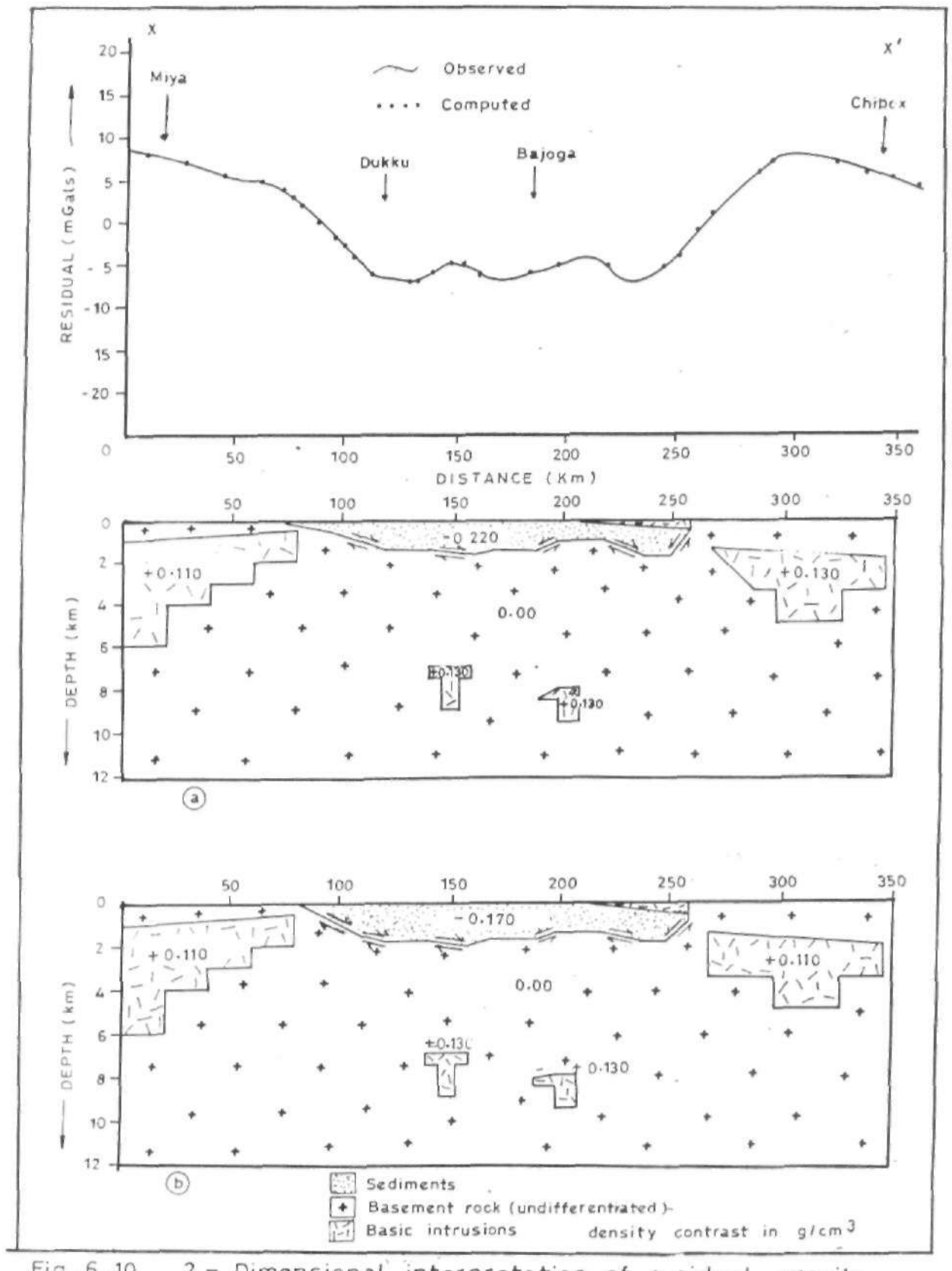


Fig. 6.10 2 - Dimensional interpretation of residual gravity anomalies along profile X X'

The general structure along profile XX' can be said to be that of horst and graben with associated magmatic intrusion at depth.

Profile YY': The residuals along the profile have a single major minima over the sedimentary portion, with amplitude of -25 mGals. There are three maxima, two of which are along the edges of the basin and the third one centres on the Biu plateau which is seen to intrude the basement on the eastern end of the study area.

The interpreted model for this profile (Fig. 6.11) suggest the existence of a major graben structure centred on the sedimentary portion of the profile. The interpreted model for this profile suggest that the graben is about 80 km wide in the area, that contain sediments as thick as 4.5 km. (Fig 6.11a). Fig. 6.11b which is an alternative model of this profile suggest that the sediments are up to 5 km thick along this graben. The results suggest that the area has been affected by normal faulting (block faulting) that resulted in the formation of this graben. The throws of this faults are suggested by the model (Fig 6.11a) to range from 0.8 - 0.9 km.

The interpreted model also suggest the existence of igneous intrusives on both sides of the trough adjacent to the sediment-basement contacts. These intrusives are also seen from the model to intrude the basement rocks that underlie the graben in the area, and are also suggested from the model to intrude the basement on the eastern end (i.e. around the Biu plateau). The basic intrusives

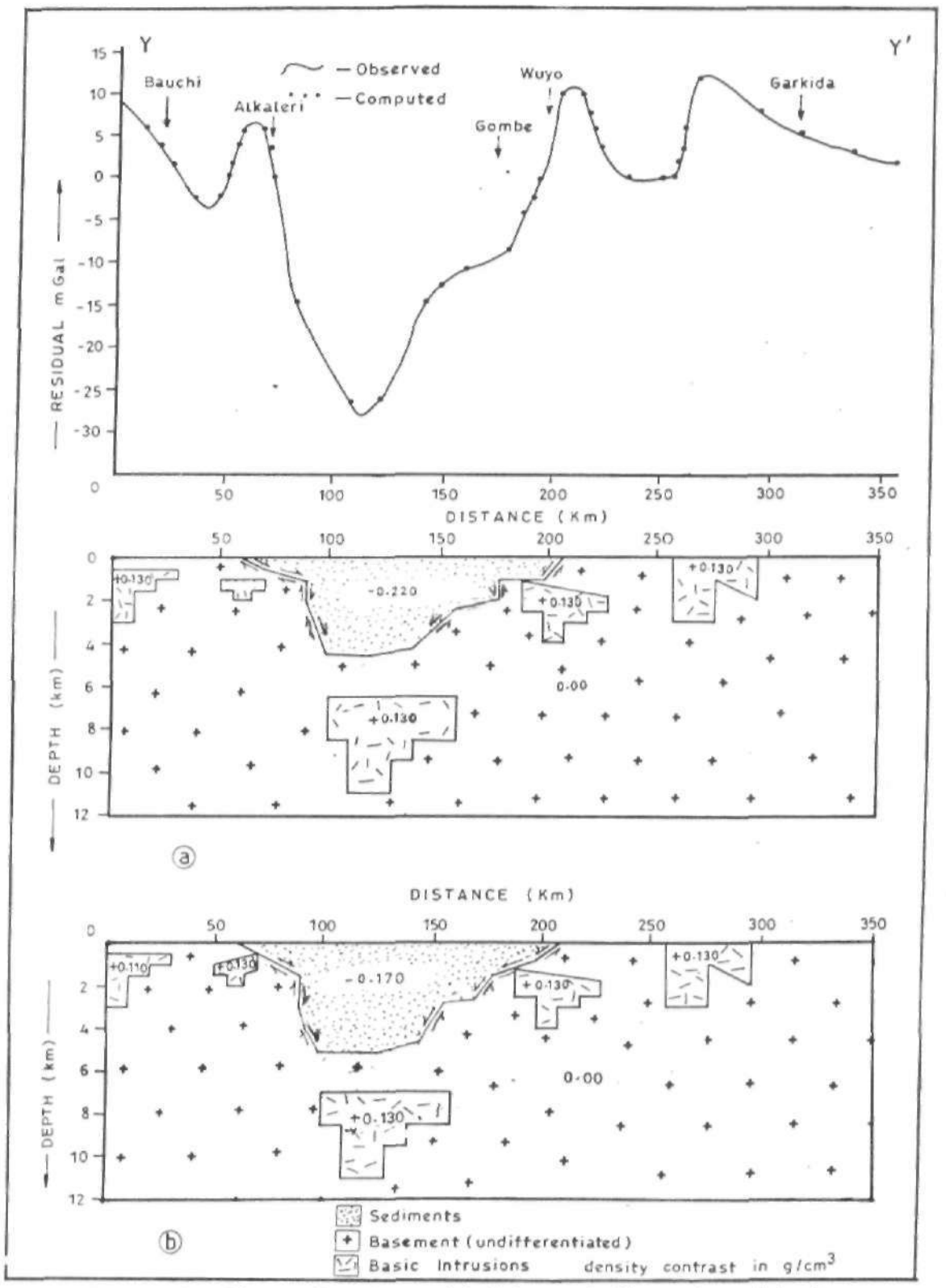


Fig. 6.11 2 - Dimensional model interpretation of residual gravity anomalies along profile Y Y'.

suggested from these models have densities of about 2800 kg m^{-3} suggesting tha they are probably of gabbroic composition. These basic intrusives are suggested by the models (Fig 6.11a&b) to occur as shallow as on the surface (Tertiary basalts o the Biu Plateau, fig. 6.5) to as deep as 7 km. Recent field mapping (undertaken by the author and others) in the area reveals that the area has been intruded by basic intrusive materials. These basic rocks were picked up as small fragments on the surface.

The basement complex on the western edge of the profile is seen to contain high density metamorphic basement (2780 kg m^{-3}) folded into the basement

Profile ZZ': This profile runs across the trough in an E-W direction, cutting across the basement on the western edge into the sediments and again on to the basement on the eastern edge.

The residual anomaly along this profile has a small minima centred between 60 and 140 km and yet another very small one between 180 and 240 km. These minima have a gravity relief of -10 mGals. The western end of the profile is characterised by a broad positive anomaly of relief 5 mGals. The residual high on the western end of the profile is seen to coincide with the basement-sediments contact, while the broad positive anomaly around the centre of the profile is seen to be overlain by sediments.

The interpreted models for these profile (Fig. 6.12a&b) suggest that the residual minima in the area basically consists of sediments of density (2450 - 2500 kg m^{-3}), that range in thickness from 0.3 km to about 2 km. The interpreted model also suggest that the two small grabens separated by a horst exist in the area. The 1st graben is about 100 km wide and is filled by sediments that are up to 3 km thick (Fig 6.12b), while the 2nd graben of about 60 km width is filled with sediments of thickness up to 1.7 km. The horst on the other hand is about 45 km wide and is covered by sediments less than 0.5 km (Fig. 6.12a&b).

The results of the modelling along this profile also suggest that the residual high on the western end of the area that is in contact with the sediments, is due basically to high density intrusion at depths of between 1 and 7 km. Results of the modelling also suggest the existence of these basic intrusives within the basement in the area, at depth ranging from as shallow as 1 km to as deep as 8 km (Fig. 6.12a&b). The high density nature of the intrusives (2800 kg m^{-3}) suggest that they are probably gabbroic in composition. These basic intrusives are believe to intrude the basement rocks in the area, as they were seen to be and essential component of the model in order for a fit to be obtained between the observed and calculated anomalies.

The broad positive anomaly of relief 5 mGals centred around the centre of the profile is seen from the model to be as a result of basement uplift (horst) with associated basic intrusive at shallow depths of 2 km and also at greater depths of between 7-8 km.

6.7 Crustal Structure of the Gongola Arm of the Benue Trough.

The crust and upper mantle under the Gongola arm of the Upper Benue Trough and adjacent areas were modelled along profile QQ' using the gravity field over the area and density values of 2.85×10^3 k gm^{-3} for the crust and 3.02×10^3 kg m^{-3} for the upper mantle. These density values fall within the range published by Telford *et al.* (1976) and Grant and West (1965) for the rocks at the base of the crust and mafic rocks. A small density contrast of $+0.17$ g cm^{-3} between the crust and upper mantle was therefore used. In addition, there is evidence of decreasing P_n velocity with depth from 8.0 to 7.8 km s^{-1} beneath the Yola arm of the trough (Fairhead and Okereke, 1990) which is adjacent to the present area of study. According to these authors the decrease in P_n velocity suggest that there may exist an anomalous low density material beneath the Yola rift; thus suggesting that there may exist an anomalous low density lens of upper mantle material beneath the Gongola rift.

Fig. 6.13a shows a plot of the Bouguer anomalies along profile QQ'. The observed Bouguer anomalies along this profile were resolved by matching marginal gradients and extending them smoothly, as carried out by Ajayi (1987b) for the gravity data within the Benue Trough, into the following three components :

1. a very long wavelength (λ=350 km) negative anomaly, and assumed to be due to asthenospheric rise under the trough (Fig 6.13a).

2. an intermediate (λ=250 km) positive anomaly, also centred over the trough which is considered to be due to crustal thinning (Moho uplift) under the area of study (fig. 6.13b) and

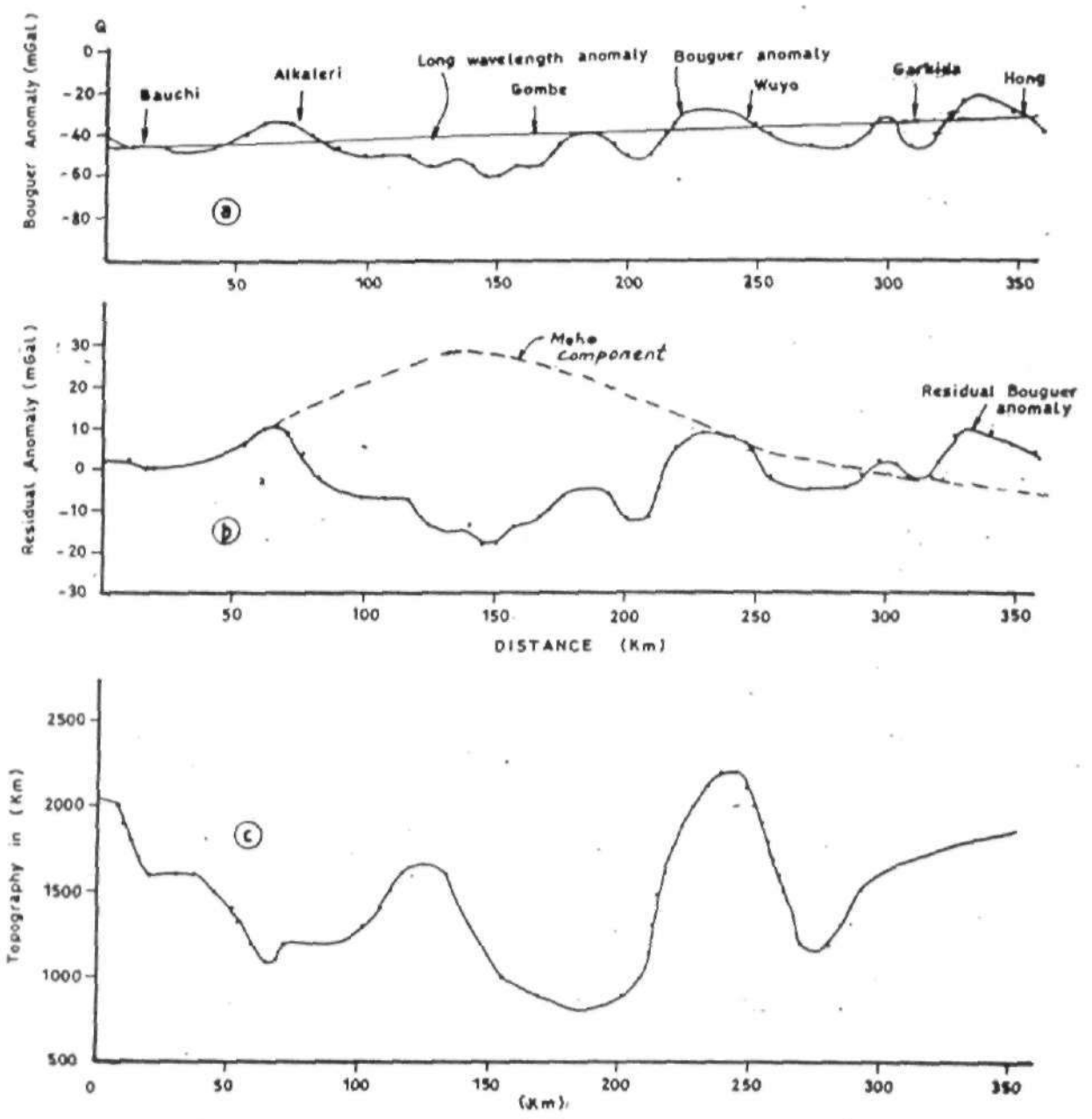


Fig. 6.13 Bouguer gravity and topography of profile Q – Q' (see Fig. 6.1b for location) across the Gongola Arm of the upper Benue Trough.

3. a short wavelength (λ=180 km) negative anomaly due to the Cretaceous and Tertiary sediments filling the trough.

Fig. 6.13c is a plot of the topography along this profile (QQ'). The topography along this profile is plotted in order to be able to determine whether or not the area is isostatically compensated.

Figs. 6.13a and 6.13c show that an inverse relationship exist between the Bouguer anomalies (fig. 6.13a) and topography (fig 6.13c) across the area of study. The topographically lower areas along the profile are seen to correspond to areas of relatively high Bouguer anomalies, while the topograhically higher areas correspond to the areas with relatively lower Bouguer anomalies. This inverse relationship suggests that the area is isostatically compensated. The only point along the profile where this inverse relationship does not hold occurs between 210 - 260 km (Figs. 6.13a and c). At this point there exist a correlation between elevation and Bouguer anomaly; thus suggesting that the area is not isostatically compensated. An excess mass (probably the Biu Plateau basalts) is believe to be the cause of the excess uncompensated mass in that area.

Two dimensional modelling was carried out for Profile QQ' (fig. 6.1b) to determine the crustal structure in the area. An average crustal thickness of 34 km was obtained in the project area using the Woollard (1959) method. This value corresponds to that obtained by Fairhead and Okereke (1987) for the Yola arm of the Benue trough just to the south-east of the present project area.

Fig. 6.14 shows the interpreted gravity model for Profile QQ'. A density contrast of +0.17g cm^{-3} between the base of the crust and upper mantle was used. The model for the dense mantle body has outward sloping flanks which are steeper on the western margin than the eastern one. This assymetry probably reflects, to some extent, the nature of the upper mantle beneath the Biu Plateau (Fig.3.1) to the northeast. The width of the crust beneath this uplifted Moho (crustal thinning) is about 50 km giving a Moho rise of 5.5 km from 34 km. It can be seen (Fig. 6.14) that the uplifted Moho broadens at the base extending over about 200 km. Thus crustal thinning of up to 5.5 km in the Gongola arm of the Upper Benue Trough is indicative from this study, a value very close to the 5 km thinning obtained by Ajayi (1987b), and other workers (Artsybassev and Kogbe, 1974 ;Osazuwa *et al.*, 1981) in the Upper arm of the Benue trough of which the current area is part.

The two dimensional model in figure 6.14 also suggests a maximum thickness of about 3 km for the sedimentary fill in this part of the project area. Another feature of the model is the inclusion of high density basic intrusive bodies at the eastern and western margins coincident with the gravity highs of the area. There is also a prominent one deeper and larger at a depth of about 7 km under the thick sediments (fig. 6.14). These bodies especially the one at 7 km depth which could not be picked by the gravity survey, show as prominent clusters of solution in the area by the analysis of magnetic data, using the Werner deconvolution method. The crustal structures alos indicates a granitic body (density contrast - 0.050 g cm^{-3}) occurring between 273 - 285 km along the profile. This body can be seen as an outcrop shown by the geology map of the area (Fig 3.1).

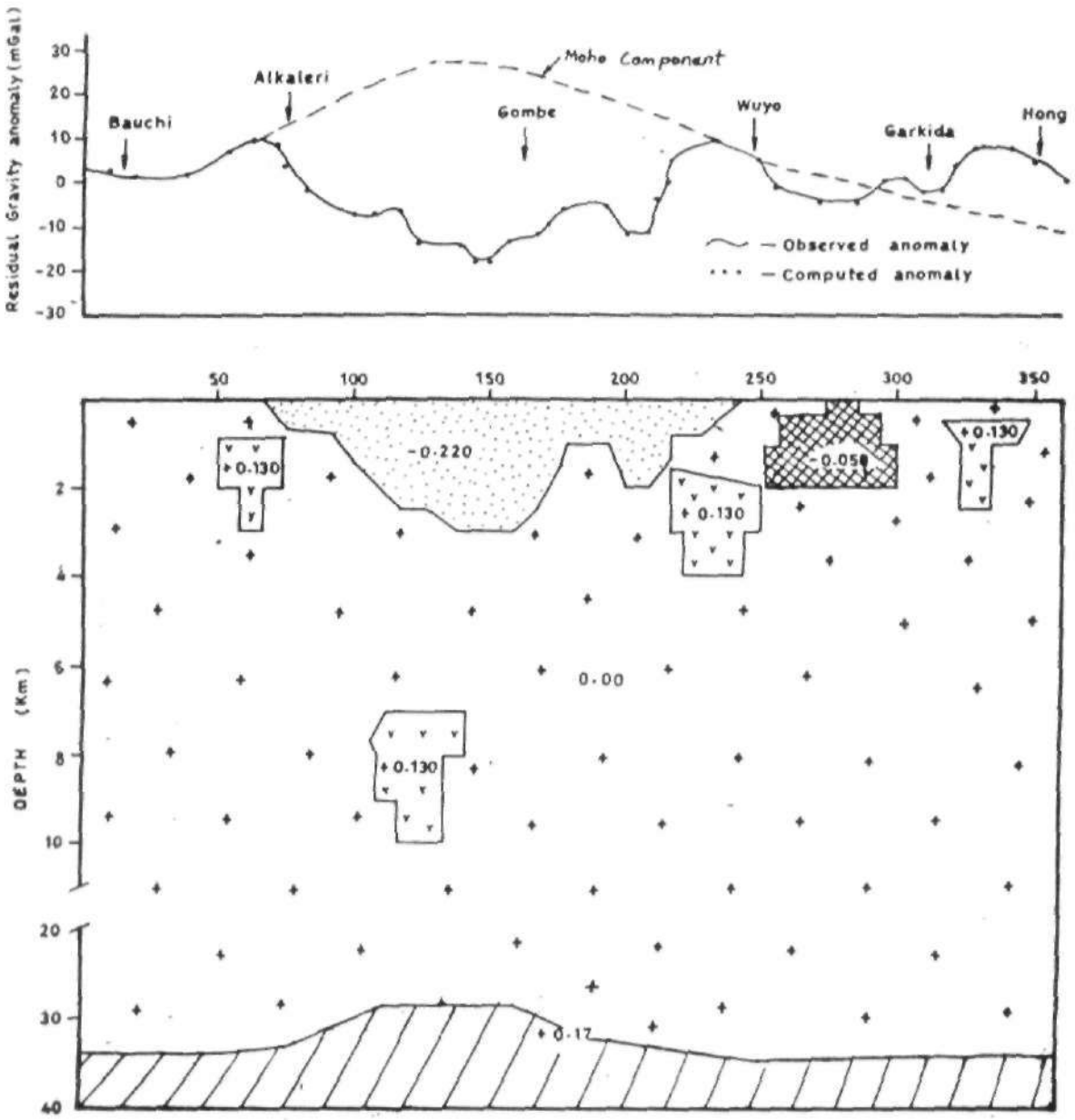


Fig. 6.14 A Two-dimensional crustal Model of the Gongola Arm of the upper Benue Trough Along Profile Q–Q'

(density contrast in g/cm^3)

Sediments | Older granite | Basic Intrusives | Upper mantle

The model also suggests that the smallest crustal thickness in the area may not be less than 28.5 km. Thus, neither crustal separation nor the existence of a spreading ridge, suggested by Burke *et al.* (1970) for the trough, did occur in Gongola arm of the Benue Trough. Rather model suggests the existence of a short-lived spreading ridge as suggested by Grant (1971).

CHAPTER 7

INTERPRETATION OF AEROMAGNETIC DATA

7.1 Introduction

Aeromagnetic data interpretation took a giant step forward with the introduction of digital processing and interpretation techniques using computers; giving rise to rapid, objective and high resolution of anomalies (Hartman *et al.*, 1971).

Different approaches have been adopted for the interpretation of aeromagnetic data, but all generally fall into the three basic groups, as shown below:

i) Qualitative methods - Visual interpretation of maps

ii) Profile methods - Study of selected profiles

iii) Map method - Involving mathematical process applied to map data (Reford and Summer, 1964).

In qualitative interpretation, simple concepts are employed to obtain information by visual inspection of magnetic anomaly maps. The excellent correlation that often exist between magnetic data and geology is a clear indication of the potential of the qualitative method of interpretation of magnetic anomaly maps. However, it is often important to extract definite parameters from magnetic data. Therefore, the more sophisticated quantitative methods of data treatment are usually employed. Typical instances are like in oil surveys where thickness of

sediments and/or depth to basement are required. On the other hand, in mineral prospecting, determination of susceptibilities, shape, size and dips of anomalous structures (bodies) are more important. With an appropriate assumption on geometry of the magnetic source, the problem of determining these parameters often reduces to simple mathematical expressions that can be solved by the profile method. Several other interpretation techniques involving the use of residual maps, derivatives and continuation of surfaces can be grouped into the map method and is capable of yielding information on depths to the causative bodies as well as emphasize special attributes of the total field map.

7.2 Qualitative Interpretation of Magnetic Anomalies of the study Area.

The total magnetic intensity composite maps of the area of study are shown in figures 7.1a and 7.1b as density and contour plots respectively. The dynamic range of the total intensity magnetic field is 700 nT, the contour levels ranging from 7400 nT to 8100 nT, with and average value of 7880 nT. A close examination of the contour map (fig. 7.1b) reveals some clustered areas with mainly short wavelength anomalies from near surface geology. These short wavelength anomalies are circular or elliptical and mostly oriented along an E -W direction thus defining a fabric that is commonly found on the Basement Complex of Nigeria (McCurry, 1971 ; Ball, 1980).

The most prominent features evident on both composite maps (figures 7.1a

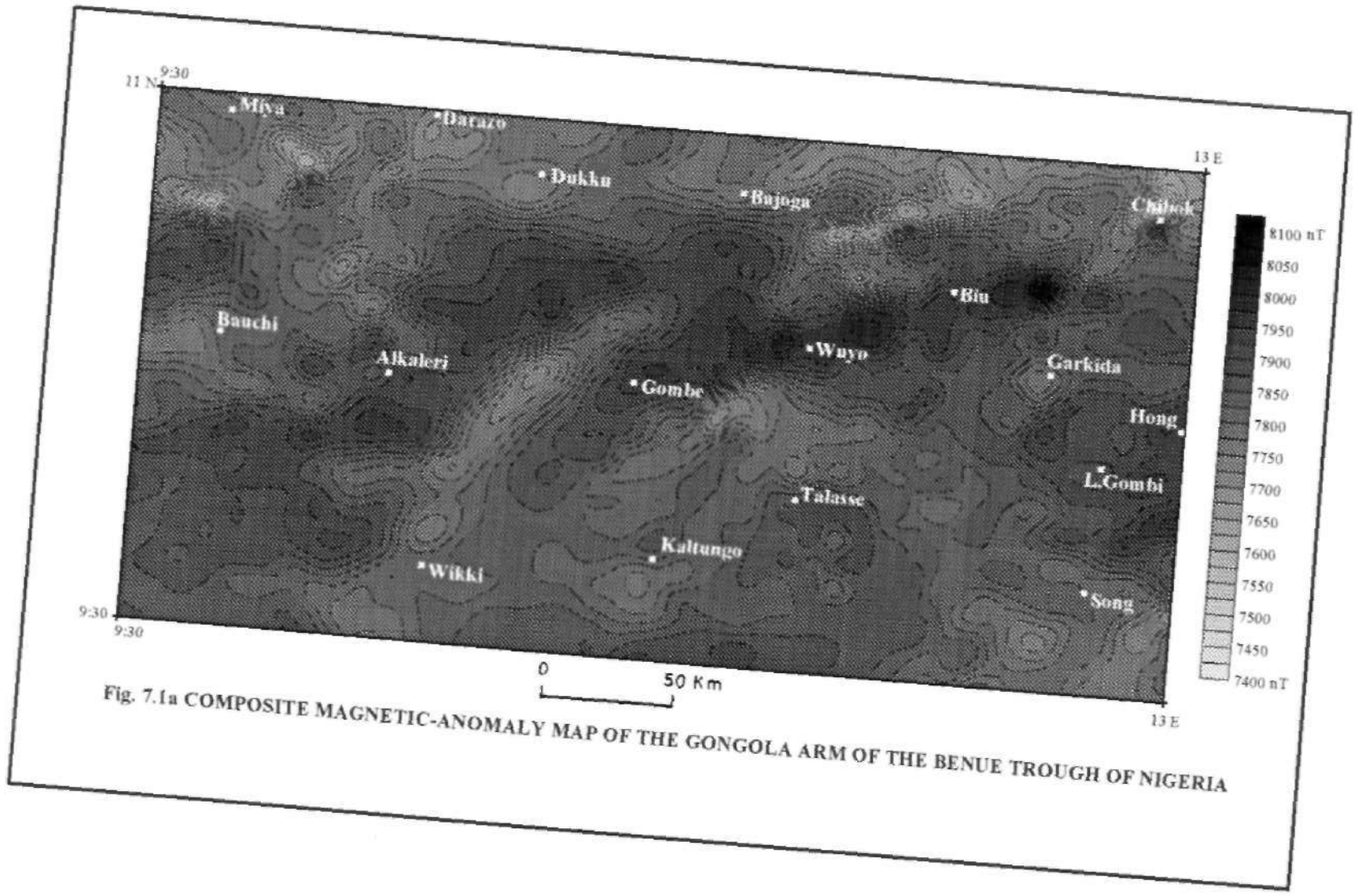


Fig. 7.1a COMPOSITE MAGNETIC-ANOMALY MAP OF THE GONGOLA ARM OF THE BENUE TROUGH OF NIGERIA

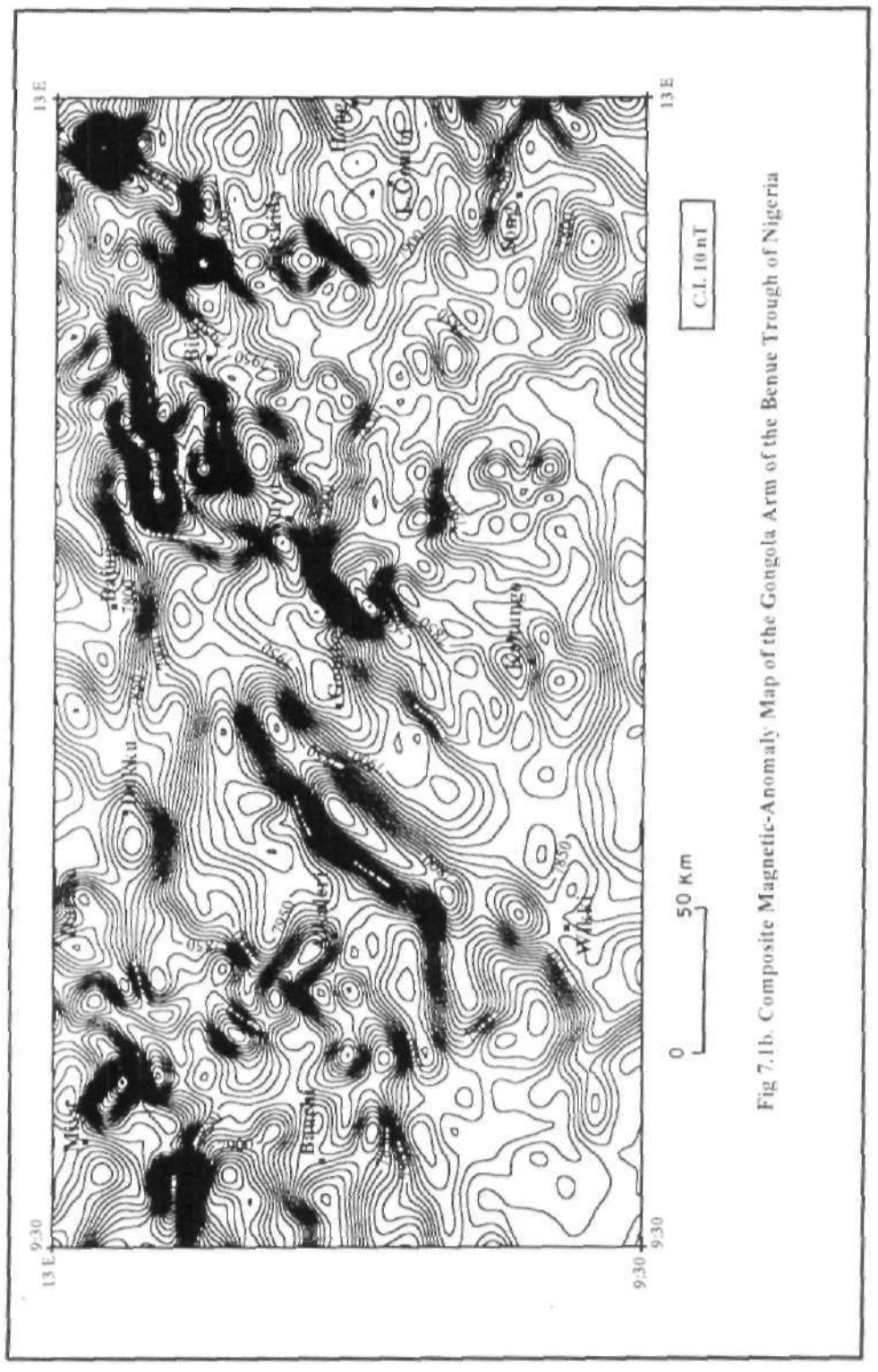


Fig 7.1b. Composite Magnetic-Anomaly Map of the Gongola Arm of the Benue Trough of Nigeria

and 7.1b) is the large scale NE-SW trending magnetic anomaly (marked as AA' in Fig 7.2) beginning around Wikki and runs through the axis of the area of study passing between Alkaleri and Gombe through to the North-eastern part of the study area. There are two other lineaments parallel to this major lineament, one around Kaltungo and another close to Gombe. These lineaments are marked out as solid broken lines as AA', BB' and CC' in figures 7.2 and each (all) of which strike in the NE-SW direction. Lineament AA' shows as a continuous narrow belt that has an average width of about 25 km and stretches for a distance of over 250 km (Fig 7.2) and has a curviplanar surface suggestive of the existence of a low angle reverse fault (wrench fault) at depth in the area of study, which may be part of the numerous dextral NE -SW African wrench faults observed in other parts of the Nigerian Basement Complex (McCurry, 1976; Ball, 1980). Anomaly BB' also appears as a continuous narrow belt with an average width of about 20 km which stretches for about 80 km while anomaly CC' also shows up as a narrow belt that averages about 15 km in width and extends over 100 km in length.

The characterisation of these magnetic lineaments either as faults, fractures etc. is of vital importance in the understanding of the tectonic history of the area of study. Wright (1968) mapped out a pair of conjugate NE-SW and NW-SE fractures in the middle Benue trough (which the study area is part of); the Cameroon Rift Valley, the Middle Niger lineament and the Chad and Congo Basins. Wright attributed these features to sequence of events at possible sites of partial release of distorting stresses which accumulated from wedging apart of Africa and South America during the Cretaceous period, and the subsequent readjustment of the shape

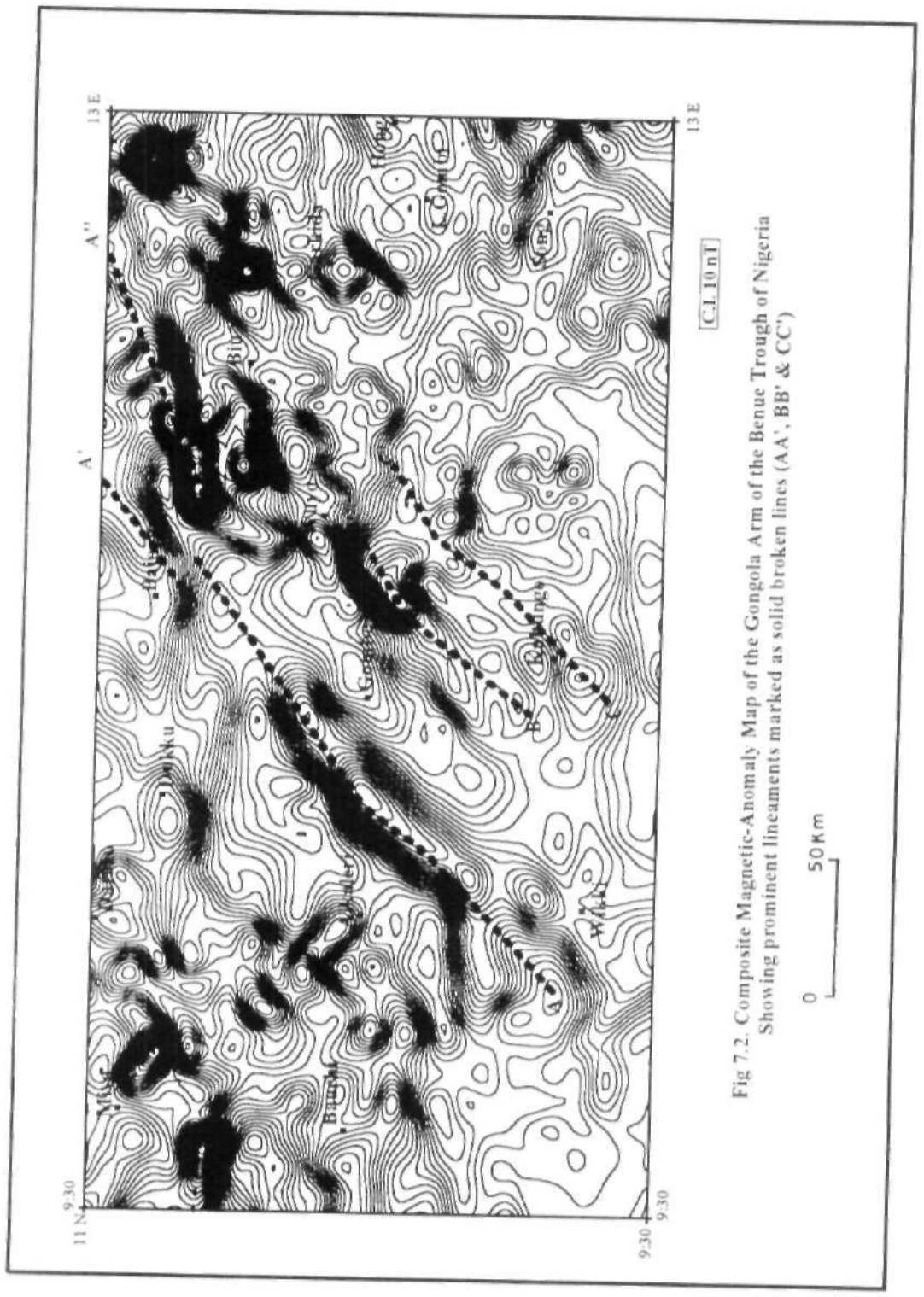


Fig 7.2. Composite Magnetic-Anomaly Map of the Gongola Arm of the Benue Trough of Nigeria
Showing prominent lineaments marked as solid broken lines (AA', BB' & CC')

of Africa during the separation of South America from Africa. Ajakaiye *et al.* (1986) reported the existence of similar narrow magnetic lineations trending ENE-WSW in the Benue trough of which the present study area is part. According to Ajakaiye *et al.* (1986), the magnetic lineaments show up as continuous narrow belts (10-15 km wide) ranging in length from 10 to 650 km. They therefore concluded that the lineaments are of sufficient prominence in length to suggest that they are probably the signatures of regional structural features representing major tectonic trends, because they cut across both basement and sedimentary cover. According to these authors, two of the major lineaments observed marked the structural boundary of the Benue trough and the two match the onshore extensions, under the Niger delta, of the Chain and Charcot oceanic fractures.

Popoff *et al.* (1983) in their interpretation of LANDSAT and radar imageries over the Benue trough clearly identified prominent NE-SW lineaments mainly in the Upper Benue area, one of the major lineaments cut across the Kaltungo inlier and affecting both the sediments and basement rocks in the area. This lineament direction is seen to agree with lineament CC'. Benkhelil (1982) suggested the existence of a narrow fault zone at depth within the basin, which lineament AA' indicated on the magnetic anomaly map (fig. 7.2) appears to represent.

Maurin *et al.* (1986) from the analysis of folds South of the Kaltungo inlier observed that folds occurring within a tabular cover are clearly aligned, and concluded that this alignment suggests a control by a deep-seated fault (probably

lineament AA') trending parallel to the Kaltungo fault zone (CC' on figs 7.2). Thus, the alignment of the three major lineament trends identified in the present study is in agreement with the general tectonic framework of the area of study. The three prominent lineaments probably represent pre- existing lines of weakness in the continental crust which became rejuvenated during the tectonic phase of the Pan African Orogeny. These lineaments probably provide zones of weakness along which basic intrusive were emplaced on the surface and at depth in the trough. This view is supported by the fact that lineament BB' and CC' are seen to coincide with the zone of basic intrusives earlier identified from the gravity results of the present work (fig. 6.4). The author is therefore of the view that this lineament represents a geosuture line at depth within the basin. This geosuture line is most probably a zone of weakness inherited from the Pan African Orogeny (Sykes, 1978) in the continent. Thus lineaments AA', BB' and CC' could therefore be considered to be part of signatures of geosutures, shear/fracture zone or zones of weakness that could have resulted from the readjustment of the shape of Africa during the separation of South America from Africa.

7.3 Quantitative Interpretation

7.3.1 Introduction

Quantitative interpretation of potential field data can be done either in map form or on profiles with each form of interpretation having it's own advantages and limitations. The map interpretation technique has the advantage of presenting the

total picture available without any assumptions regarding strike and lateral extent of the source (Jain, 1976). However, these maps are often produced from computed gridded data which may not be a true representation of the original data because the intervals used in the gridding procedure invariably impose limitations on the resolution achievable which, in turn, introduces errors in the contours.

Profile interpretation methods, on the other hand, allow interpretation of data as recorded or, at least, eliminates contouring related errors. However, a limitation of this technique is that it often assumes the profiles are normal to the strike direction and that the bodies extend to great distances on either side of the profile. In practice, the latter limitation is often satisfied while the effect of the former can be minimised by comparison of results from adjacent profiles.

A major problem often associated with magnetic interpretation relates to the degree of geological interpretation that should be attempted. Some explorationists feel that magnetic interpretation should be mostly qualitative and should never go beyond generalised basement depth maps while others engage in more rigorous mathematical analysis to produce more detailed geological and geophysical information at the disposal of the interpreter. According to Jacobson (1961), geophysicist generally agree with the following conclusions:

i) Careful analysis of intrabasement-type magnetic anomalies may yield a reliable and useful generalised basement depth map.

ii) Local basement relief based on a study of the usually smaller, suprabasement magnetic anomalies cannot be reliably interpreted from magnetometer work alone.

For the present study, digital data were recovered from contoured maps by digitisation along five selected profiles AA', BB' XX', YY' and ZZ' (Fig 7.3). In recognition of the foregoing limitations and mindful of the danger of attempting to obtain more data than is warranted, the profile interpretation was adopted with the following objectives

i) analysing the relatively large anomalies to obtain the depth estimates of the causative bodies,

ii) using the result of (i) to estimate the thickness of sediments in the area of study

iii) obtaining relevant information on depth of occurrence, nature of magnetic bodies, and other parameters that will aid in the magnetic modelling of the causative bodies.

7.3.2 Magnetic Depth Estimates.

Sedimentary rocks are generally known to have very weak magnetic susceptibilities compared with values for basement rocks. Variations of magnetic intensities over sedimentary basins are therefore believed to originate in the basement structure, intrusive and extrusive bodies either within the basement or the basin itself and, occasionally, in variation of susceptibilities within the basement (Behrendt and Klitgord, 1980; Cordell and Grauch, 1985). Calculation of estimated depth-to-magnetic-basement is, therefore, one of useful applications to which magnetic data over sedimentary basins can be put (Ojo, 1990).

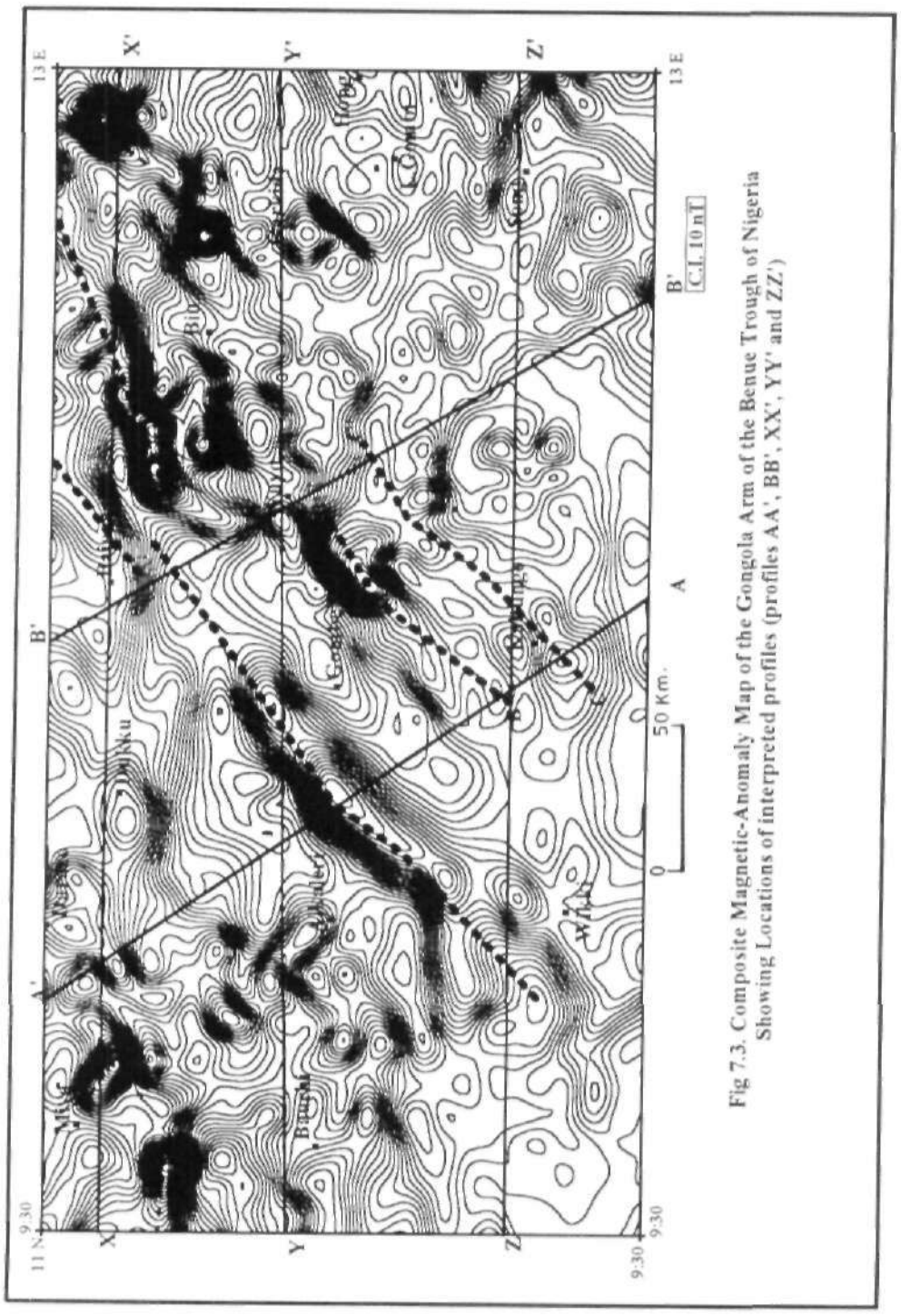


Fig 7.3. Composite Magnetic-Anomaly Map of the Gongola Arm of the Benue Trough of Nigeria
Showing Locations of interpreted profiles (profiles AA', BB', XX', YY' and ZZ')

A variety of methods have been applied for automatic interpretation of digitised magnetic profile data (Koulomzine *et al.*, 1970; Spector and Grant, 1970; Hartman *et al.*, 1971; Nabighian, 1972; Jain, 1976). Some of these methods are discussed below as computational methods used.

7.3.3 The computational method used in this work:

The Werner deconvolution technique, first described by Werner (1953), was used for this study to calculate the physical parameters (i.e. depths, horizontal locations, dips and susceptibilities) associated with the magnetic sources when they are assumed to be thin dykes. This method is able to separate anomalies due to a particular dyke from the interference of neighbouring dykes. The method also considers the whole shape of an anomaly rather than just a few parameters of the anomaly. Hartman *et al.* (1971) and Jain (1976) expanded the usefulness of the technique by considering the thin dyke body as an approximation in resolving other kinds of anomalies. They showed that the magnetic anomaly for a thin sheet is precisely the same as the derivative of the magnetic anomaly for a similarly positioned interface. Therefore, by performing Werner-based deconvolution on both the total field and the calculated horizontal derivative of the total field, it is possible to identify thin sheets and individual interference as well as wide sheets

Kilty (1983) extended the Werner deconvolution technique to the analysis of gravity data using both the residual anomaly and it's first and second horizontal

derivatives. Ku and Sharp (1983) further refined the method by using iteration for reducing and eliminating the interference field and then applied Marquardt's non-linear least-squares method to further refine automatically the first approximation provided by deconvolution. The theory and technique of the Werner deconvolution technique is discussed below.

7.3.4 Basic theory of the Werner deconvolution technique:

Using the concept of magnetic "charge" or "pole strength" according to Hartman *et al.* (1971), the expression for the total magnetic field due to a thin dyke with infinite strike length and depth can be written as:

$$F(x) = \frac{A(x - x_0) + Bz}{(x - x_0)^2 + z^2} \quad \ldots\ldots(7.1)$$

where, F = the total magnetic field intensity at x,

x = horizontal distance along the profile,

x_0 = horizontal distance along the profile to the centre point above the dyke,

A and B are constants that are functions of field strength susceptibility and source geometry.

When observation is made on a level plane over level bounded bodies whose length and depth are infinite and whose strike is perpendicular to the direction of the profile, equation (7.1) can be rearranged into the form

$$x^2F = a_0 + a_1x + b_0F + b_1xF \ldots\ldots(7.2)$$

where x and F are as defined before,

$$a_0 = -Ax_0 + Bz, \quad a_1 = A$$

$$b_0 = -x_0^2 - z^2, \quad \text{and} \quad b_1 = 2x_0 \ldots\ldots(7.3)$$

It follows from above that the depth and horizontal position of the dyke are given by

$$z = \pm 0.5\sqrt{(-4b_0 - b_1^2)}\ldots\ldots(7.4)$$

$$x_0 = 0.5b_1$$

Allowing for the possibility of interference and assuming that the interference can be represented by a polynomial, equation (7.1) now becomes

$$F(x) = \frac{A(x - x_0) + Bz}{(x - x_0) + z^2} + c_0 + c_1x + \ldots c_nx^n \ldots\ldots(7.5)$$

where n is the degree of the polynomial, and the C's are the coefficients. Therefore, instead of 4 unknowns in equation (7.2) there are now (n+5) unknowns in equation (7.5) which are solved by the computerised calculations. In practice, a first or

second degree polynomial is generally sufficient, so that 6 or 7 data points are required for the solution.

Generally the field that results from geologic distribution of sources in space can be viewed as the two dimensional convolution of the spatial impulse response with the source distribution function (Hartman *et al.*, 1971). The problem of determining the source parameters from the recorded field, is therefore, reduced to a deconvolution. Therefore, by deconvolving both the total filed and the calculated horizontal gradient of the total field, it is possible to identify thin sheets (dykes, sill, etc.) and individual interference (faults, dipping contacts edges of intrusive bodies, etc.).

7.4 Interpretation Procedure

For the interpretation whose results are presented below, two profiles selected to coincide with the gravity profiles AA' and BB' were analysed using a computer program WERNER (based on Werner, 1953 and Hartman *et al.*, 1971). Along each profile the data points were digitised at equal linear intervals of 0.5 km and plotted for each of the profiles (fig 7.4). A second degree polynomial was considered adequate for the interference component of the magnetic field so that seven points were required fort the solution of equation (7.2). The program examines seven successive data points and solves the resulting set of linear equation for physical parameters of interest. The whole sequence is advanced by one point

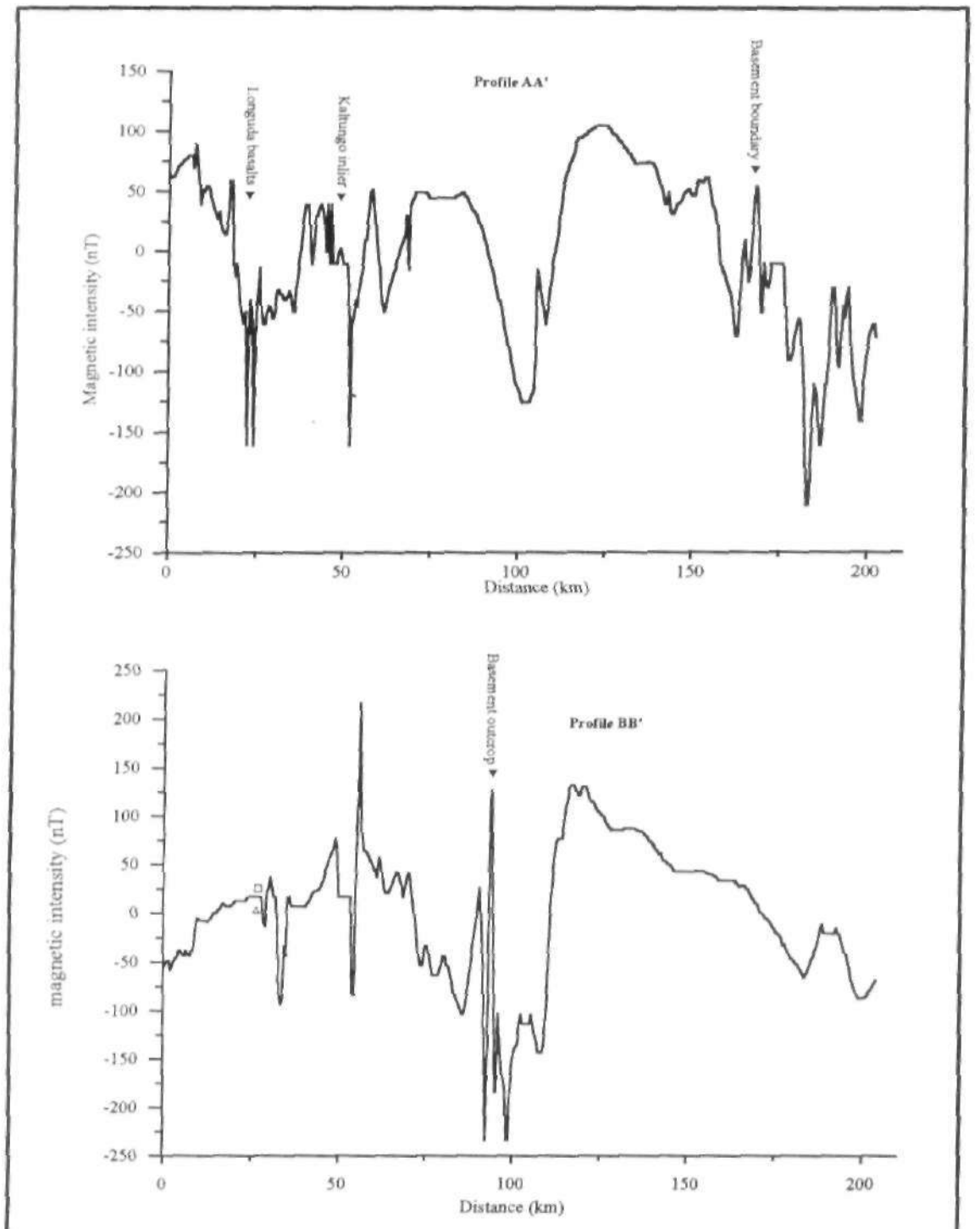


Fig 7.4 Typical plot of total field intensity along profiles AA' and BB' (see Fig 7.3 for Location of profiles)

and the examination repeated. If a succession of such examinations consistently indicates a source for an anomaly, and if these indications are themselves consistent, the apparent depth and horizontal location along the profile of the source is recorded. Susceptibility and dip values are computed from A and B, and the local inclination and declination of the main field on the assumption that magnetisation is induced.

The "depth-penetration" of the process depends on the distance between the data points operated upon, i.e. the operator length. The broader a given anomaly, the longer must be the operator length required to recognise it. Consequently the computation sequence described above is repeated for a number of times with the operator length successively increased. Before each pass, the data is smoothed with a low pass filter to remove high frequency ('shallow') anomalies that have already been recognised and which would otherwise mask deeper anomalies (Hartman *et al.*, 1971; Friedberg, 1975).

Accepted depth points along each profile are plotted as a function of the horizontal position of the source along the profile to produce the so-called 'Werner profiles'. Interpretation of the 'Werner profile' to define, for example, the basement surface requires relevant professional experience and the availability of relevant geologic information on the area of study will greatly assist in this task.

7.5 Estimation of Depth-to-Magnetic Basement

Figures 7.5 and 7.6 shows typical Werner deconvolution profiles (for profiles AA' and BB') processed in order to define magnetic basement beneath the principal anomalies. The depth points are plotted with the nominal flight height of 152.4 m subtracted form the computed depths. It is evident from figures 7.5 and 7.6 that there is considerable scatter in the plotted depth points, rendering the definition of the magnetic basement surface a difficult task that involves a discriminatory evaluation of the computed depth points in the light of available geologic information. Factors that contribute to the large vertical scatter of the computed depth points include:

i. the fact that a particular feature can be recognised on more than one pass of the operator, and

ii. most sources often yield both total field depths (deeper) and horizontal gradient depths (shallower) (Friedberg, 1975).

The ability to identify the nature of the source helped to improve the accuracy of the interpretation. According to Hartman *et al.*, (1971), the correct depth points appear close to the top of the group of points. They also quoted an accuracy of 10 percent from an application of the technique to digitally recorded data. The choice of reliable depth points in the case of this study was therefore highly dependent on the geologic maps available in the area. This could have introduced errors higher than the ones reported by Hartman *et al.* (1971). Another factor that could give rise to a higher error margin recorded here is attributable in

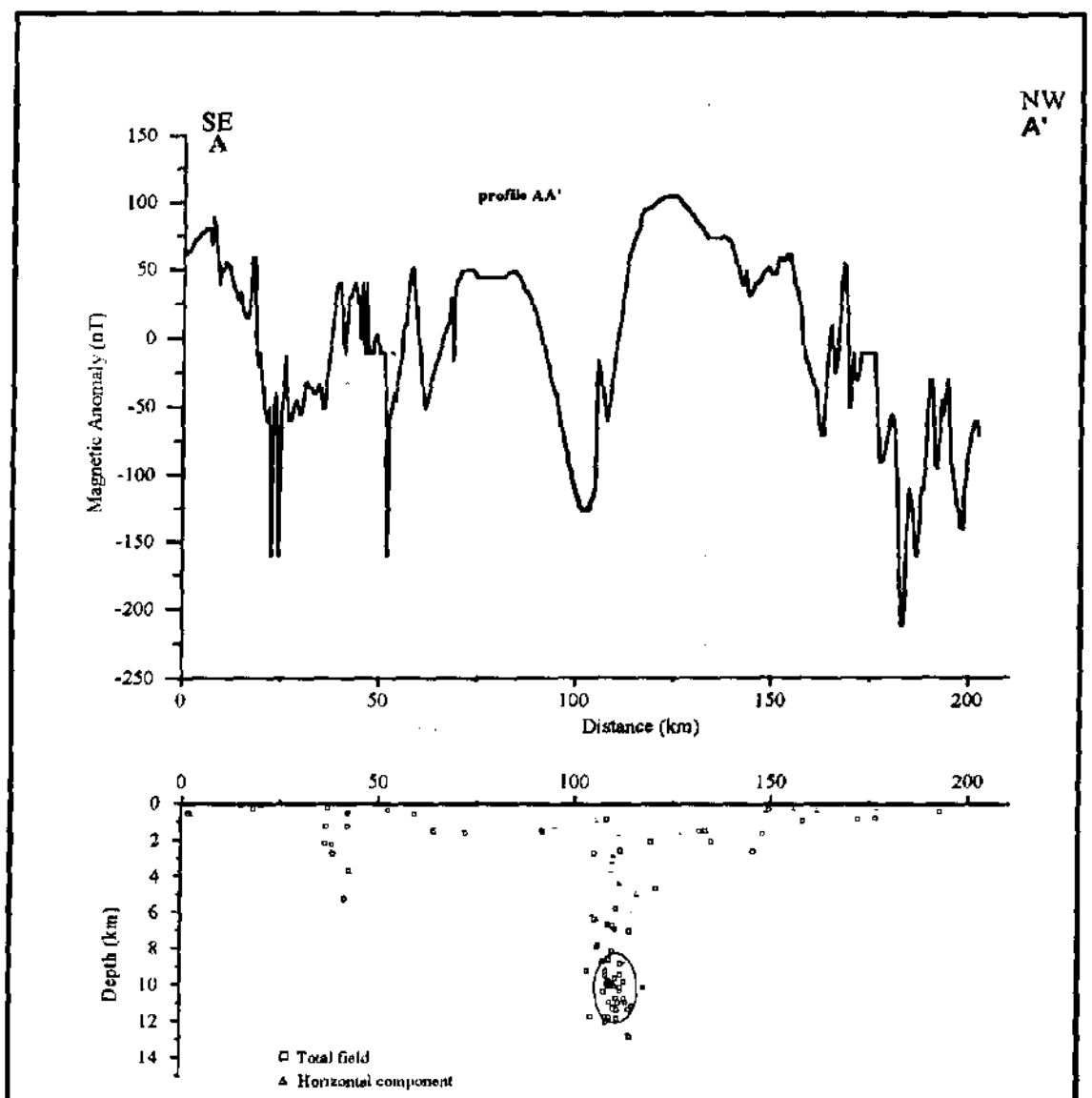


Fig. 7.5 A typical Werner profile processed to define magnetic basement beneath profile AA'

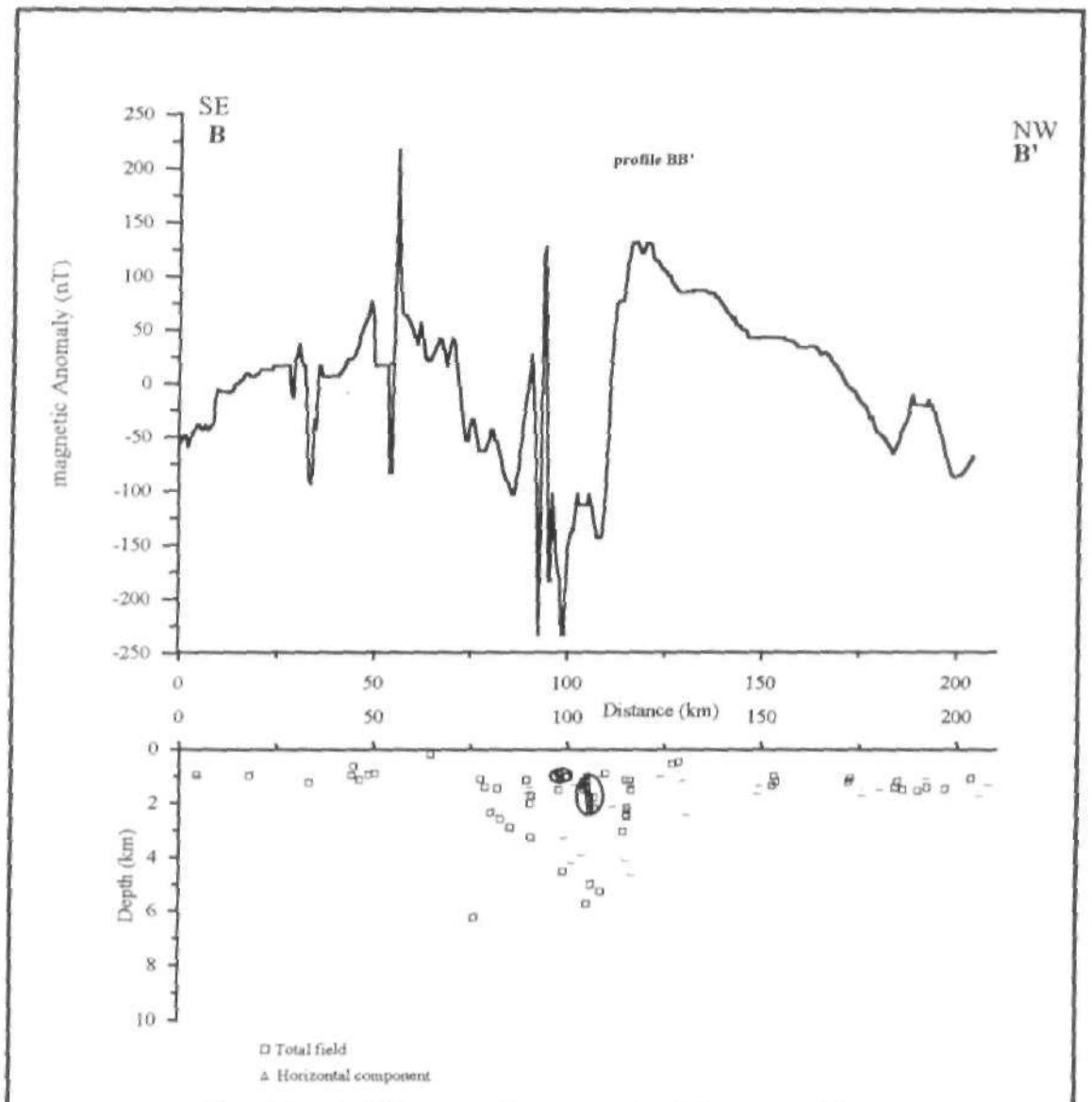


Fig. 7.6 A typical Werner profile processed to define magnetic basement beneath profile BB'

part to the low quality of the data set that was used which was recovered from magnetic contour maps instead of digitally recorded data.

Figures 7.7 and 7.8 show the Werner profiles after interpretation using the procedure outlined above. The dotted line represent the interpreted magnetic basement surface beneath the two profiles and shows that sediment thickness in the area of study is generally less than 5 km and shows variation in the two profiles. Considerable interpolation had to be carried out to obtain these surfaces. Of great significance to this study, however, are clustered solutions obtained for the long wavelength negative anomalies along the profiles (AA' and BB') which are encircled (Figs. 7.7 and 7.8).

The solutions in the figures (Fig 7.7 and 7.8) are consistent in their occurrence on the profiles and their association with the long wavelength magnetic low but they vary in depth of occurrence from profile to profile. Significant clusters of solutions associated with this magnetic anomaly occur at depths of 8 km (Fig 7.7) and 1 km (fig. 7.8) respectively.

Even though the depth estimates from Werner technique can be obtain relatively unambiguously (Ojo, 1990), the same is not true for susceptibility estimates which depends on the thickness of the dyke. Susceptibility estimates from the Werner program were, therefore, used later for the modelling only as initial guides. The results obtained generally show that susceptibility estimates for the solutions associated with the magnetic low were much higher (about five or more)

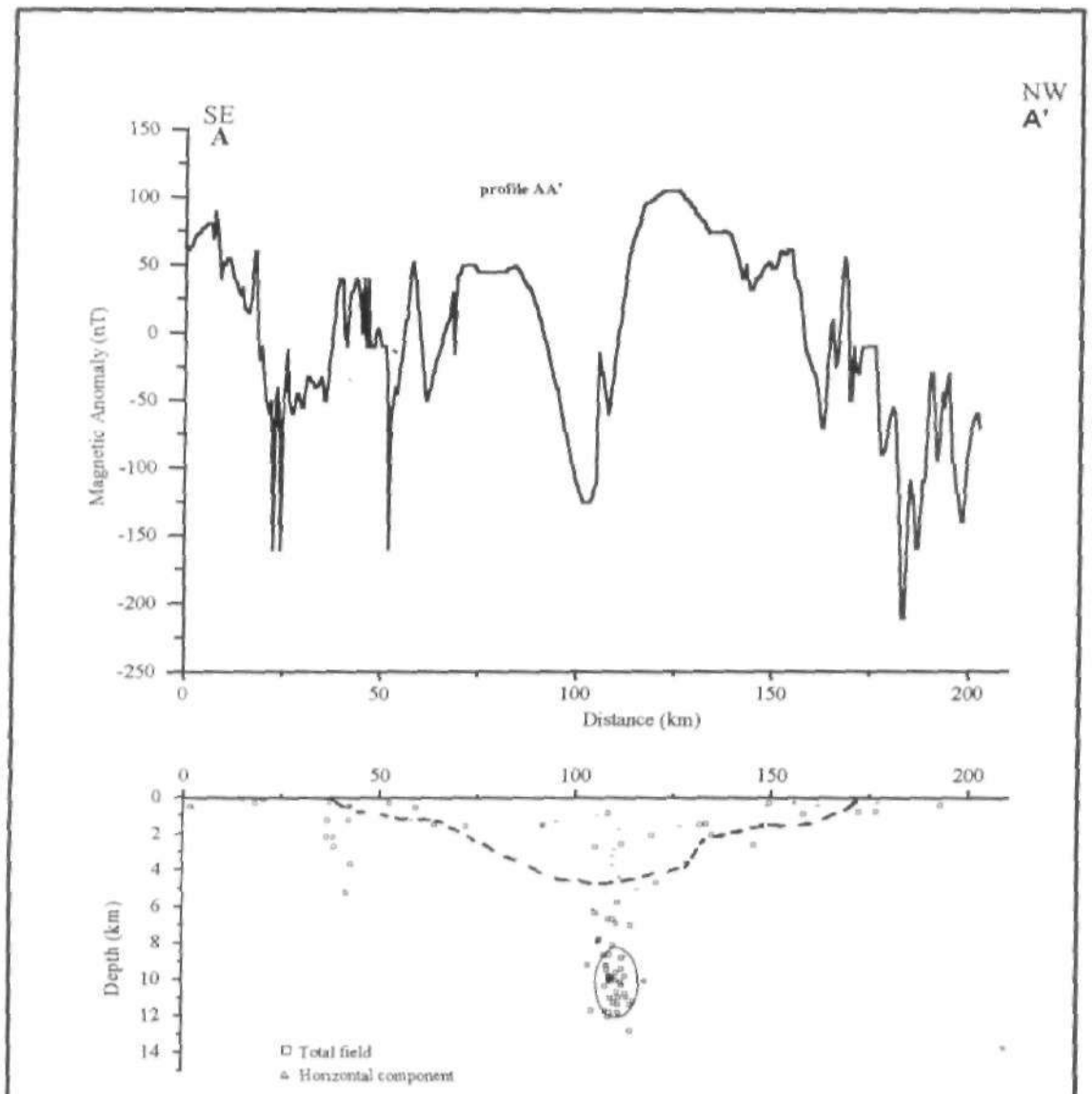


Fig. 7.7 A Werner profile showing the interpreted basement surface (as dashed lines) For Profile AA'. Significant clusters of solution are indicated by a circle

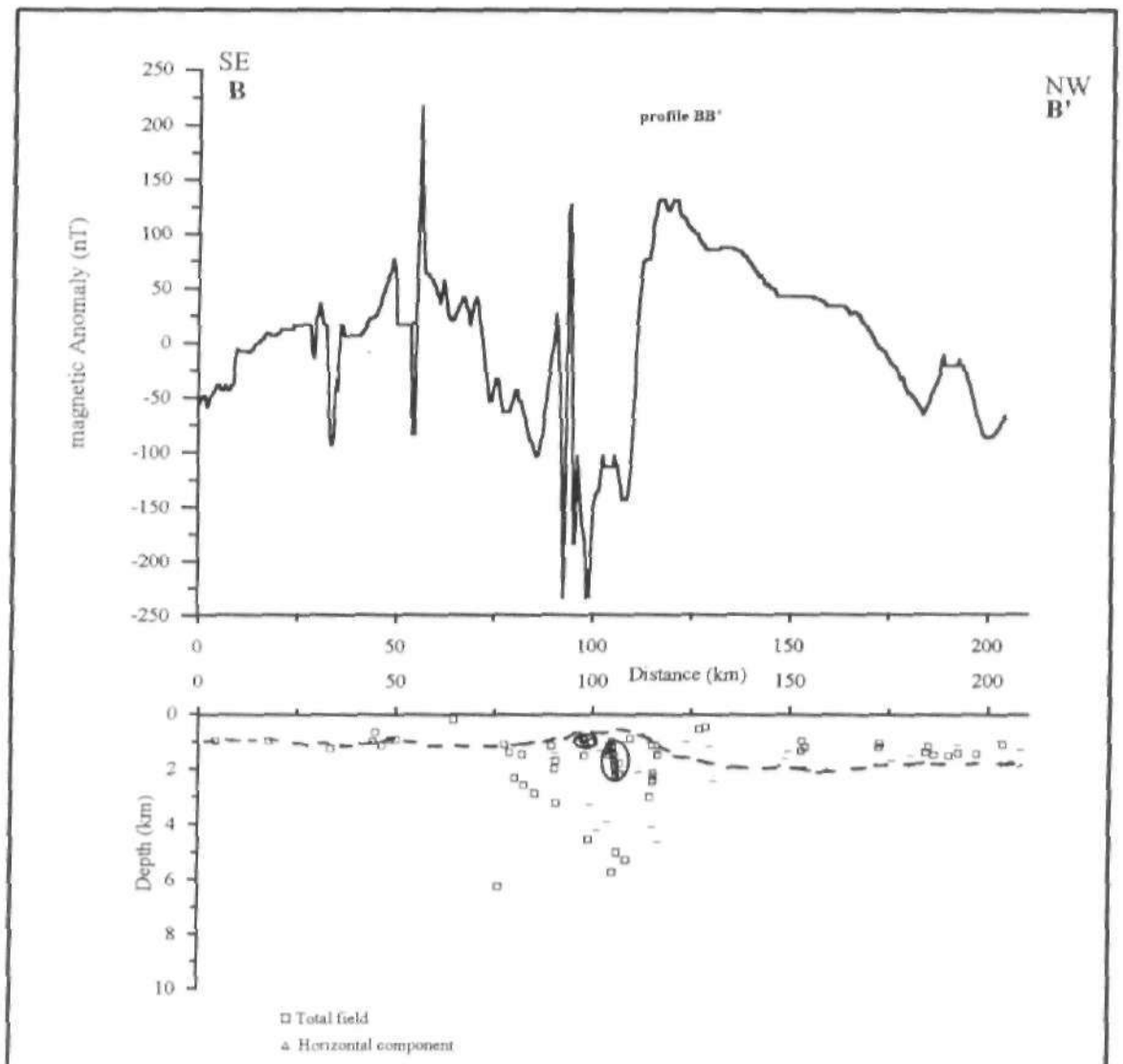


Fig. 7.8 A Werner profile showing the intepreted basement surface (as dashed lines) For Profile BB'. Significant clusters of solution are enclosed in a circle.

than the ones obtained for the basement surface, suggesting that the bodies responsible for this prominent magnetic low may be of basic to ultrabasic composition.

Profiles XX', YY' and ZZ' were processed in a similar manner as profiles AA' and BB' described above and the results obtained were used as inputs for the two-dimensional magnetic modelling of these profiles.

7.6 3-Dimensional Modelling of Magnetic Anomalies

The three dimensional (3-D) method of Talwani (1965) was used to interpret the residual magnetic anomalies along profiles AA' and BB' (Fig. 7.3). The method uses a computer program MAGPOLY (Godson, 1983b) which calculates the magnetic effect of three-dimensional models that consist of elements that form polygons in plan view (Plouff, 1975b; 1976). The elements of the models are bounded by two horizontal planes and a series of intersecting vertical planes.

The calculations use an exact formula rather than using the numerical integration approach of previous Talwani (1965) programs. Thus, values can be obtained on or inside the model. A least-squares comparison between the calculated anomalies and an observed field was used to determine the best total magnetisation vector (amplitude, declination and inclination) and also the best magnetic susceptibility for the assemblage of polygonal prisms. Fig 7.9 is a plan of the polygonal prism used in the modelling of the profiles AA' and BB'.

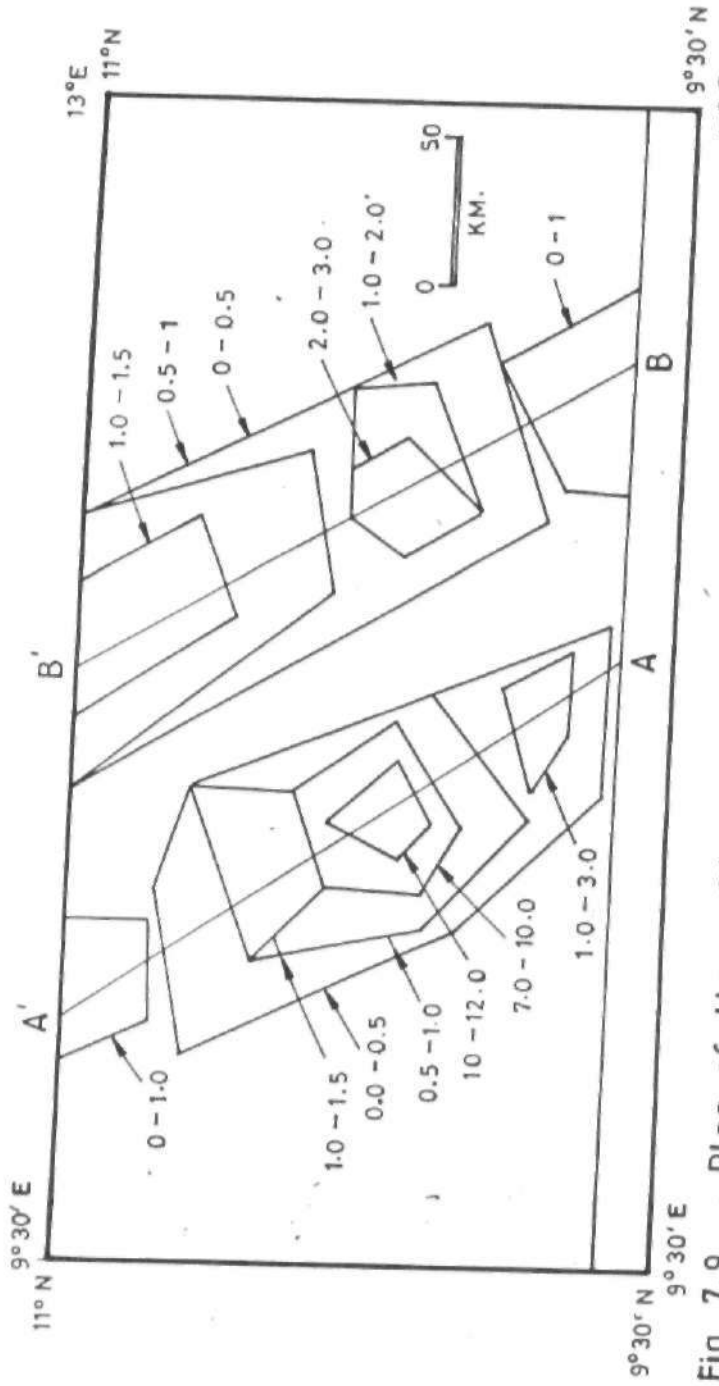


Fig. 7.9 Plan of three-Dimensional model of Bodies used for major anomalies modelled (depth values are in Km).

Model input to the program consists of x, y, and z co-ordinates of polygon corners. Parameter input such as plotting variables, magnetic susceptibility and inclination, declination and magnitude of the field, were entered from a command file. Fieldpoint locations and observed values at these locations were read in from a disk file.

Output from the program consisted of printed information about the bodies and fieldpoint co-ordinates and values.

7.6.1 The Interpretation

The results of the 3-Dimensional interpretation of profiles AA' and BB' using the program MAGPOLY are hereby presented below.

Profile AA': This profile runs NW-SE (Fig. 7.3) and cuts across the basement rocks (close to Darazo), the sedimentary sequence, and cuts across lineament AA'(Fig 7.2). It stretches for a distance of about 200 km.

Figure 7.10a&b shows the result of three-dimensional polygonal model for profile AA'. The magnetic anomaly has been continued upwards to 2.5 km above flight elevation so as to eliminate the effect of near surface short-wavelength variations in the magnetic anomalies. The depth to the top of the high-susceptibility body and the basin

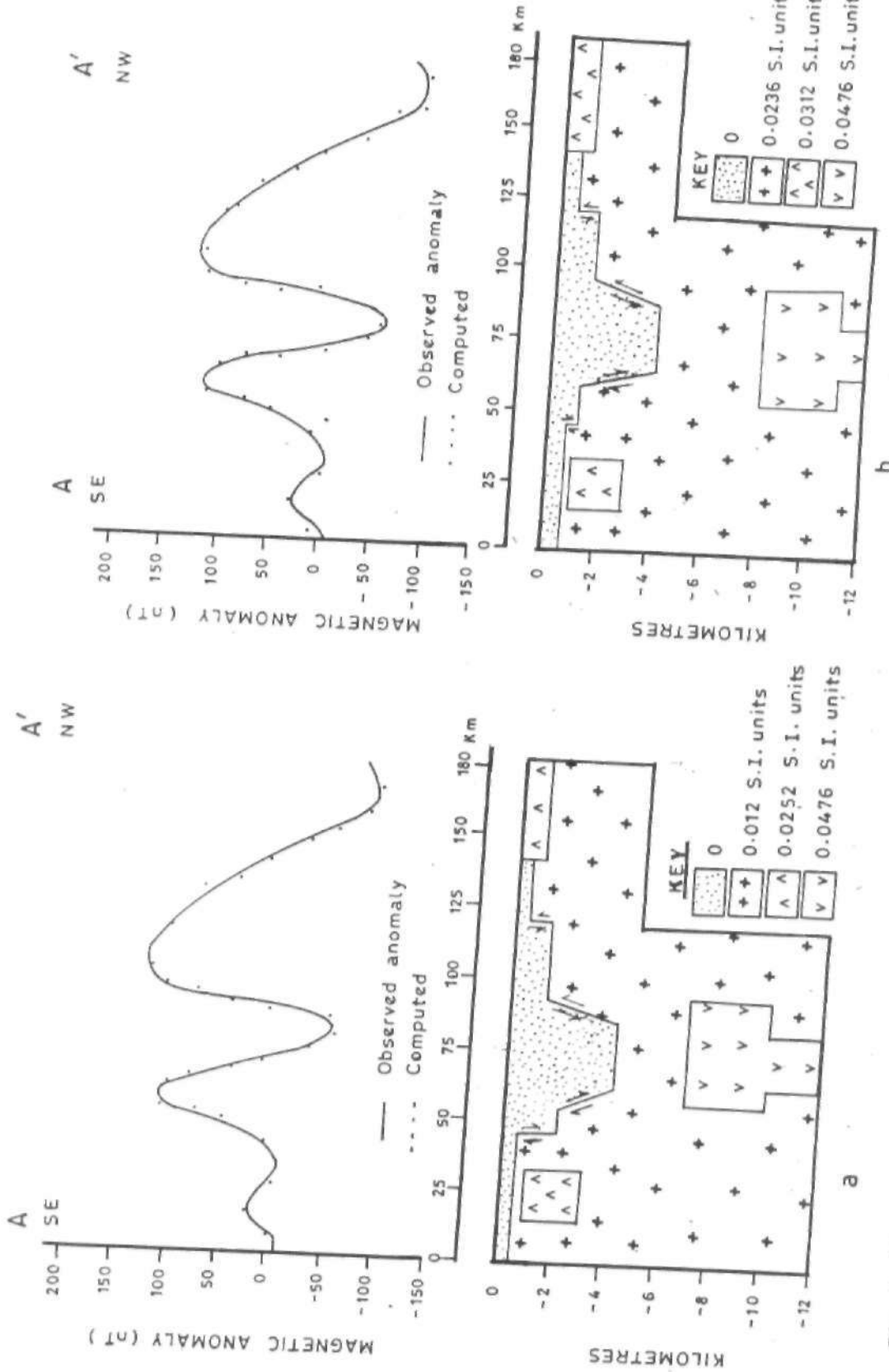


Fig. 7.10 X — section of 3 - dimensional model of profiles A A' using magnetic susceptibilities shown.

floor topography were constrained by the depth solutions from the Werner interpretation.

For this interpretation the basin was assumed to be underlain by granite-gneiss, the dominant rock type of the Nigerian basement complex (McCurry,1973). The choice of susceptibility values used in the modelling was based on reported susceptibility ranges in the Benue Trough (of which the present area of study is part) of 0.0059-0.0097 SI units (Ajakaiye, 1981) and 0.150-1.030 SI units (Osazuwa, 1978).

A susceptibility value of 0.012 SI units which represents an overall average for the basement rocks as reported by Osazuwa (1978) was used for the host rock in fig. 7.10a. Susceptibility value of 0.0476 SI units was required for the magnetic body to obtain a good fit. This value falls between the range of values for basic rocks and basalt (Dobrin and Savit, 1988; Telford *et al.*, 1976).

The model consists of a layer of sedimentary rocks that has susceptibility of 0 , thickening at the centre of the profile (thickness of sedimentary layer up to 4.5 km). This sedimentary layer in underlain by basement rocks of granitic composition with susceptibility of 0.012 SI units. The most prominent feature along this profile is a high susceptibility body (of susceptibility 0.0476 SI units), which occurs at a depth of about 8-12 km. This is modelled to be the cause of the prominent magnetic anomaly occurring at the centre of this profile. The model also suggest that this body is a basic

intrusion at depth within the crust that is probably associated with the formation of the Benue Trough.

Figure 7.10a is however just one out of the many susceptibility by depth combinations for the body that are possible for a fit to be obtained between the observed and computed anomalies. Fig 7.10b is therefore an alternative model of the same profile with the susceptibility value of the host rocks (basement) increased to 0.0236 S.I units. For this model also, the high susceptibility rock unit is seen to be a prerequisite for a fit to be obtained between the observed and computed anomalies. This high susceptibility rock material is seen to occur at depth of about 7.5 km an below.

The results of the models suggest that a high susceptibility body (igneous rocks?) is very essential in explaining the high amplitude magnetic low observed along the profile.

Profile BB': This profile was chosen to coincide with profile BB' (fig 6.5) whose gravity field has already been modelled. The aim was to obtain a magnetic model for the high residual gravity anomaly observed along the profile, which was modelled in terms of some basic intrusive at depth (Fig. 6.8). The profile was also chosen so as to ascertain the nature of existence of the body giving rise to the gravity high observed along profile BB, that occurs around the Biu plateau (fig 3.1).

Fig 7.11a shows the results of three-dimensional modelling of the magnetic low observed along the profile. A susceptibility value of 0.012 S.I units was used for the host body and a value of 0.0476 S.I units was used for long wavelength magnetic low along the profile. Depths constrained were imposed on the depth to top of the high susceptibility body and the basin floor topography.

Fig 7.11b represents modelling results obtained with the susceptibility of the host body increased to 0.0236 SI. Results of these modelling show that the high susceptibility body (probably a basic igneous body) is required to explain the long wavelength magnetic low observed along the profile.

7.7 Two-Dimensional Interpretation of Magnetic Anomalies

A two-dimensional interpretation of magnetic anomalies along profiles XX', YY' and ZZ' chosen to coincide exactly with those of the gravity was carried out. The profiles run E-W and extends over a distance of 357 km (fig. 7. 12) across the axis of the trough in the area of study (the Gongola Arm). They were so chosen in order that their results may be used to corroborate those of the gravity interpretation and hence obtain a clearer picture of the structure and nature of the area of study. The results of the interpretations are therefore presented here below

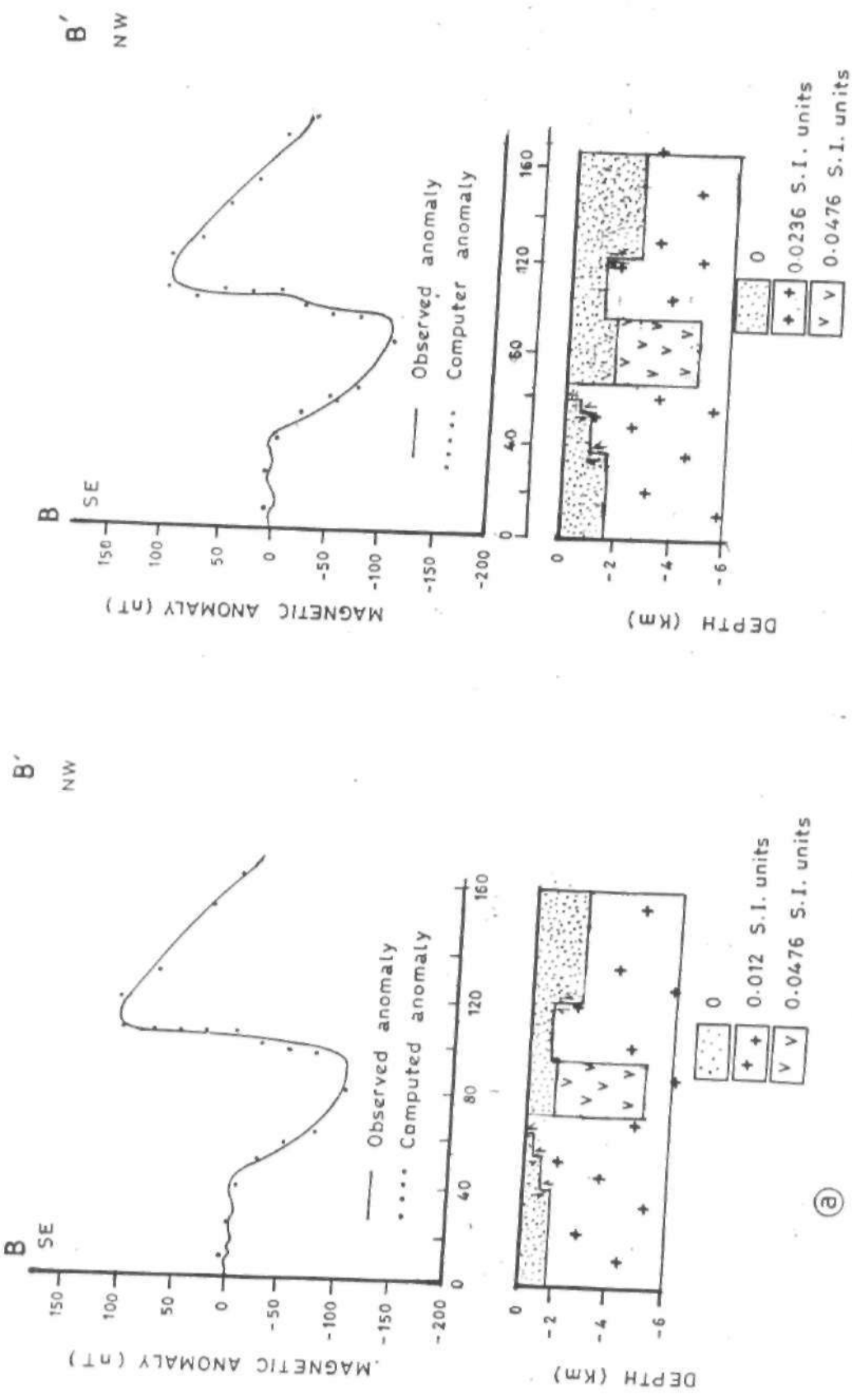


Fig. 7.11 X - section of 3 - dimensional models of profile B B' using magnetic susceptibilites showing.

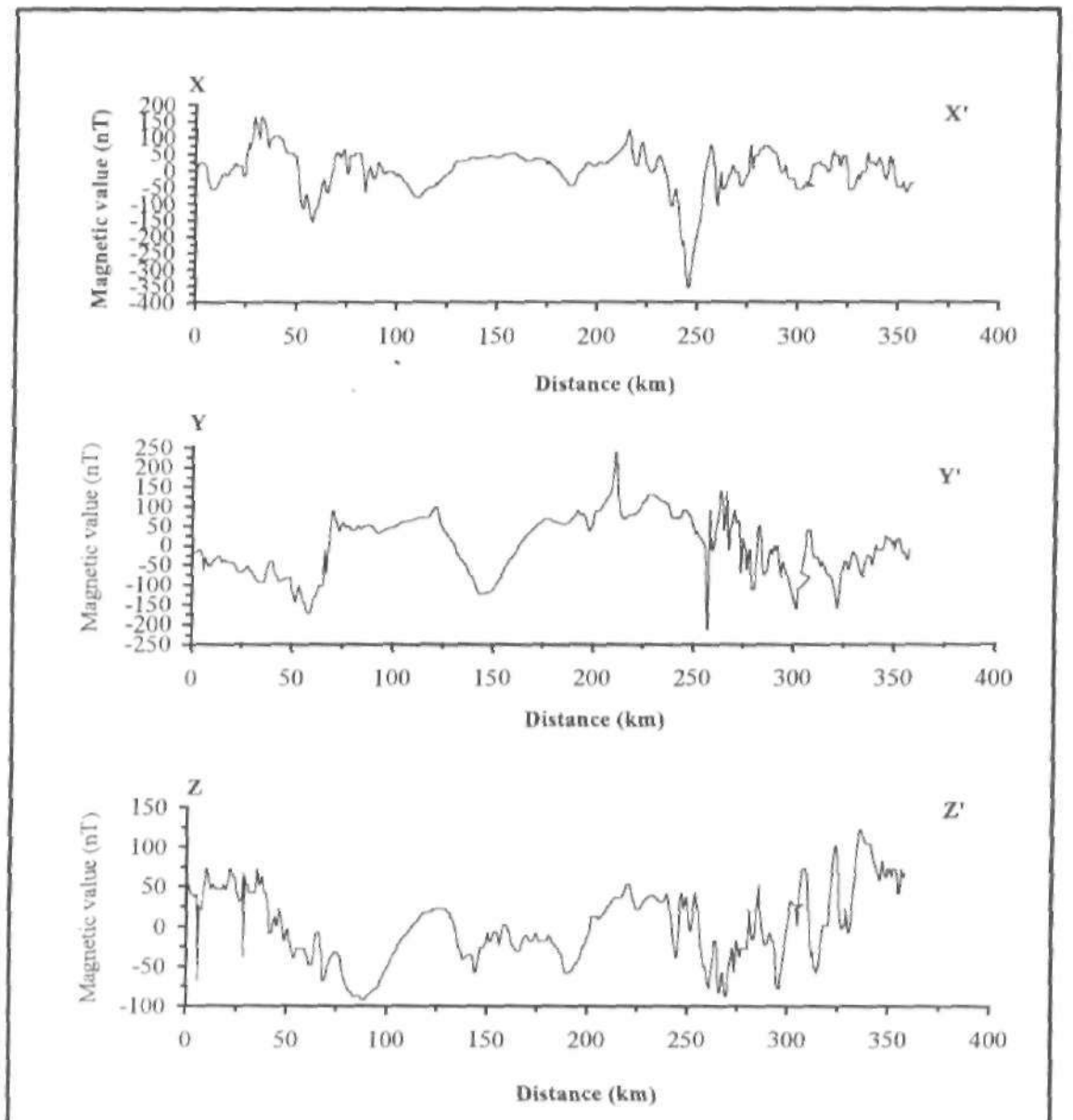


Fig 7.12 Plot of Digitised Aeromagnetic (residual) data along profiles XX', YY' and ZZ'

7.7.1 Profile XX'

This profile runs E-W across the entire width of the trough in the area of study, from basement to basement and cuts across lineament AA' (Fig 7.3). The profile shows 4 long wavelength anomalies (Fig. 7.13a), 2 of which coincides with the sedimentary outcrop. The other 2, one on the left which coincides with the basement outcrop, while the one on the right coincides with the Biu Basalt. The extreme right of the profile is characterised by a series of short wavelength anomalies. These anomalies are seen to coincide with the basement complex and most likely represent small dyke-like intrusions in the basement rocks.

The magnetic anomaly has been continued upwards to 2.5 km in order to eliminate the near surface short-wavelength variations in the magnetic anomalies. The results of Werner Deconvolution carried out for the profile was used as a control on the occurrence and depth of the basic bodies along the profile.

Fig 7.13a&b shows the result of 2-Dimensional modelling long profile XX'. The interpreted model for this profile suggest that the Cretaceous sediments filled and covered the horst and graben structures that resulted from the tectonic activities that gave rise to the formation of the trough. The interpreted models also suggest the existence of high magnetic susceptibility materials at depth in the trough. A susceptibility of 0.0476 SI units was required in order to obtain a good fit for the profile. These high magnetic susceptibility material were seen to occur at depths ranging from as shallow as 1 km to as deep as 8 km. The susceptibility value of 0.0476

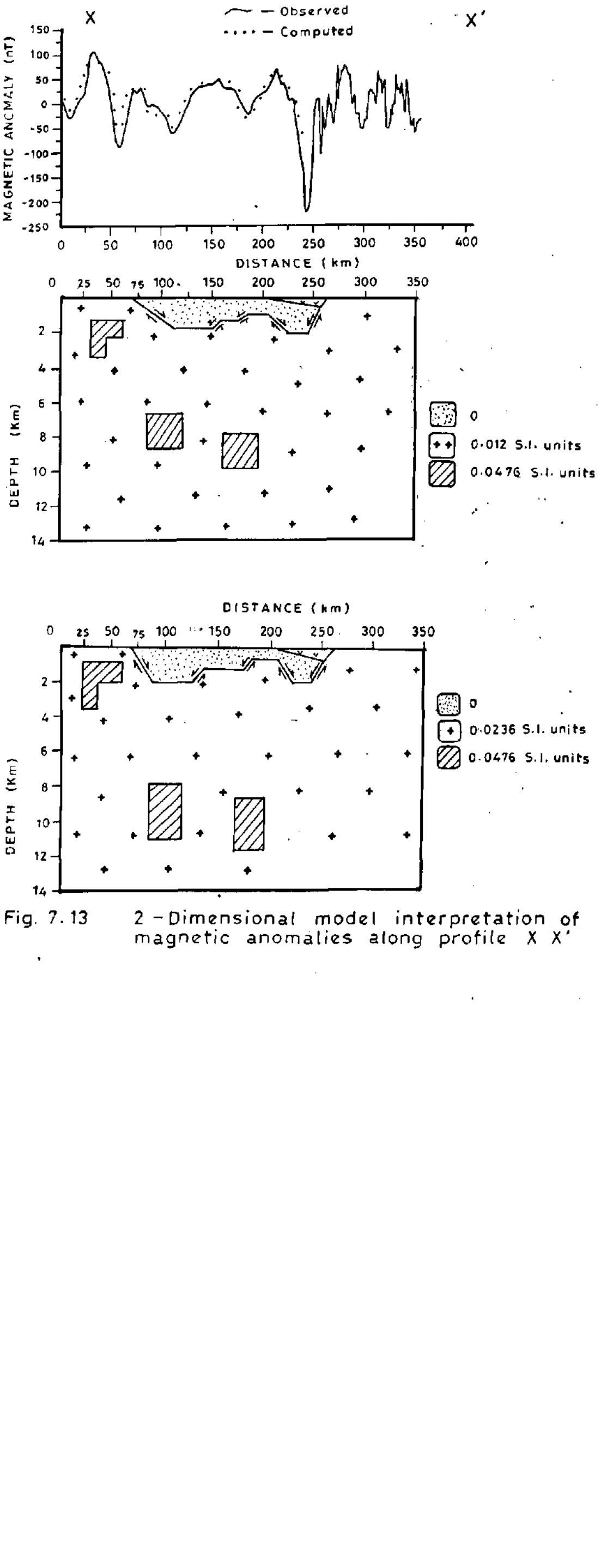


Fig. 7.13 2 – Dimensional model interpretation of magnetic anomalies along profile X X'

SI units used for the basic materials fall between the range of values for average basic igneous rocks and basalt (Telford *et al.*, 1976).

Fig. 7.13a is however, only one possible model that satisfies the observed magnetic anomalies, and a large number of susceptibilities by depth combinations for the body is possible. Fig. 7.13b therefore shows another model which satisfied the observed anomaly, and in this model a host rock susceptibility of 0.0236 SI units is used. From this models it was observed that the high-susceptibility blocks (basic rocks?) are essential requirement needed to explain the high amplitude short-wavelength magnetic lows. This strongly suggest the existence of these basic rocks at depth as seen from the magnetic models.

7.7.2 Profile YY'

This profile (Fig. 7.14a) after been upward continued to 2.5 km in order to eliminate the effect of near surface short-wavelength variations in the magnetic anomalies shows two major high amplitude, short-wavelength anomalies. The extreme right of the profile is characterised by series of short wavelength anomalies occurring in the basement.

Fig. 7.14a&b shows the results of the two-dimensional interpretation of magnetic lows observed along the profile. A susceptibility value of 0.012 SI units was used for the host body and a value of 0.0476 SI units was used for the bodies causing the long wavelength magnetic lows along the profile.

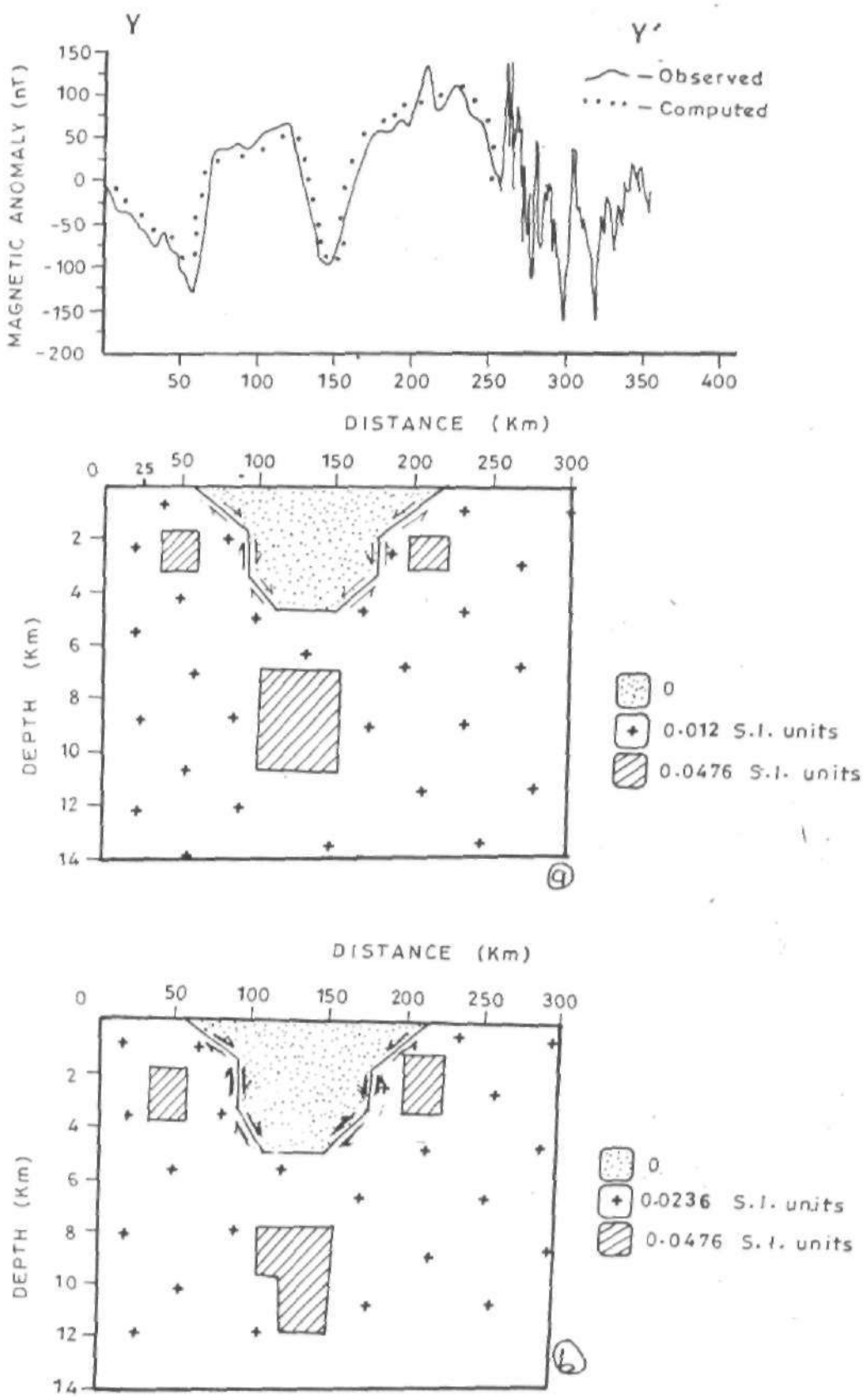


Fig. 7.14 2 - Dimensional model interpretation of magnetic anomalies along profile Y Y'

Results of the interpretation along this profile suggests that high susceptibility bodies exist at various depths ranging from as shallow as 1.8 km to as deep as 8 km (Fig. 7.14a&b). Fig. 7.14b which is an alternative model of the same profile, but using a susceptibility value of 0.0236 SI units for the host rocks also reveals that the high susceptibility bodies (probably basic igneous bodies) are essential in order to obtain a good fit.

Thickness of sediments along this profile is seen to have an upper limit of 4.8 km (Fig. 7.14a&b).

7.7.3 Profile ZZ'

This profiles runs in the E-W direction through the south-western end of the study area, across the axis of the trough in the area of study from basement to basement.

The magnetic anomaly along this profile has been continued upwards to 2.5 km above flight elevation in order to eliminate the near-surface short-wavelength variations in the magnetic anomalies. Fig 7.15a shows a result of two-dimensional modelling for this profile. The model shows that the high amplitude low magnetic anomaly on the left hand side of the profile is as a result of a high magnetic susceptibility body at depth in the area. This body was modelled to have a magnetic susceptibility of 0.0476 SI units (a value that falls within the range of values for

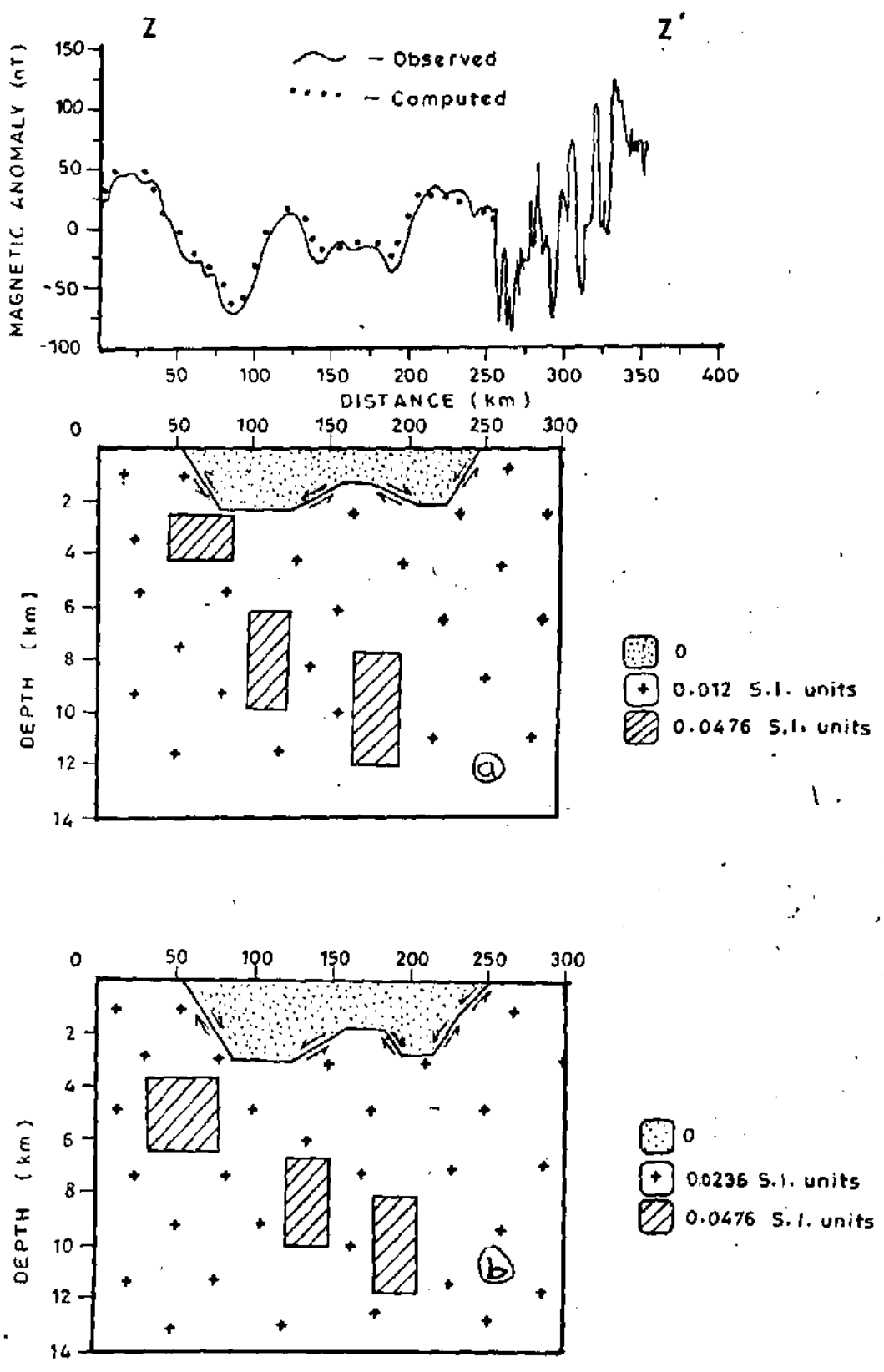


Fig. 7.15 2-Dimensional model interpretation of magnetic anomalies along profile Z Z'

average basic igneous rocks and basalt). These high magnetic susceptibility materials are also believed to be essential for the high amplitude magnetic low around the centre of the profile.

Fig. 7.15b is an alternative model for this profile with the host rock susceptibility changed to 0.0236 SI units. The model also indicates that these high susceptibility bodies are essential before a good fit can be obtained, therefore suggesting that these bodies do exist in that part of the trough at depth. Results of the modelling suggest that these basic intrusives exist at depths between 2 and 8 km.

The sediments along this profile are seen to attain a maximum thickness of 2.8 km (Fig. 7.15a&b)

CHAPTER 8

DISCUSSION, DEDUCTIONS AND CONCLUSIONS

8.1 Correlation of Gravity and Magnetic Results.

Results from both the gravity and magnetic methods have revealed that the thickness of sediments in the Gongola Arm of the Benue Trough is generally less than 5 km. While the results of three-dimensional and two-dimensional modelling of gravity data indicates a maximum sediment thickness of 4.5 km for the graben structure along profiles AA' (Fig. 6.7) and YY' (Fig. 6.11), that of the magnetics along the same profiles indicates a sediment thickness of 4.8 km. This indicates a degree of agreement of about 94% between both the gravity and magnetic data interpretation. Also results of both gravity and magnetic interpretations both suggest that the structure of the basin along the profiles is that of horst and graben. The horst and graben nature of the area of study is supported by the geology of area around this profiles. Inliers such as those around Kaltungo, Gombe and Zambuk are probably part of the horsts, while the grabens are represented by basinal structures such as those modelled along the profiles (Fig. 6.7 and 6.11).

The results of three-dimensional and two-dimensional modelling of profiles AA', BB', XX', YY' and ZZ' (Figs 6.7, 6.9, 6.10, 6.11, 6.12) for the residual gravity and magnetic (figs 7.10, 7.11,7.13, 7.14 & 7.15) suggest a faulted contact between the sediments and basement rocks along the western margin in the area of study as suggested by Adegoke *et al.* (1986).

The positive residual gravity anomaly 5 in the vicinity of Wuyo was modelled along profile BB' to be as a result of a basic intrusive at depth of between 1 and 4 km(Fig 6.8). This is seen to correlate well with the results of the magnetic modelling which reveals a high susceptibility body (0.476 SI units) occurring also at about 1 km to a depth of about 4.5 km (Fig 7.11a&b), thus suggesting that basic intrusives exist at depth in the area.

The presence of basic intrusives at various depths in the area of study have been suggested by both the gravity and magnetic models. Fig 6.11 which is a two-dimensional interpretation of the gravity anomalies along profiles YY' suggest the presence of a basic intrusion at a depth of about 6 km and centred between 100 and 140 km from the western end of the profile. Fig 7.14 on the other hand which is the magnetic interpretation of the same profile suggest that this intrusion is at a depth of about 7 km and is centred between 100 and 150 km along the profile. The results therefore indicate a general agreement between the occurrence of this basic intrusion, with only a difference of about 1 km in depth to the top of the body between the gravity and magnetic interpretations. This gives an agreement of about 87.5 % between the results of gravity and magnetic modelling, with the magnetic interpretations generally indicating greater depths of occurrence.

8.2 Discussion of Results and Deductions.

As adequate accurate geologic maps and sufficient borehole data which should have both combined to minimise the ambiguities normally inherent in gravity and magnetic interpretation (Nettleton, 1954; 1973 and Bott and Smithson, 1967), were not available, the interpretation made above (i.e. so far in this work) are considered tentative. However with the new wave of exploration for oil by different Oil Companies in different parts of the project area, it is hoped that improved and accurate geologic maps of the area including detailed and deep borehole data will soon be available. These more accurate and detailed information, when available will lead to improvement in future interpretation of anomalies observed in the present work (in the project area).

Notwithstanding the above limitations to accurate interpretation of gravity and magnetic anomalies observed in this work, the interpretations made above are hereby reviewed with respect to some specific issues on the Gongola Arm of the Upper Benue Trough in particular and the entire Benue Trough in general, and the proposed theories on the origin of the trough. The specific issues concerned are as discussed below:

8.2.1 Marginal Volcanism /Basic Intrusives

The interpretations of all the profiles taken in the area of study (profiles AA', BB', CC', XX', YY' and ZZ') suggest the existence of basic intrusives at depths at different points in the trough. The interpretation of gravity and magnetic data along all of these profiles suggest the existence of the basic intrusives at depth in the trough. For example fig. 6.7 (which is a 3-dimensional interpretation along profile AA') suggests that this basic intrusion is at a depth of about 6 km beneath the region, 80-120 km from A. Fig. 6.8, on the other hand suggests that the profile BB' intrusion is only at a depth of about 1 km between 80-100 km from B, while fig. 6.9 suggests that the Biu Plateau probably sourced it's material from an intrusive beneath the profile. Also the magnetic interpretation of the same profiles (figs. 7.10 and 7.11) all suggest the existence of these basic intrusives at depths between 1 km and 7 km beneath the same locations given above. The models suggest that these intrusives are deep-rooted and are within the basement, thereby suggesting the area of study to be an old rift. Figs. 6.10, 6.11, and 6.12 which are 2-dimensional interpretations of the residual gravity anomalies along profiles XX', YY' and ZZ' each of which across the trough from basement to basement, all suggest the presence of basic intrusion at depth.

Figs. 6.11 and 6.12 suggest the existence of marginal intrusions (volcanism?) at depth along the sediments-basement contacts. These bodies are suggested by the interpretation to be dense bodies ($\rho = 2800$ kg m^{-3}) and lie between depths of 1 and 2 km from the surface. The magnetic profile modelling results also

suggest the existence of this marginal intrusions (figs. 7.13, 7.14 and 7.15) at depths of 2 km and below the surface between 50 and 80 km from Z. The magnetic susceptibility for these marginal intrusives is seen from the magnetic modelling to be about 0.0476 SI units, suggesting that they are of basic to ultrabasic composition and thus indicating that they are mantle derived. The high density nature of these bodies (ρ= 2800 kg m^{-3}) and magnetic susceptibilities of 0.0476 SI units as seen from both the gravity and magnetic interpretations suggest that the bodies are basic to ultrabasic in composition and are, therefore, to be most likely volcanics.

According to Benkhelil *et al.* (1989), magmatic activity in the upper Benue trough (of which the study area is part) occurred in two major episodes. The first episode took place in the Mesozoic and this includes the Burashika complex of Jurassic age, and the basaltic venues of Cretaceous age, restricted to faults trending N 55^0 E (Carter *et al.*, 1963). The second phase occurred during the Tertiary, corresponding to the intense alkaline magmatic activity in relation to the Cameroon volcanic line. These tertiary phase of magmatic activity is seen to occur in the present area of study in form of the Biu basalt (see geologic map of area of study), and also in form of isolated volcanic bodies which occur in different parts of the trough between Gombe and Kaltungo.

The existence of these two major episodes of magmatism in areas adjacent to the study area (Burashika complex and Biu Plateau), especially the Tertiary episode which outcrops in the area in form of basalts (Biu Basalt) strongly suggest that the marginal intrusives observed at depth in the area of study (profile XX' and ZZ')

are a product of volcanism at depth in the area. The above observations suggest a rift origin for the Gongola Arm of the Benue Trough.

Previous workers in the Benue Trough, (Ajayi, 1979, Ajayi and Ajakaiye, 1981, Ofoegbu, 1985) of which the study area is part, have suggested the existence of deep rooted basic intrusions, which implies the existence of deeply penetrating fractures within the area.

On the basis of the facts, that the area of study (Gongola Arm of the Benue Upper Trough) is seen to be underlain by basic intrusives at different depths and the suggested presence of marginal intrusives from the interpreted models, the author is of the opinion that the Gongola Arm of the Benue Trough originated through rifting. The presence of basic intrusives at depth in the area and at different areas in the area of study strongly suggest a rift origin for this part of the trough. These basic intrusives have been inferred from results of geophysical studies conducted in different parts of the world over major rift systems such as the Rhine Graben (Bosum and Hahn, 1967) and the Bhaikal rift (Zorin *et al.*, 1975; Zorin, 1971 and 1981). Though marginal surficial evidences for rifting such marginal surface volcanism are lacking in the area of study, the suggested presence of marginal intrusions at depth (volcanism), as suggested by results of the gravity and magnetic modelling in this work, and as confirm from satellite imagery (Ananaba, 1997, pers comm.) indicates that the area of study is a rifted zone.

8.2.2 Dukku Sub Basin

In this work, the prominent negative residual gravity anomaly (Anomaly 2 Fig. 6.4 & 6.5) occurring between Dukku, Gombe and Alkaleri has been interpreted as a basement depression which has been filled with sediments. This graben structure is hereby called the Dukku sub-basin or Dukku Graben.

Two profiles (AA' and YY') were taken across the anomaly in order to accurately determine the details of this graben structure. Profile AA' runs in the NW-SE direction, while profile YY' runs E-W across the axis of the entire trough (Upper Benue), extending from basement to basement. Interpretation of these profiles suggest that the graben is filled with sediments of thickness up to 4.5 km. (Fig. 6.7 and 6.11 a&b). An interpretation of the residual magnetic field along profiles AA' and YY' also suggest the existence of this graben in this area and that the graben is filled with sediments of thickness up to 4.8 km thick. (Figs. 7.10a&b, 7.14a&b). Thus, the interpreted models from both gravity and magnetic residual fields over the area suggest that an almost N-S trending graben which is about 80 km in length (fig. 6.5) exist within the area of study.

For the sediments to have attained a thickness of about 4.5 km, within such a short distance from the basement, suggests that block faulting most likely took place in the area. The results of both the gravity and magnetic interpretations presented in chapters 6 and 7 have suggested that the area has been affected by

block faulting. This is in agreement with the suggestion of Adegoke *et al.* (1986), Enu (Pers. Communication, 1995). Field evidence suggests that block faulting took place in the area. This evidences includes the Kaltungo inlier that outcrops within that study area, and the highly sheared/fractured basement outcrop (inlier) around Gombe also in the area of study. These inliers are thought by the author to have been brought up to the surface by this normal faults and thought to be most likely the upthrown blocks of the faults movement, while the down-thrown blocks most likely form the grabens such as the one seen in this area.

Several authors have also suggested the existence of block faulting in different parts of the Benue trough of which the study area is part. Burke and Dewey (1973) and Burke (1977) suggested that this block faulting resulted from mantle plume activity giving rise to emplacement of intrusive bodies along lines of weakness (as earlier described in section 8.2.1) and consequently block faulting. According to Burke and Dewey (1973), subsidence is believed to have taken place under the weight of sediments deposited. It is also believed that post-depositional erosion and subsequent deposition or rapid deposition (Ajayi and Ajakaiye, 1981) may have covered the marginal faults. The process of post rifting erosion and deposition could have extended the Trough beyond it's original margins, thus suggesting that the marginal faults are farther into the trough than the present margins suggest. This process is most likely what extended the Dukku Graben to a width of about 80 km, as suggested by the interpreted models.

8.2.3 A Geosuture zone within the Trough ?

The composite magnetic anomaly map covering the project area (fig. 7.2) suggests the existence of some linear belts indicated by solid broken lines and marked as AA' which trend in the NE-SW direction. This lineament stretches for a distance of about 250 km and has an average width of 25 km.

The results of the quantitative interpretation of the magnetic data (Figs. 7.7, 7.8, 7.10a&b, 7.11a&b, 7.13a&b etc.) using both Werner deconvolution, 3-dimensional and 2-dimensional modelling along profiles AA', YY' and ZZ' which cut across this prominent magnetic lineament, all suggests that this prominent magnetic anomaly observed along the profiles is probably due to intrusives at depths of between 6 and 8 km (figs. 7.13 - 7.15).

In order for the nature and depth of occurrence of this magnetic lineament to be clearly understood, three profiles stretching in the NW-SE (RR', SS' and TT') were taken across this lineament (Fig 8.1). These profiles were digitised at 0.5 km interval and interpreted. The occurrence of this lineament is seen to be consistent along all the three profile, as indicated by the prominent lows seen along these profiles. The lineament is seen to occur between 50 and 80 km along profile RR' (fig. 8.2), 45-80 km along profile SS'(fig 8.3) and between 60-90 km along profile TT' (fig. 8.4).

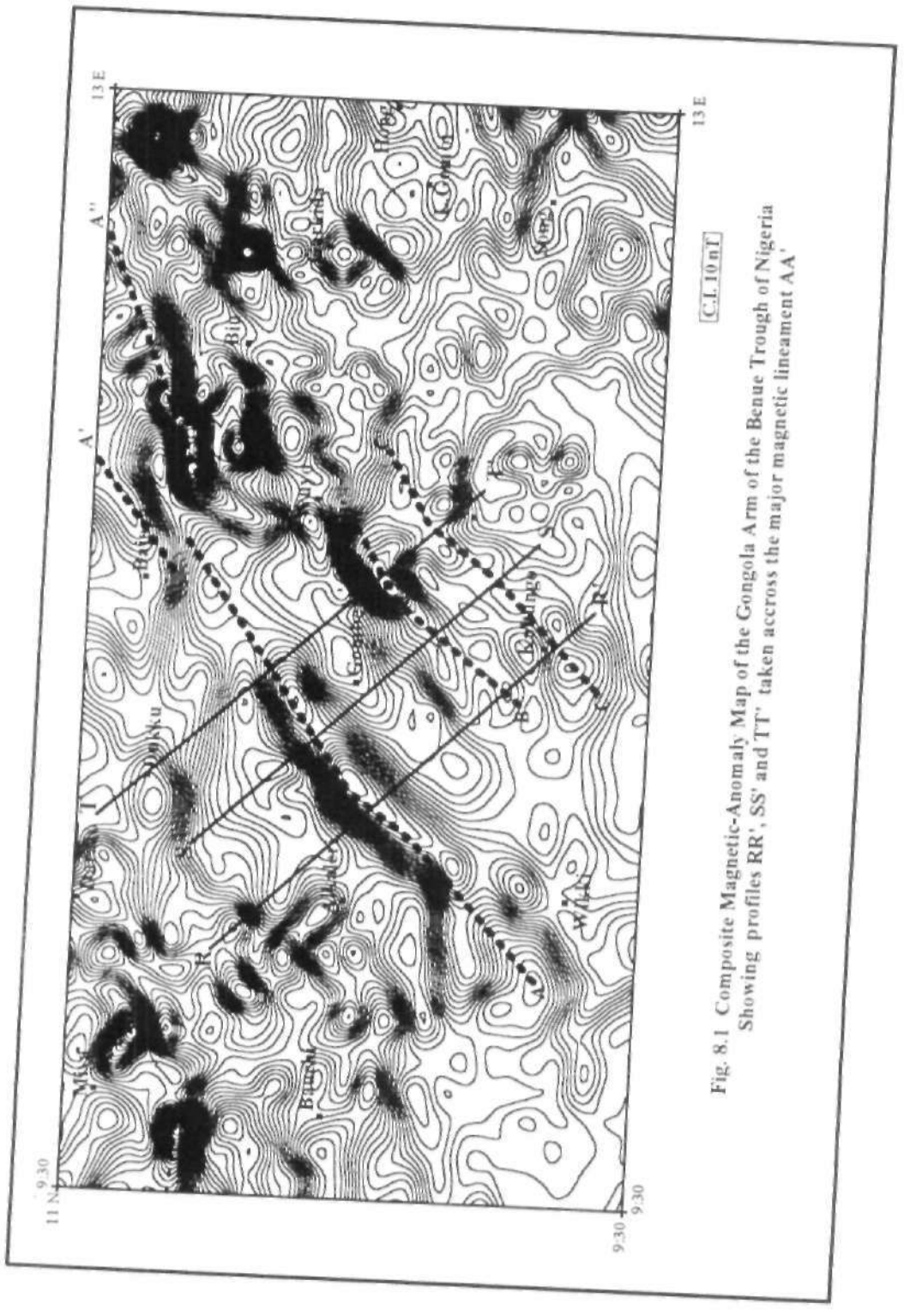


Fig. 8.1 Composite Magnetic-Anomaly Map of the Gongola Arm of the Benue Trough of Nigeria
Showing profiles RR', SS' and TT' taken accross the major magnetic lineament AA'

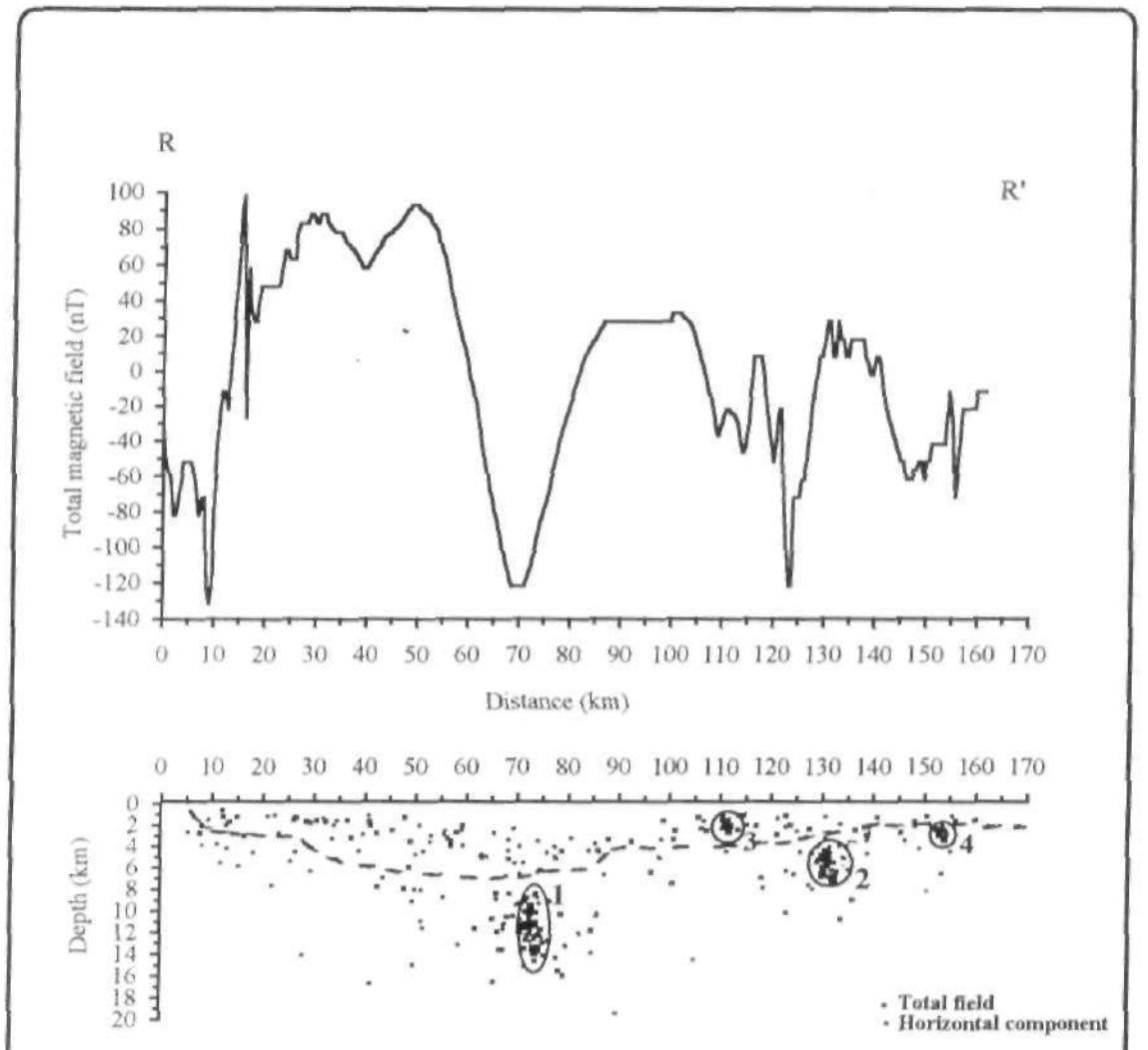


Fig. 8.2 Plot of werner profile showing the interpreted basement surface (as dashed lines) for profile RR'. Significant clusters of solution are indicated by circles.

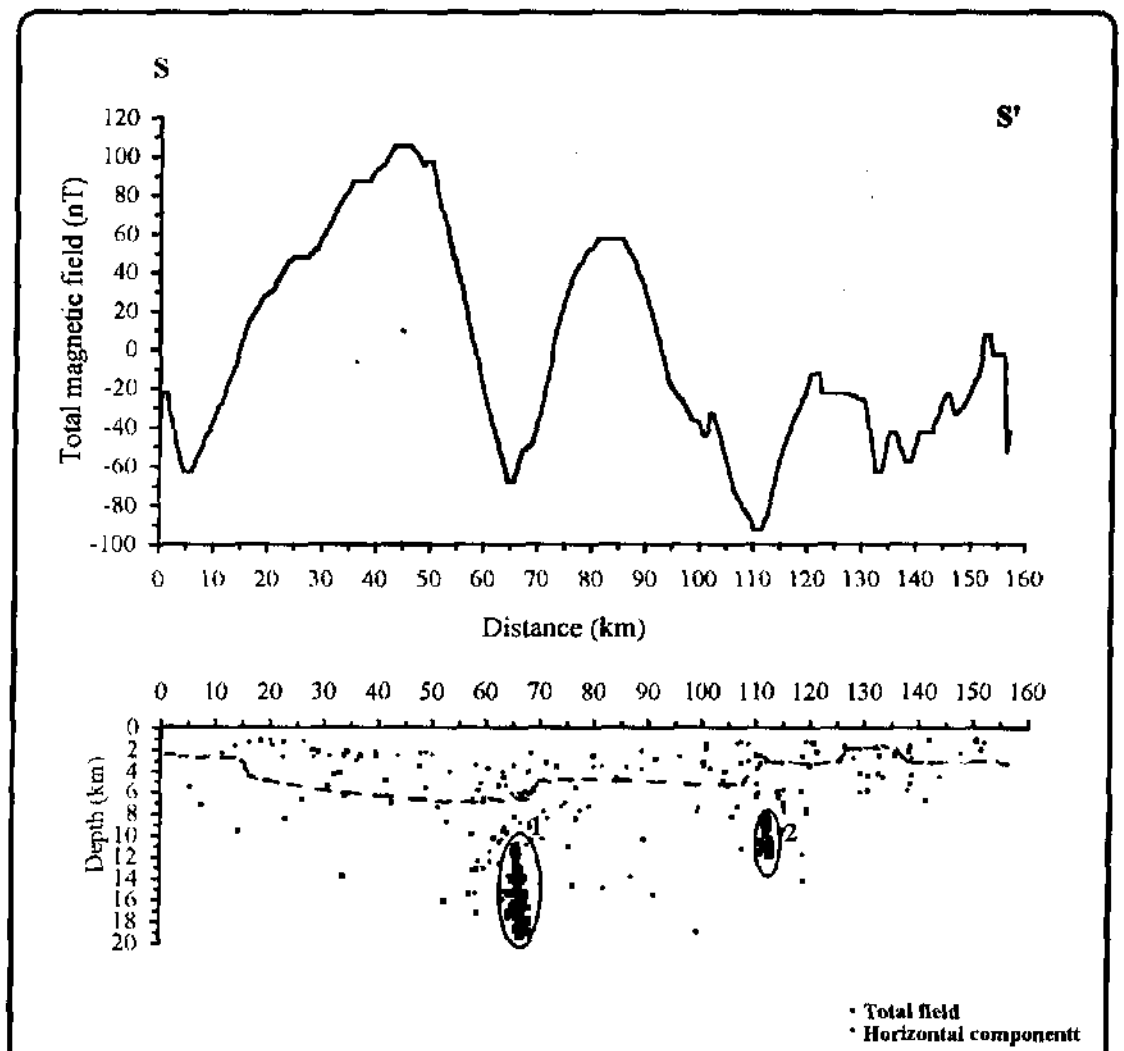


Fig 8.3 Plot of Werner profile showing interpreted basement surface (as dashed lines) for profile SS'. Significant clusters of solution are indicated as circles

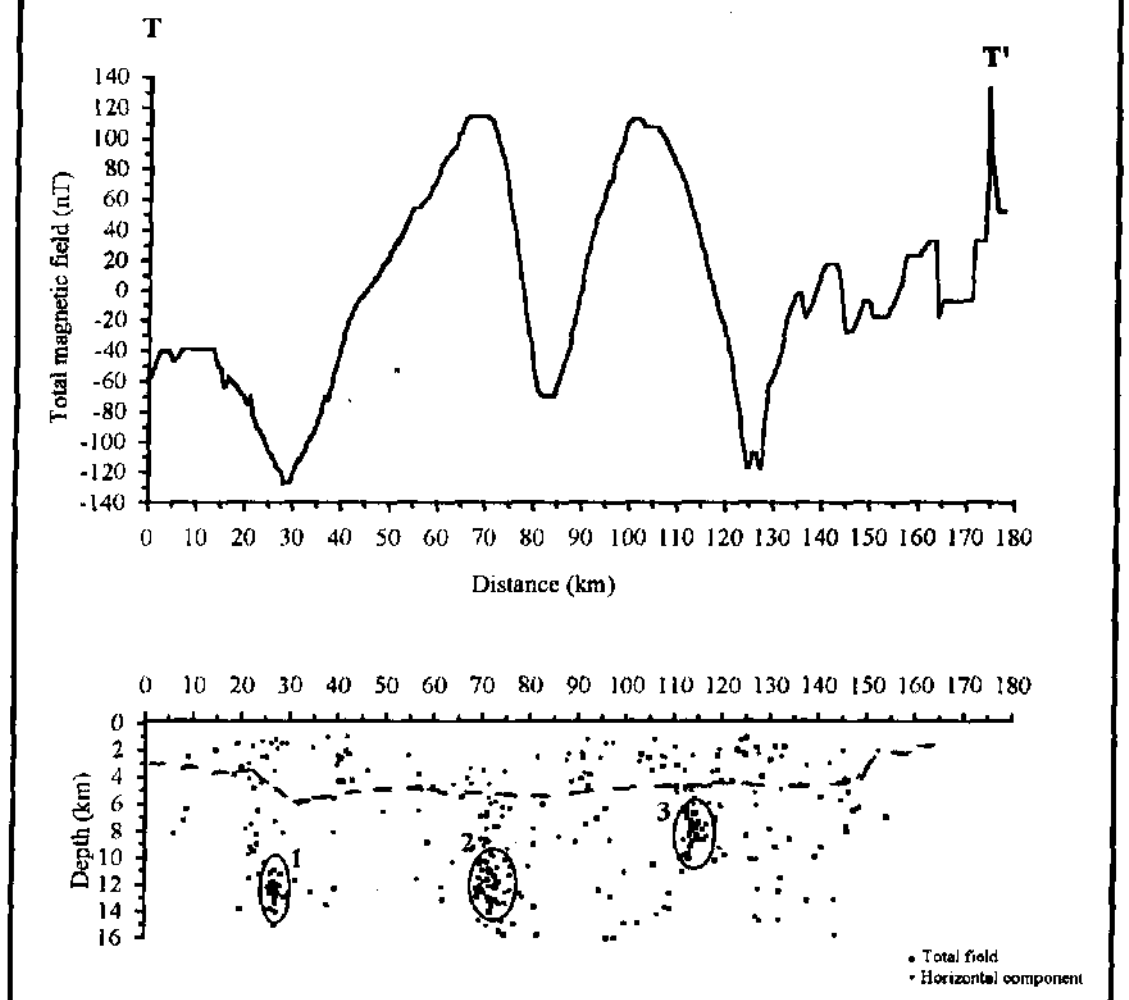


Fig 8.4 Plot of Werner profile showing interpreted basement surface (as dashed lines) for profile TT'. Significant clusters of solutions are indicated by circles

Figs 8.2, 8.3, and 8.4 shows the results of the Werner deconvolution carried out for these profiles(RR', SS' and TT'). All of the Werner profiles indicate strong solutions at depths of between 7 and 8 km over this lineament, thus, suggesting that this lineament is most probably a magnetic body at depth beneath the profiles. Two-dimensional interpretation of the same profiles (RR', SS' and TT') was carried out and the results of these interpretations are shown in figs 8.5, 8.6 and 8.7. The results of the interpretation of the magnetic data along these profiles also suggest that the lineament causing the magnetic anomalies seen on profiles RR', SS' and TT', is a body that has susceptibility value of about 0.0476 SI units. This goes to suggest that the materials constituting that body causing the anomaly are of basic to ultrabasic composition and are probably mantle derived, thus further suggesting that this lineament could be made of volcanic rocks at depth.

Previous workers in the Upper Benue Trough, (Carter *et al.*, 1963; Benkhelil *et al.*, 1989) which includes the present study area, have suggested that a series of magmatic activities took place in the upper Benue trough.

On the eastern margin of the Gongola Arm (the study area) i.e. around the Biu Plateau (in the study area) tertiary volcanic activity is seen to have taken place in the area giving rise to the Biu basalt (see geologic map). In view of the fact that magmatic activity is seen to have taken place along the eastern edge of the sediment/basement boundary (fig. 3.1), and the fact that the magnetic susceptibility of the magnetic bodies causing the anomalies in the area is about 0.0476 SI units, which indicates that these bodies are of basic to ultrabasic composition, the author is

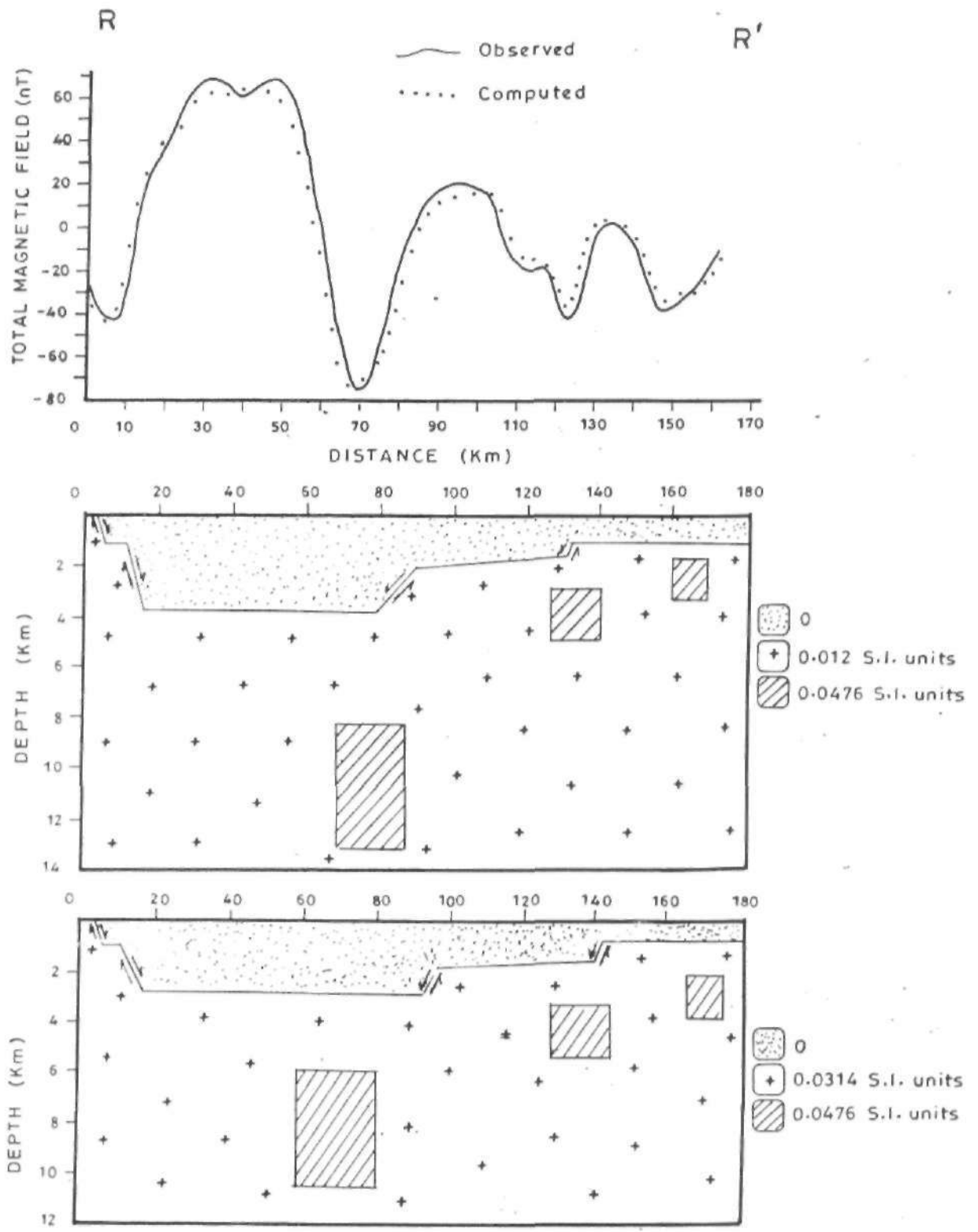


Fig. 8.5 2 – Dimensional model interpretation of magnetic anomalies along profile R R'

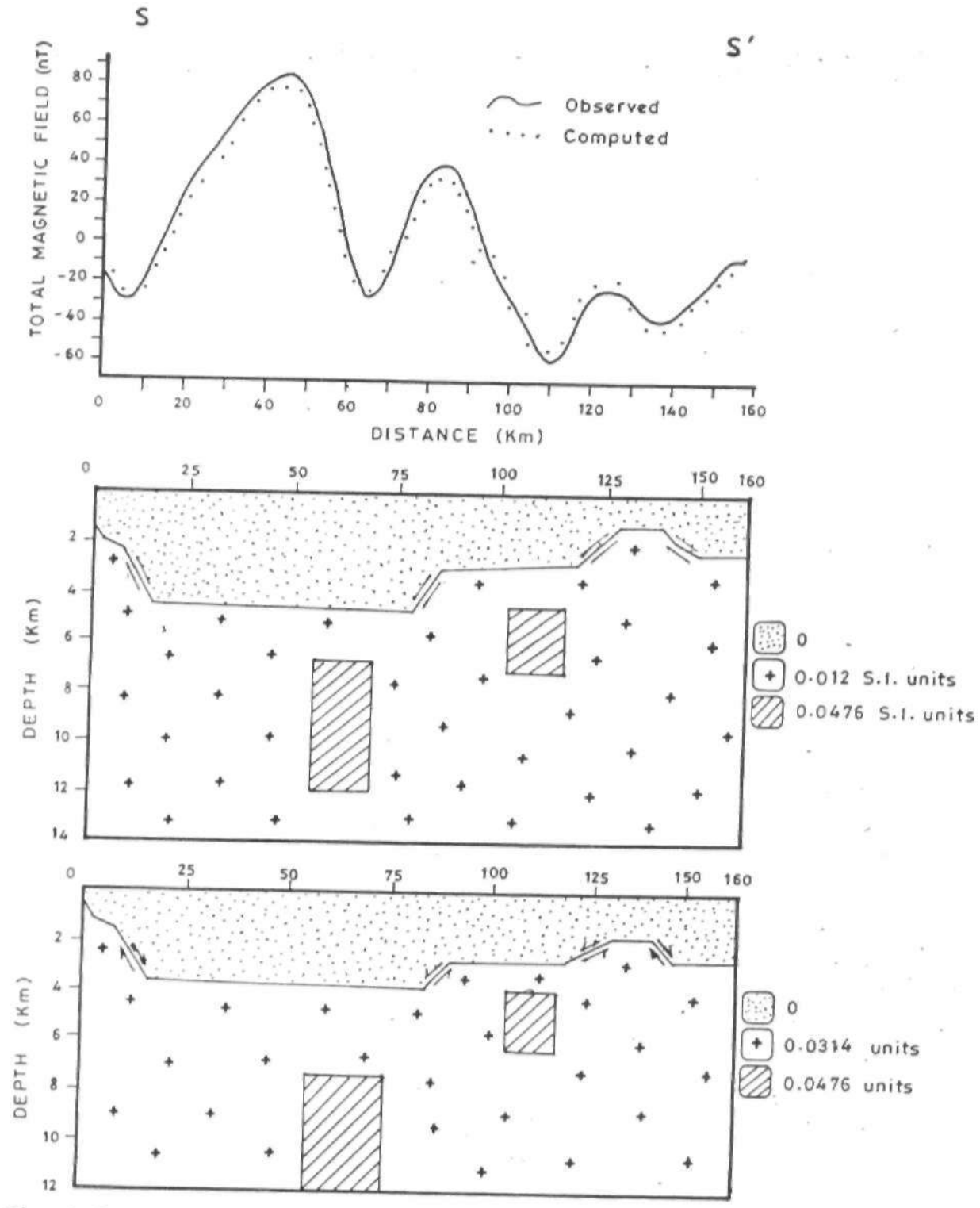


Fig. 8.6 2 - Dimensional model interpretation of magnetic anomalies along profile S S'

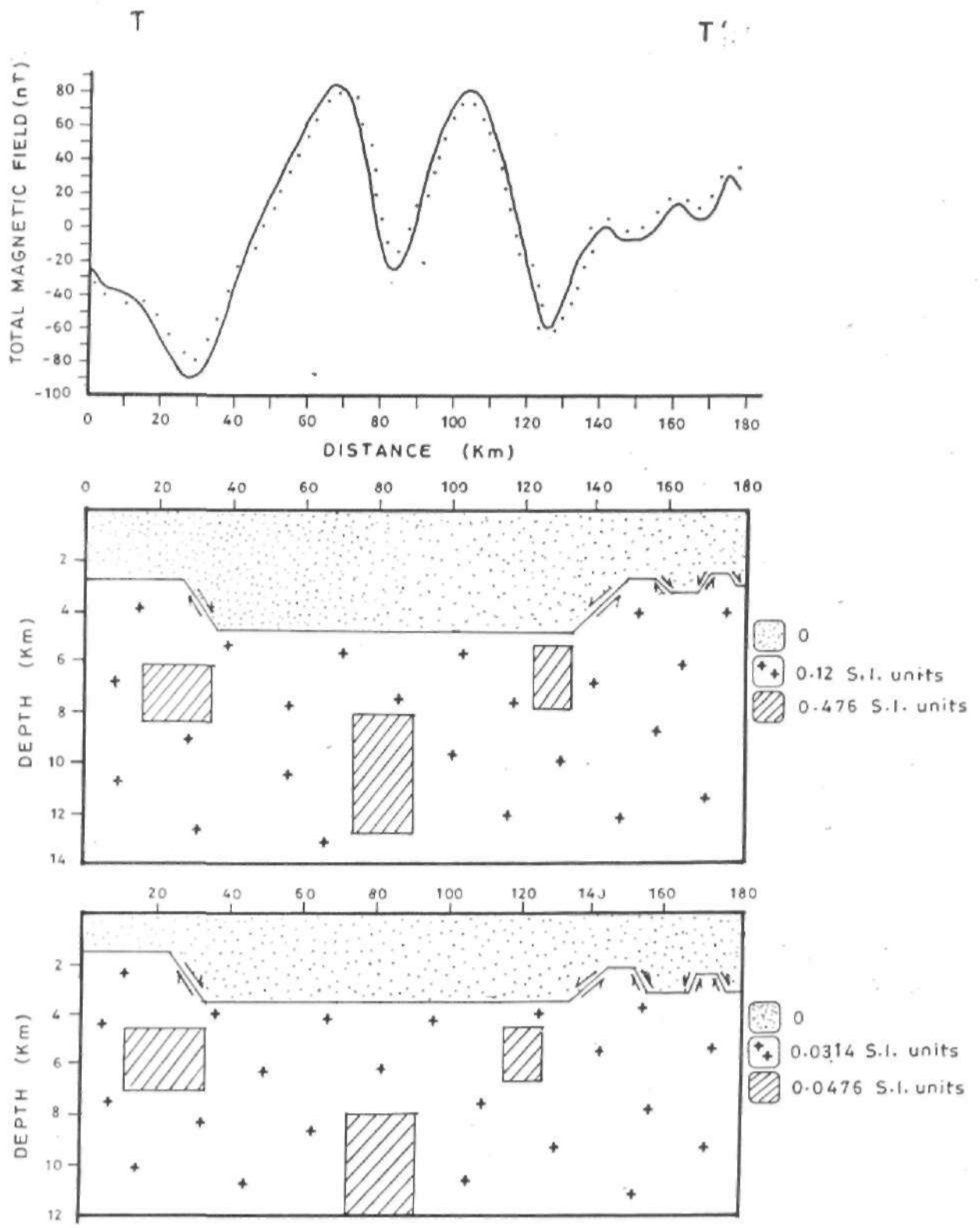


Fig. 8.7 2 – Dimensional model intepretation of magnetic anomalies along profile T T'

of the view that this magnetic lineament is a geosuture zone (a volcanic line) buried at depth in the Gongola Arm of the Benue trough. This geosuture zone is most likely similar to the Cameroon volcanic line that outcrops on the surface with the difference being that the one in the Gongola Arm is buried at depth within the basement rocks.

The source of this volcanic lines could have been a migrating mantle plume that moved eastwards from the Gongola Arm of the Benue trough, (where it never persisted long enough so as to provide the cracks and enough magmatic material that could move from the mantle to the surface in the Gongola Arm of the Benue Trough) to the present day Cameroon volcanic line. The view of the author here is supported by Olade (1975) model for the origin of the Benue trough. Olade's hypotheses on the origin of the trough suggested that the R-R-R tripple junction of the Benue trough arose from doming and rifting associated with the rise of a mantle plume beneath the present day Niger delta. He suggested that limited outpouring of the alkaline-mafic lava and volcanoclastics associated with the doming and rifting in the Benue trough are expressed in the Abakaliki pyroclastics. Olade went further to suggest that rifting within the Benue would then ceased, followed by rapid subsidence and deposition. The temporary cessation of mantle upwelling could have caused folding of the Albian sediments through a process of subcrustal contraction. By the Turonian times, upwelling resumed, and rifting occurred along the old lines of weakness. According to Olade (1975), mantle upwelling ceased in the santonian (or migrated south-east to beneath the present Cameroon line). Fitton (1980), also

suggested the presence of a hot-spot in the Benue Trough that could have migrated south-east to below the Cameroon volcanic line.

8.3 The Origin of the Benue trough

Different models have been proposed by various authors for the origin of the Benue trough since the early 1950's and this theories have been summarised by Ajayi and Ajakaiye (1981). According to these authors, King (1950) used geomorphological evidence to arrive at the rift theory for the origin of the Benue trough. The main arguments so far advanced against the trough being a rifted belt is the absence of marginal surface indication typical of a rift, Lees (1952), despite the fact that the trough is a belt of Cretaceous sediments whose elevations hardly exceeded 300 m and which is also sandwiched between highlands of crystalline rocks of Palaeozoic age (Oyawoye, 1970). According to Ajayi and Ajakaiye (1981), another peculiarity of the Benue Trough is it's abnormal width (between 130-200 km) when compared with widths normally associated with rifted systems (about 50 +/- 15 km). However previous workers (Cratchley and Jones, 1965; Ajayi, 1979; Ajayi and Ajakaiye, 1981) have on the basis of gravity data suggested that the Benue trough may consist of two parallel grabens separated by an axial horst. (Ajayi, 1979; Ajayi and Ajakaiye, 1981), also demonstrated that through other process of regional isostatic adjustment to sedimentary and water loading resulting from rapid deposition of sediments in the Benue trough surface, depression of large

grabens could be increased to as large as five times the original width. The peculiarities of the Benue trough highlighted above are discussed in context of the results obtained from the present study with the aim of suggesting a model for the are of study (Gongola Arm of the Benue Trough).

8.3.1 On the origin of the Gongola arm of the Upper Benue Trough

Wright (1970) proposed a rift model for the Benue Trough of which the study area is part. A simple graben in which the crust was either flat or buckled prior to rifting was his model. The main defects of this model according to Ajayi and Ajakaiye (1981) is that a simple graben cannot be used to explain the width and other peculiarities of the trough. Olade (1975), proposed another rift model for the trough based on the existence of a periodic on-and-off Cretaceous hot-spot beneath the present day Niger delta. Olade's model suggests that upwelling and cessation of mantle plumes in the area culminated into rifting of the trough and subsequent folding of the sediments contained in it. His strongest support for this model was the apparent lack of thrust faults in the trough. However, Ajayi (1979) and Ajayi and Ajakaiye (1981) suggested the existence of thrust faults along the axial ridge of the trough. According to Ajayi and Ajakaiye (1981), other observations that seem to favour the existence of a thrust fault in the Middle Benue trough are the asymmetrical nature of both the Giza syncline and the Keana anticline (all in the Middle Benue Trough).

Based upon the modelling results presented in this work and work completed by previous workers, a general geologic picture may be suggested for the Gongola Arm of the Benue Trough. The data of this study have led to the indications of gross properties of the Gongola Arm of the Upper Benue Trough in terms of structure and composition:

1: The Bouguer anomalies in the Gongola arm of the Benue trough are negative.

2. The Location of the Gongola Arm of the Upper Benue trough was determined by the pre-existing zones of weakness immediately offshore in the Gulf of Guinea: the Chain, Romanche and Charcot fracture zones. According to Lehner and De Ruiter (1977) these oceanic fracture zones along the Atlantic margin of Africa have related tectonic trends onshore. One of such related tectonic trend observed in the present area of study (magnetic lineament AA', Fig 7.2) has the same direction and trend (NE-SW) as the Charcot Fracture Zone. This magnetic lineament has sufficient prominence and length (extends for over 250 km in length and averages about 25 km in width) to suggest that it is probably a signature of regional structural feature representing a major tectonic trend. The results of 2- and 3-Dimensional modelling suggests that this lineament is associated with magmatism at depth, therefore suggesting that it is probably a geosuture zone

This magnetic lineament could therefore be considered to be part of the signatures of the megalineament, geosutures, shear zones or zones of weakness associated with the opening of the Atlantic ocean. These zones were reactivated during the early stages of the continental rifting, parts of which became the foci of intrusive of basic intrusives into the crust, thus suggesting that the area is an old rift system.

3. Examination of the residual gravity anomaly (Fig. 6.4) and the 2- and 3-Dimensional modelling of profiles AA' and BB' (Fig. 6.7 and 6.8), profiles XX', YY' and ZZ' (figs. 6.10 - 6.12) suggests that the area of study is essentially made up of graben and horst structure, with associated basic intrusion at depth. The differential block faulting observed in the area is believed to be as a result of mantle upwelling and regional tension that were concentrated near deep crustal faults, and emplacement of basic intrusions in close association to these faults.

4. The results of the gravity and magnetic interpretations suggest the existence of volcanic intrusions at depth in the area of study, with a major volcanic line being lineament AA' (fig. 7.2)

The results of this study indicates that the Gongola arm of the Upper Benue trough is a rifted structure whose origin, entirely relates to the evolution of the Benue trough. Of the hypothesis presented about the origin of the Benue, the author is more in support of the Olade (1975) hypothesis on the origin of the trough, which

has been earlier highlighted is section 8.2.3. The rifting that subsequently led to the formation of the trough in this area could however be explained in terms of the model of rift (fig 8.8) proposed by Salveson (1978) and discussed in Ajayi and Ajakaiye (1981).

8.4 SUGGESTIONS FOR FUTURE WORK

A number of issues have been raised (such as present of basic intrusives at depth and the presence of a geosuture in the area) in this interpretation that need confirmation using other geophysical exploration methods. A geophysical investigation in the area that will involve the use of deep seismic reflection and refraction methods along profile YY' aimed at mapping the crust/mantle boundary will aid in confirming the existence or otherwise of the geosuture zone believed to exist in the Gongola Arm of the Benue trough as suggested by the magnetic investigation results. The results of such a survey will also give better insight into the thickness of sediments in the area, especially in and around the grabens (e.g. Dukku Graben?) and also map other smaller intrasediment intrusive that might be present in the area. Such information will greatly aid in assessing the viability of the area for petroleum occurrence. Along this line an integrated research approach that will involve the use of both gravity, magnetics and seismic reflection/refraction is recommended for the Gongola Arm of the Benue Trough. This approach will give a

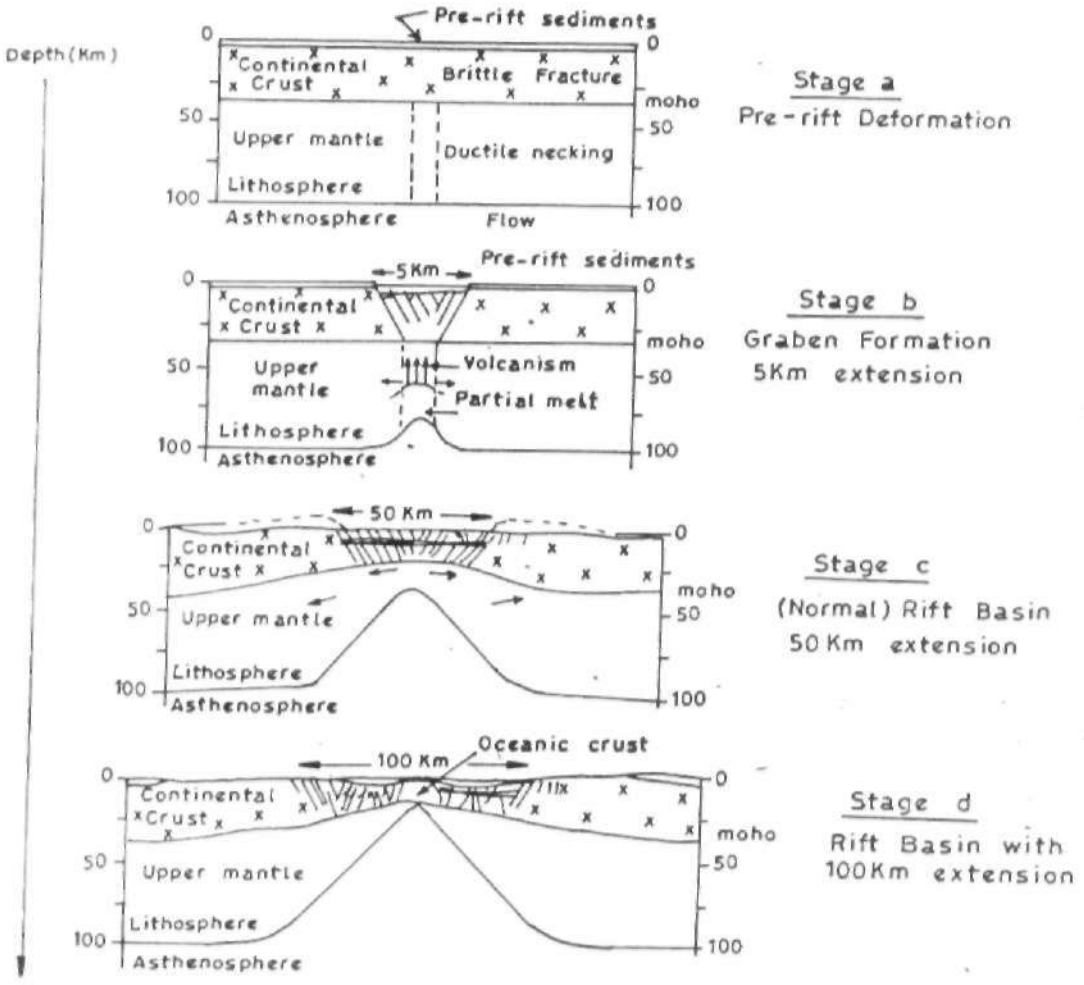


Fig. 8.8 Salveson's model of Rift basin Formation (after Salveson, 1978).

better insight into the structures underneath the area. A structure such as the suture zone deduced from the magnetic data to be deep seated and stretches through the axis of the trough can be clearly mapped using deep seismic refraction. This will enable it's nature and origin to be clearly understood.

Seismic reflection/refraction when carried out in the area of study will give a better insight into the graben and horst nature of the area of study as well as define more correctly the sizes of the grabens and horsts and the amount of sediments contained in this structure. It will also help establish more the nature of the basement topography as well as the presence and nature of occurrence of the basic intrusives seen both from the results of the gravity and magnetics to occur in the area of study.

Finally deep seismic profiling will greatly aid in understanding the nature of the crust under the Gongola Arm of the Benue Trough as well as map the Moho in the area. This will be of great use in determining the amount of crustal thinning and extension that took place in the area of study (the Gongola Arm of the Benue trough) in contrast to other parts of the Trough where it is believed that considerable thinning took place.

8.5 Conclusions

The detailed gravity investigation of the Gongola Arm of the Benue Trough supported with interpreted aeromagnetic data over some selected profile in this work has thrown more light in the understanding of the origin and structural setting of the area. It has also helped to reveal thickness of sediments that overlie the area.

The results of the study show that the area of study is characterised by negative Bouguer anomalies that range in values from -75 to -10 mGal, with an average value of -42 mGals (fig 6.1). A first order polynomial was used to approximate the regional anomalies in the area (fig. 6.3) The long wavelength regional was interpreted in terms of Moho uplift of up to 7 km in the area of study (fig 6.13). Selected profiles were taken across the residual anomalies (fig 6.5) and were interpreted. The interpreted residual gravity anomalies suggest that area is underlain by horst and graben structures, with some of the graben being as wide as 80 km and filled by sediment as thick as 4.5 km (fig, 6.7,6.11) . The interpreted results also suggested the presence of basic intrusives(of density about 2800 kg m^{-3}) at depths as shallow as 1 km to as deep as 8 km (fig 6.7, 6.8, 6.9, 6.10, 6.11 and 6.12). The interpreted results also suggest that the eastern margin of the trough in contact with the Biu Plateau is further inside than it is now (figs 6.10 and 7.13a&b). The models suggests that the flow of Basalt from the Biu Plateau to lower levels was in form thin covers over the sedimentary rocks (Bima Formation) at the

margins with the Plateau. Field evidence during data collection also shows this basalts constitutes a thin cover over the sediments in that part of the margin.

Magnetic data interpretation along some selected profiles that coincided mostly with the interpreted gravity profiles also suggests that the area is characterised by horst and graben structures. The grabens are seen from the results of the interpretation to be filled with sediments as thick as 4.8 km. The magnetic modelling results also suggested the existence of high magnetic susceptibility rocks at depth of between 1 and 8 km in the area of study. The magnetic modelling suggested that the susceptibility of these materials is about 0.0476 S.I units, thus suggesting that they are of basic to ultrabasic in composition. A prominent magnetic lineament identified as AA'(Fig. 7.2) was interpreted in terms of a geosuture zone at depth beneath the Gongola Arm of the Benue Trough.

Among the major information obtained from the present study are:

1) The structure of the area is that of horst and graben with estimated thickness of the sediments in the different parts of the area of study, which were established from gravity and magnetic interpretation to have an upper limit of 5 km.

2) The margin of the trough with the Biu Plateau on the east is probably beyond the present mapped margin on the surface as suggested by interpretation of profiles XX' (figs. 6.11 and 7.13).

3) Buried basic intrusives most likely exist at different locations beneath the trough at depths ranging from 1-8 km. This suggests the existence of deep fissures in the crust beneath the area of study which might have originated during rifting and thus further suggesting a rift origin for the area (Gongola Arm of the Benue Trough).

4) The study has identified three prominent magnetic lineaments that are within a probable zone of weakness along which basic intrusives are modelled to occur at depths of between 1 and 8 km in the study area, suggesting that the magnetic lineaments are of probable tectonic origin. The results have also suggested that the lineaments are magmatic (heat) related. This result is significant both from economic point of view because of the establishment that the Pb-Zn mineralisations in the trough are heat related and are controlled along particular trends (NE-SW direction) in the Benue Trough regional tectonics. This therefore marks out this lineament zones for further detailed investigations as potential areas that will host heat related mineralisation such as the Pb-Zn mineralisation that occur in the Benue Trough.

5) Results of the regional anomaly interpretation suggest a thinning of the crust of up to 7 km in the area of study, with the resulting from compensation due to the lighter Cretaceous sedimentary rocks in the area.

6) The results also suggest that the smallest crustal thickness in the area may not be less than 27 km, Thus neither crustal separation nor the existence of a spreading ridge suggested by Burke *et al.* (1970) for the trough did occur in Gongola arm of the Benue Trough, thus suggesting the existence of a short-lived spreading ridge as suggested by Grant (1971).

7) The results of the present study have suggested the Gongola arm of the Benue Trough is most probably an old rift system (that has been covered by sediments) whose origin is associated with the opening of the Atlantic Ocean.

REFERENCES:

Adegoke, O.S., Jan du Chene, R.E., Agumanu, A.E. and Ajayi, P.O.(1986). New Stratigraphic, Sedimentologic and Structural data on the Kerri-Kerri Formation, Bauchi and Borno States, Nigeria. *J.Afr. Earth Sci.* 5 249-277.

Adighije, C.I. (1979). Gravity Field of the Benue trough, Nigeria. *Nature Phy. sci.* 282, 199-201.

Adighije, C.I. (1981).

a) A Gravity Study of the Lower Benue Trough, Nigeria, *Geol. Mag.*, 118 59-67.

b) A Gravity Interpretation of the Benue Trough, Nigeria, *Tectonophysics,* 79 109- 128.

Ajakaiye, D.E. (1981). Geophysical Investigation of the Benue trough - a review. *Earth Evol. Sci.*, 1 126-136.

Ajakaiye, D.E. and Burke, K.E. (1972). A Bouguer gravity Map of Nigeria. *Tectonophysics,* 16 103-115.

Ajakaiye, D.E., Hall, D.H. and Millar, T.W. (1985). Interpretation of Aeromagnetic data Across the Central Crystalline Shield area of Nigeria. *Geophys. J.*, 83 503-517.

Ajakaiye, D.E., Hall, D.H., Millar, T.W., Verheijen, P.J.T., Awad, M.B. and Ojo, S.B. (1986). Anomalies and Tectonic Trends in and Around the Benue Trough, Nigeria. *Nature* 319(6054) 582-584.

Ajayi, C.O. (1979). A detailed gravity survey of the Middle Benue. Ph.D Thesis, Ahmadu Bello University, Zaria Nigeria.

Ajayi C.O. (1987).

a. Origin of salt springs and barytes in the Middle Benue Trough: a suggested model from gravity data. *NMGS abstracts,* 23 5.

b. A preliminary lithospheric (crust and upper mantle) interpretation of the gravity data from the Benue trough and adjacent areas. In Matheis and Schandeimeier (eds). *Current researches in African earth sciences,* Balkema, Rotterdam, 293-294

Ajayi, C.O. and Ajakaiye, D.E. (1981). The Origin and Peculiarities of the Benue Trough: another look from recent gravity data in the Middle Benue. *Tectonophysics,* 80 285-303.

Ajayi C.O. and Ajakaiye D.E. (1985). Stuctures Deduced from Gravity data in the Middle Benue, Nigeria. *Journal of African Earth Sciences*, 5 359-369.

Alli, O.H. (1988). Separation of Residual from Bouguer gravity data measured over deep sedimentary basin, western Sudan. *Journal University Kuwait*, 15 347-357

Allix, P., Grosdidier, E., Jardine, S. Legoux, O. and Popoff, M. (1981). Decouverte d'Aptien superieur a Albien inferieur date par Microfosiles dans la serie detrique cretacee du la Benoue (Nigeria). *C.R. Acad. Sci.*, Paris 292, 1291-1294.

Artsybashev, V.A. and Kogbe, C.A. (1974). Crustal structure of the Benue Valley area (Nigeria). *Geol. Rundschau*, 64 324-329.

Ball, E. (1980) An example of very consistent brittle deformation over a wide intracontinental area: The late Pan-African fracture system of the Taureg and Nigerian Shield. *Tectonophysics*, 61 363-379

Behrendt, J.C. and Klitgord, K.D. (1980). High-Sensitivity aeromagnetic survey of the U.S. Atlantic continental margin. *Geophysics*, 45 1813-1846

Benkhelil, J. (1982). Benue Trough and Benue Chain. *Geol. Mag.*, 119(2) 158-168.

Benkhelil, J. (1986). Carteristiques structrales et evulotion geodynamique du basin intracontinental de la Benoue (Nigeria). These d'etat, Nice 275 pp.

Benkhelil, J. (1988). Structure and geodynamic evolution of the intracratonic Benue Trough (Nig.). *Bull. Centres Rech. Explor-Prod. Elf-Aquitance*, 12 (1) 29-128.

Benkhelil, J. (1989). The origin and evolution of the Cretaceous Benue Trough Nigeria. *Journal of African Earth Sciences*, 6 (2/3/4) 251-282.

Benkhelil, J. and Guiraud, R. (1980). La Benoue (Nigeria): une chain intracontinentale de style alasique. *C.R. Acad. Sci., Paris*, 290 1517 1520.

Benkhelil, J. and Robineau, B. (1983). Is the Benue Trough a Rift? *Bull. Centres. Rech. Explor. Prod. Elf-Aquitane*,7 315-321.

Benkhelil, J., Dainelli, P., Ponsard, J.F., Popoff, M. and Saugy, L. (1988). The Benue Trough: Wrench fault related basin, on the border of the Equitorial Atlantic. In (Manspeizer, W. Ed.), Triasic-Jurassic Rifting, Continental Breakup and the origin of theAtlantic Ocean andpassive Margins. (*Developments in Geotectonics, 22)*, Elsevier Amsterdam, 789-819.

Bosum,W. and Hahn, A. (1967). Aermagnetic Surveying in Upper Rhine graben. *Abh. geol. Landesamt Baden- Wurtt*, 6 89-91.

Bott, M.K.P. and Smithson, S.B. (1967). Gravity and investigation of subsurface shape and mass distribution of granite batholiths. *Geol. Soc. Am. Bull.*, 78, 859-878

Brown, C. and Girdler, R.W. (1980). Interpretation of African gravity and it's implicatons for the Break-up of the continents. *Journ. Geopy. Res*, 85 B11 6445 6455

Burke, K. (1977). Aulacogens and continental breakup. *Ann. Rev. Planet Sci.*, 5 371-396

Burke, K.C., Dessauvagie, T.F.J. and Whiteman, A.J. (1972). Geological history of the Benue Valley and adjacent areas. *In*: Dessauvagie, T.F.J., and Whiteman, A.J., (Ed.), *African Gelogy* Ibadan University Press, Ibadan, 187-206.

Burke, K.C., and Dewey, J.F. (1970). Orogeny in Africa *In*: Dessauvagie, T.F.J. (Ed.) *African Gelogy* . Ibadan University Press, Ibadan, 206-213

Burke, K.C. and Dewey, J.F. (1973). Plume-generated tripple junctions: Key indicators in applying plate tectonics to old rocks. *Journal of Geol.*, 81 406-433.

Burke, K.C., Dessauvagie, T.F.J. and Whiteman, A.J. (1971). Openning of the Gulf of Guinea And Geological History of the Benue Depression and Niger Delta *Nature Phys. Sci.*, 233, 51-55

Burke, K.C., and Dewey, J.F. (1974). Two Plates in Africa during the Creataceous? *Nature, Lond.*, 249, 313-316.

Burke, K.C., Freeth, S.J. and Grant, N.K. (1976). The structure and sequence of geological events in the basement complex of the Ibadan area, western Nigeria. *Precamb. Res.*, 3 537-545.

Carter, J.D. Barber, W., and Tait, E.A. (1963). Geology of Adamawa Bauchi and Bornu Provinces in Northeastern Nigeria. *Bull. Geol. Surv. Nigeria*, 30,1-108.

Cordell, L., and Grauch, V.J.S. (1985). Mapping basement magnetization zones from aeromagnetic data in the San Juan Basin, New Mexico *In*: Hinze, W.J., (ed.), *The Utility of Regional Gravity and Magnetic Anomaly Maps*. Tulsa, Society of Exploration Geophysicists, 181-197.

Cratchley, C.R. and Jones, J.P. (1965). An interpretation of the geology and gravity anomalies of the Benue Valley, Nigeria. *Overseas geol. Surv. Geophys. paper*, 9, 1-28.

Cratchley, C.R., Louis, P. and Ajakaiye, D.E. (1984). Geophysical and Geological Evidence for the Benue-Chad Basin Cretaceous Rift valley Systems and its Tectonic Implications. *Journal of Afric. Earth Sciences*, 2(2) 141-150.

Chukwu-Ike, I.M. (1977). Regional Photogeological Interpretation of the Tectonic Features of the Central Nigerian Basement Complex- A Statistical Imagery Based Study. P.hD. Thesis, University of London.

Dessauvagie, T.FJ. (1975). Geological Map of Nigeria 1:1000 000. *J.Min.Geol.*,9, 1-28.

Dobrin M.B. and Savit, C.H. (1988). *Introduction to Geophysical Prospecting.* (fourth edition) McGraw-Hill Book Company 867 pp.

Dorn, W.S. and McCracken, D.D. (1972) *Numerical methods with FORTRAN IV case studies.* John Wiley and Sons Inc.

Drake, C.L and Girdler, R.W. (1964). A geophysical study of the Red Sea. *Geophys. J., R. Astron. Soc., London,* 8, 473-495.

du Preez, J.W. (1949). The Geology and Hydrogeology of Biu Division. *Geol.* Surv. Nig Unpub. Report no. 751.

Elf Nig. Ltd. (1985). Structural Interpretation of the Benue Trough and the Bornu Basin. Unpublished report, Lagos 59 pp.

Ekine, A.S. (1979). Gravity Survey Around the Wuse-Akiri salt Spring area of the Middle Benue Valley. Unpublished M.Sc Thesis, Ahmadu Bello University Zaria Nig.

Emery, K., Uchupi, O.E., Phillips, J., Bowin ,C. and Mascle, J. (1975). Continental Margin off West Africa Angola to Sierra Leone. *Am. Ass. Petrol. Geol. Bull.,* 59 2209-2265.

Falconer, J.D. (1911). *The Geology and Geography of Northern Nigeria.* Macmillan & Co., Ltd, London, 295pp.

Fairhead, J.D. (1988). Mesozoic plate tectonic reconstruction of the central South Atlantic Ocean: The role of the West and Central African Rift System. *Tectonophysics,* 155 1181-191.

Fairhead, J.D. and Green, C.M. (1988). Controls on rifting in Africa and the regional tectonic model for the Nigerian and East Niger rift basins. In: (B. Rosendall Ed.) *African Rifting, Spec. Publi.,* 8 231-249.

Fairhead, J.D. and Okereke, C.S. (1987). A regional gravity study of theWest African Rift System in Nigeria and Cameroon and its tectonic interpretation. *Tectonophysics,* 143,141-159.

Fairhead, J.D. and Okereke, C.S. (1990). Crustal thinning and extension beneath Benue trough based on gravity studies. *Journ. African Earth Sci.,* 11(3/4) 329-335.

Fitton, J.G. (1980). The Benue Trough and Cameroon Line- a Migrating Rift System in West Africa. *Earth and Plan. Science Lett.*, 51 132-138.

Fitton, J.G. (1983). Active versus Passive continental rifting evidence from the West African rift system. *Tectonophysics*, 94 373 478.

Ford, S.A. (1981). The Economic Mineral Resources of the Benue Trough. *Earth Evolution Sciences*, 2 154-163.

Freidberg, J.L. (1975). Understanding and use of Werner deconvolution in aeromagnetic interpretation. *Aero Services Corporation, Huston, Texas* pp 1 - 29

Garland, G.D. (1965). *The Earth's shape and Gravity.* Pergamon Press, Oxford, 183pp

Godson, R.H. (1983a). GRÀVPOLY: A Modification of Three-Dimensional Gravity Modelling Program. *US Geological Survey Open File Reoprt*, 83-346 50pp

Godson, R.H. (1983b). MAGPOLY: A Modification of Three-Dimensional magnetic Modelling Program. *US Geological Survey Open File Reoprt*, 83-345 62pp

Grant, F.S. and West, G.F. (1965). *Interpretaion Theory in Applied Geophysics.* McGraw Hill Book Company, London 250pp

Grant, N.K. (1971). South Atlantic, Benue Trough and Gulf of Guinea Cretaceous Tripple Junction. *Bull. geol. Soc. Am.*, 82, 2295-2298.

Harbough, J.W. and Merriam, D.F. (1968). *Computer Applications in stratigraphic Analyses.* John Wiley and Sons Inc. London, 230pp

Hartman, R.R. Tesky, D.J. and Friedberg, J.L. (1971). A system of rapid digital aeromagnetic interpretation. *Geophysics*,36 (5) 891-918

Heiskanen, W.A. and Heltmurtz, M. (1967). *Physical Geodesy.* W.H. Freeman San Francisco.

Hiertzler, J.R. and Hayes, D. E. (1967). Magnetic Boundaries in the North Atlantic Ocean. *Sciences*, 157 185-187.

Holt, R., Egbuniwe, I.G., Fitches, W.R. and Wright, J.B. (1978). The relationships between low grade metasedimantary belts, calc-alkaline volcanism and the Pan-African Orogeny in NW Nigeria. *Geol. Rundsch.*, 67 631-646.

Hoque, M. (1984). Pyroclastics from the lower Benue Trough and their tectonic implications. *J.Afric. Earth Sci.*, 2 351-358.

Hoque, M. and Nwajide, C.S. (1984). Tectono-Sedimentological evolution of an elongate intracratonic basin (aulocogen): the case of the Benue Trough of Nigeria. *Journ. Mining Geol.*, 21 19-26.

Jacobson, P. Jr. (1961). An evaluation of basement depth determinations from airborne magnetometer data. *Geophysics*, 26 (3) 309 - 319

Jain, S. (1976). An Automatic method of direct interpretation of magnetic profiles. *Geophysics*, 41 531 - 541.

Jin, D.J. (1974) Two-Dimensional mass distributions from gravity anomalies: a computer method. *J. Geophys. Res.*, 22: 761-764.

Kennedy, W.O. (1965). The influence of Basement structure on the evolution of the coastal (Mesozoic and Tertiary) Basins. In: Institute of Petroluem London (Ed.,), *Salt basins around Africa* Elsevier Publish. Co., Amsterdam. 7-16

King, L.C. (1950). Outline and Disruption of Gondwanaland. *Geol. Mag.*, 87, 353-359

Kilty, K.T. (1983). Werner deconvolution of profile potential field data. *Geophysics*, 48 234 - 237.

Koulomzine, Th., Lamontagne, Y. and Nadeau, A. (1970). New methods for direct interpretation of magnetic anomalies caused by inclined dykes of infinte length. *Geophysics*, 359 (5) 812-830

Krumbein, W.C. (1959). Trend surface anlyses of contour-type maps with irregular control points spacing. *Joun. Geophy. Res.*, 64 823- 834.

Ku, C.C. and Sharp, J.A. (1983). Werner deconvolution for automatic magnetic interpretation and it's refinement using Marquardt's inverse modelling. *Geophysics*, 48 754- 774

Lawal, O. (1979). Microbiostratigrahie des formations cretacee de la region de Gombe, Nigeria Nord-Oriental. These 3eme cycle, Nice 62pp.

Lees, G.M. (1952). Foreland folding. *Quaterly Journ.,Geol. Soc., London*, 108 1-34.

Lehner, P. and De Reuiter P.A.C. (1977). Structural History of the Atlantic Margin of Africa. *Bull. Amer. Ass. Pet. Geol.*, 61,7 961-981.

Le Pichon, X. and Hayes, D.E. (1971). Marginal offsets, fracture zones and early openning of the South Atlantic. *J. Geophys. Res.*, 76 6283-6293.

Mareschal, J. (1983). Mechanisms of Uplift Preceeding Rifting, *Tectonophysics*, 94, 51-66.

Maurin, J.C., Benkhelil, J. and Ronineau, B. (1986). Fault rocks of the Kaltungo linearment, NE Nigeria and thier relationship with the Benue trough tectonics. *J.Geol. Soc. Lond.*, 143 587-599.

McCurry, P. (1971). Pan African Orogeny in Northern Nigeria. *Bull.geol. Soc. Am.*, 82 3251-3261.

McCurry, P.and Wright, J.B. (1971). On place and time in orogenic granite plutonism. *Bull. geol. Soc. Am.*, 82 1717-1746.

Milos, P., Jan, P. and Vincenc,V. (1973). *The Theory of the Earth's Gravity field.* Elservier Scientific publ. company

Morgan, W.J. (1983). Hotspot Tracks and the Early Opening of the Atlantic. *Tectonophysics*, 94, 123-139.

Myada, E.E. (1979). Mafa- Dikwa geophysical anomaly and their interpretation. Unpblished Ph.D Thesis, Ahmadu Bello University Zaria Nigeria.

Nabighian, M.N. (1972). The analytic signal of two-dimensional magnetic bodies with polygonal cross section: its properties and use for automated interpretation. *Geophysics*, 37 (3) 507 - 517

Neev, D. (1977). The Pelusium Line - A Major Transcontinental shear. *Tectonopysics*, 38 T1-T8.

Neev, D., Hall, J.K. and Saul, J.M. (1982). The Pelusium Megashear System Across Africa and Associated Lineament Swarms. *Journ. Geopysical Research*, 87 1015-1030.

Nettleton, L.I. (1954). Regionals, Residuals, and Structures. *Geophysics*, 19 (1) 1-22

Nettleton, L.I. (1973). Elementary Gravity and Magnetics for Geologists and Seismologists. Monograph series No. 1 *The Society of Exploration Geophysicists.*

Nwachukwu, S.O. (1972). The Tectonic Evolution of the Southern Portion of the Benue Trough, Nigeria. *Geol. Mag.*, 109(5) 411-419.

Offodile, M.E. (1976). The Geology of the Middle Benue, Nigeria. *Cretaceous Research*, 1 101-124.

Offodile, M.E. and Reyment, R.A. (1976). Stratigraphy of the Keana-Awe area of the Middle Benue region of Nigeria. *Bull. Geol Inst. Univ. Uppsala*, 7 37-66.

Ofoegbu, C.O., (1984).
a) Interpretation of aeromagnetic anomalies over the Lower and Middle Benue Trough of Nigeria. *Geophys. J.R. astro. soc.*, 79 813-823.

b) A model for the Tectonic evolution of the Benue Trough of Nigeria. *Geol. Rundsch,* 73 1007-1018.

c) Aeromagnetic anomalies over the Lower and Middle Benue Trough, Nigeria. *Nig. Journ. Mining Geol.,* 21 103-108.

Ofoegbu, C.O. (1985). Interpretaion of an aeromagnetic profile accross the Benue Trough of Nigeria. *J.Afri. Eart Sci.,* 3 293-296.

Ofoegbu, C.O. (1986). Prelimimary results of pseudogravity study of the Benue Trough, Nigeria. *J. Afri. Earth Sci.,* 5 187-192.

Ofoegbu, C.O. (1988). An aeromagnetic study of part of the Upper Benue Trough, Nigeria. *J. Afri. Earth Sci.,* 7 77-90.

Oldham, C.H.G. and Sutherland, D.B. (1955). Orthogonal Polynomials: their use in estimating the regional effects. *Geophysics,* 20 295-306

Ojo, S. B. (1974). Gravity Investigation of the Midlle Niger Basin Area, Nigeria M.Sc., Thesis Ahmadu Bello University Zaria, Nigeria.

Ojo, S.B. (1990). Origin of a major aeromagnetic anomaly in the Middle Niger Basin, Nigeria, *Tectonophysics,* 185 153-162

Okeke, P.O., Ofoebgu, C.O. and Amajor, L.C. (1988). On the origin of the highly altered basalts, Benue trough, Nig. *Geok. Mineralogia Petrol.,*24 55-67

Olade, M.A. (1975). Evolution of Nigeria's Benue Trough (Aulacogen): A Tectonic Model. *Geol. Mag.* 112, 575-581.

Osazuwa, I.B. (1978). A Gravity and Magnetic Survey of The Upper Benue Trough. M.Sc Thesis Ahmadu Bello University, Zaria Nigeria.

Osazuwa, I.B. (1985). The Establishment of a Primary Gravity network for Nigeria. Unpublished Ph.D Thesis, Ahmadu Bello University, Zaria, Nigeria, 320pp

Osazuwa, I.B., Ajakaiye, D.E. and Verheijen P.J.T. (1981). Analysis of the structure of Part of the Upper Benue Rift Valley on the Basis of new Geophysical data. *Earth Evol. Sci.,* 2 126-135.

Oyawoye, M.O. (1970). The Basement Complex of Nigeria In: Dessauvagie, T.F.J. and Whiteman A.J. Ed. *African Geology*, University Press, Ibadan, Nigeria 91-97.

Paterson, N.R. and Reeves, C.V. (1985). Application of Gravity and Magnetic Surveys: The State of the Art in 1985. *Geophysics,* 50 (12) 2258 - 2294

Plouff, D. (1975a). Derivation of Formulas and Fortran programs to compute gravity anomalies of prisms. *U.S Geological Survey Report,* 90p.

Plouff, D. (1975b). Derivation of Formulas and Fortran programs to compute magnetic anomalies of prisms. *U.S Geological Survey Report,* 112p.

Plouff ,D. (1976). Gravity and Magnetic Fields of Polygonal Prisms and Application to Magnetic Terrain Corrections. *Geophysics,* 41 (4) 727-741

Popoff, M., Benkhelil, J., Simon, B. and Motte, J.J. (1983). Geodynamic approach to the Benue trough (NE Nigeria) Using field and teledetection data. *Bull. Centres Rech. Explor. Prod. Elf-Aquitane,* 7 323-337.

Popoff, M., Kampunzu, A.B., Coulon, C. and Esquevin, J. (1982). Decouverte d'un volcanisme mesozoique dans le nord-est du Nigeria: datations absolues, caracteres magmatiques et significant geodynamque dans l'evolution du rift de la Benoue. *Bull Centres Rech Explor. Prod. Elf-Aqitutaine,* 19 47-70.

Quereshi, I.R and Mula, H.G. (1971). Two-Dimensional mass distributions from gravity anomalies: a computer method. *Geophys. Prospect.,* 19, 180-191.

Reford, M.S. and Sumner, J.S. (1964). Aeromagnetic review article. *Geophysics,* 29 (4) 482 - 516.

Salveson, J.O. (1978). Variations in the geology of rift basins-a tectonic model. *Proc. 1978 Int. Symp. On the Rio Grande Rift,* Santa Fe, N.M.

Saugy, L. (1987). The Benue Trough and Bornu Basin: New geophysical data. enlightenning the distribution of Cretacoeus Sedimentary basins. *Bull. Centres Rech. Explor. Elf-Aquitane,* 11(1) 178-180.

Sharma, P.V. (1986). *Geophysical Methods in Geology.* Elsevier Science Publishing Co. Inc. Newyork 442pp .

Shell, B.P. (1957). *Gelogical maps.* 1:250,000 Sheets: Makurdi (64); Ankpa(63); Enugu (72); Ogoja (73); Umuahia(79); Oban Hills (80); Calabar (85) Geol. Surv of Nig.

Sibuet, J. and Mascle, J. (1978). Plate Kinematic Implications of Atlantic Equitorial Fracture Zone Trends. *Journ. Geophys. Res.,* 83 3401-3421.

Simpson, A. (1954). The Nigeria Coalfield: The geology of parts of Owerri and Benue Provinces. *Bull.geol.surv; Nigeria* 24 85pp

Simpson, S.M. (1954). Least - Squares Polynomial fitting to garvitation data and density plotting by digital computers. *Geophysics,* 19 255 - 269

Skeels, D.C.(1967). What is Residual Gravity? *Geophysics,* 32 (5) 872 - 876

Smith, A.E. (1951). 'Graphic Adjustment by Least squares'. *Geophysics,* 16 (2) 222-227.

Spector, A. and Grant, F.S. (1970). Statistical models for interpretation of aeromagnetic data. *Geophysics*, 35 293 - 302

Stonely, R. (1966). The Niger delta region in the light of the theory of the continental drift. *Geol. Mag.*, 103, 385-386.

Stuart, G.W., Fairhead, J.D., Dorbath, L. and Dorbath, C. (1985). A Seismic Refraction study of the Crustal Structure Associated with the Adamawa Plateau and Garoua Rift, West Africa. *Geophys. J.R.A.S.*, 81 1-12.

Sykes, L.R. (1978). Intraplate Seismicity, Reactivation of Pre-existing Zones of Weakness, Alkaline Magmatism, and other Tectonism Postdating Fragmentation. *Rev. Geophys. and Space Physics*, 16(4), 621-688.

Talwani, M., Worzel, J.L. and Landisman, M. (1959). Rapid Gravity computations for two-dimensional bodies with application to the Mendecino Submarine Fracture Zone. *J.Geophys. Res.*, 64:49-59

Talwani, M. and Ewing M. (1960). Rapid computation of gravitational attraction of three-dimensional bodies of arbitrary shape. *Geophysics*, 41 (4) 727-741

Talwani, M. (1965). Computation with help of a digital computer of magnetic anomalies caused by bodies of arbitrary shape. *Geophysics*, 30 (5) 797-817

Talwani, M. (1973). Computer Usage in Computation of Gravity Anomalies. *Methods of Computational Physics*, 13. Academic Press, New York, N.Y.

Turner, D.C. and Bowden, P. (1979). The Ningi-Burra Complex, Nigeria: dissect calderas and migrating magmatic centres. *J.geol. Soc.Lond.*, 136 105-115.

Umego, M.N. (1990). Structural interpretation of Gravity and Aeromagnetic Anomalies Over the Sokoto Basin, North Western Nigeria. Unpub. Ph.D Thesis Ahmadu Bello University Zaria.

Uzuakpunwa, A.B. (1974). The Abakaliki Pyroclastics, Eastern Nigeria: a new age and tectonic implications. *Geol. Mag.* 111 65-70.

Van Breemen, O., Hutchison, J. and Bowden, P. (1975). Age and origin of the Nigerian Mesozoic granites: a Rb/Sr isotopic study. *Contrib. Mineral. Petrol.*, 50, 157-172.

Verheijen, P.J.T. and Ajakaiye, D.E. (1980). Analysis of errors in barometric elevation in northern Nigeria. *Geophysics*, 45 (7); 144-1152

Webring M. (1987). Computer Program for interpolation of random data by iteratively minimizing the sum of the second horizontal derivatives. *U.S.G.S Open-file report*, 81 1224..

Werner, S. (1953). Interpretation of magnetic anomalies as sheet-like bodies. *Sver. geol. Unders., Ser. E,* no 508

Wood, C.A. (1983). Continental Rift Jumps. *Tectonophysics,* 94 529-540

Woollard, G.P (1959). Crustal Structures from Grvaity and Seismic Measurements. *Jour. Geophys. Res,*. 64, 1521-1544

Wilson, R. and Guirauld, R. (1992). Magmatism and Rifting in western and Central Africa, from Late Jurassic to Recent times: In P.A Ziegler (ed.) Geodynamics of Rifting Vol. II. Case History studies on Rifts: North and south America and Africa. *Tectonophysics,* 213 203-225

Wright, J.B. (1968). South Atlantic and Continental Drift and the Benue Trough. *Tectonophysics,* 6 301-310.

Wright, J.B. (1976).
a) Origins of the Benue Trough- A Critical Review. In C.A. Kogbe (Ed.) *Geology of Nigeria,* Elizabethan Publ. Co., Lagos, Nigeria, pp 309-317.

b) Fracture Systems in Nigeria and Initiations of Fracture Zones in the South Atlantic, *Tectonophysics,* 34 T43-T47.

Wright, J.B., Hastings, D.A, Jones, W.B. and Williams, H.R. (1985). *Geology and Mineral Resources of West Africa.* George Allen & Urwin, London pp 90-120.

Zeng, H. (1989). Estimation of the degree of polynomial fitted to gravity anomalies and it's Application. *Geophy Prosp.*, 37 (8) 959 973.

Zorin, Yu.A.(1971). *Recent Structure and Isostacy of the Baikal Rift Zone and Adjacent Areas.* Nauka Moscow.

Zorin Yu.A. (1981). The Baikal rift: an example of the intrusion of asthenospheric material into the lithosphere as the cause of disruption of lithospheric plates *Tectonophysics,* 73 91-104.

Zorin Yu.A., Lysake, S.V. and Golubev, V.A. (1975). On the nature of the geothermal anomaly in Baikal area In :*Baikatsky Rift,* pp 66-73, Nauka Moscow

APPENDIX A

The method of estimating coeffients of a polynomial trend function by least-squares is basically the same for any variant of the general linear model regardless of the degree and number of variables invloved.

If G(x,y) is the polynomial surface to be fitted to a set of gravity measurement g(x,y) at point (x,y), then the deviation, or residual R (x,y) at this point is

$$R(x,y)=g(x,y)-G(x,y).....A1$$

The residual can be made as small as as possible by adjustment of equation (AI).

For polynomial first of degree n, then the surface

$$G(x,y)=\sum_{i=0}^{n}\sum_{j=0}^{n-1} a_{ij}x^{i}y^{j}.....(A2)$$

where a_{ij} are coefficients to be determined for the polynomials. The least squares criterion demands that the sum of squares of the residuals over a pattern P be made minimum .Thus

$$\sum_{P} R^{2}(x,y)=\left[\sum_{P}(g(x,y)-\sum_{i=0}^{n}\sum_{j=0}^{n-1} a_{ij}x^{i}y^{j})\right]^{2}.....(A3)$$

be made minimum If,

$$I(a_{ij}'s)=\sum_{p} R^{2}(x,y).....(A4)$$

then from (A3)

$$I(a_{ij}'s)=\sum_{p}\left[\sum_{i=0}^{n}\sum_{j=0}^{n-1}\sum_{k=0}^{n}\sum_{l=0}^{n-k} a_{ij}a_{lk}x^{k+l}y^{i+j}\right]-2\sum_{p} g(x,y)\sum_{i=0}^{n}\sum_{j=0}^{n-1} a_{ij}x^{i}y^{j}+\sum_{p} g^{2}(x,y).....(A5)$$

To minimize the residual function, we differentiate partially A with respect to the coefficients a_{ij} and equate these to zeros. Thus

$$\frac{\delta I}{\delta a_{ij}}.....A6$$

and

$$2\sum_{k=0}^{n}\sum_{l=0}^{}a_{lk}\sum_{p}x^{k+l}y^{i+j}-2\sum gx^{i}y^{j}=0$$

or

$$\sum_{k=0}^{n}\sum_{i=0}^{n-k} a_{ik}\sum_{p} x^{k+i}y^{i+j}=\sum_{p} gx^{i}g^{j}.....(A7)$$

where j= 0, 1, 2, 3, ..., (n-10

i= 0,1,2,3, ..., n

Equation (A7) yields normal equations expressed in a standard matrix equation as

$$\left[\sum_{p} x^{k+i}y^{i+j}\right]\left[a_{ik}\right]=\left[\sum_{p} gx^{i}y^{j}\right].....(A8)$$

To solve equations (A8) for a_{ik}, we multiply the RHS and LHS of (A8) by the inverse matrix

$$\left[\sum_{p} x^{k+i}y^{i+j}\right]^{-1}$$

to yield

$$\left[a_{ik}\right]\left[\sum_{p} x^{k+i}y^{i+j}\right]\left[\sum_{p} gx^{i}y^{j}\right].....(A9)$$

From (A9) the computations of the coefficients a_{ik} can be carried out with the use of available data points once thier co-ordinates are known. The inverse matrix does not depend on on gravity values and may be found for any polynomial order once coefficients using (A9) introduce some inherent, truncation and roundoff errors (Dorn and MacCracken 1972).

Inherent errors refer to errors in the data while truncation and roundoff errors refer to errors that are introduced by numerica procedures themselves. In computation of the inverse series on which the operation is performed.

For rectangular pattern where gravity values are taken on regular grids, axes can be chosen so that the rectangle is symmetrical about them and ordinates ans abscissa taken to be integers. this reduces the number of elements in the equation analysis and consequently, some coefficients drop out. Orthogonal polynomial analysis has been carried out by Oldham and Sutherland (1955).

Non orthogonal polynomial is used to for treatment of data set that are not arranged on a regular grid. The only criterion is that data be equally distributed over the region of interest. The equation (A9) becomes increasingly tediuos to solve with high degree of polynomials. However, the advent of high capacity electronic computers have made such computation feasible and faster for any degree.

A computer program (Surfit) designed by USGS for IBM PC's and compatibles was used. The program is designed to compute the coefficients of surfaces up to the 19th order . Errors asoociated with the simultaneous computations of coefficients are also incoporated into the Fortran program.