A THREE - DIMENSIONAL INTERPRETATION OF A PROMINENT AEROMAGNETIC ANOMALY NEAR DANGE, SOKOTO STATE, NIGERIA

BY

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A Thesis submitted to the Postgraduate School, Ahmadu Bello University, Zaria in partial fulfillment of the requirements for the award of the degree of Master of Science in Applied Geophysics.

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January, 1996

DEDICATION

This work is dedicated to the memory of my father Mallam Haruna Gide who departed this miserable world 13 years ago. May his Soul rest in perfect peace, Ameen.

DECLARATION

The report presented in this thesis is not a published, or an unpublished work of another author. It is the result of an original study carried out by this author. To the best of my knowledge, it has not been submitted in whatever form to any other institution, organization or body other than the Ahmadu Bello University for the award of a degree. Where the work of others are made use of, such sources are appropriately acknowledged and referenced.

A. B. HARUNA.

CERTIFICATION

This thesis entitled "A Three - Dimensional Interpretation of a Prominent Aeromagnetic Anomaly Near Dange, Sokoto State, Nigeria" by Ayuba Bari Haruna meets the regulations governing the award of the degree of Master of Science of Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

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ACKNOWLEDGEMENT

I wish to take this opportunity to thank all those who have helped in the preparation of this work. In particular, I wish to express my profound gratitude to my Supervisor Professor S. B. Ojo who, not only suggested the topic but followed through with valuable contributions to ensure the successful completion of this project. An equally invaluable contribution has been made by Dr. M.N. Umego, who at various stages of the programme provided guidance and useful advice which helped in the successful completion of this work. He also supplied the gridded aeromagnetic data for the project area. I am gratefully indebted to Dr. I. B. Osazuwa for the provision of some literary materials and useful suggestions.

Many people have helped in numerous ways during the development of this work. I would like to acknowledge such assistance and participation from Messrs Sambo Shehu Oganija, Sanusi Yusuf Abubakar, Hycinth Aboh Ogbu, Emeka Anasiudu, Lawrence Adefisan and Kolawole Lawal. Also people from the Geology Department such as Mallam Umar Danbatta, and Mr Ayo Alagbe deserve special mention. I also appreciate the efforts of Peace Nnorom for typing the scripts.

From the non-teaching staff of the Physics Department my thanks goes to Mr Aboyami Fagbemi, Mr Basil Nwosu and Mr Richard, for helping in preparing and assembling some of the materials needed for this work.

Much thanks and sincere appreciation goes to Mr Roland Kangkolo who provided the computer program MAGINVI used in the project and for helping out whenever I had problems with the computer work.

I must also express my appreciation to the management of the Kano State Polytechnic for the study leave granted to me in order to undertake this course.

Finally, special recognition is due to my wife Habiba and my aged mother for the inconveniences they suffered as a result of this work.

ABSTRACT

Digital magnetic data were extracted from existing half-degree Aeromagnetic map of DANGE (Sheet 29) within the Sokoto Basin. The sheet is characterized by a prominent E-W negative anomaly with a magnetic relief of 330 gammas and aligned along latitude 12°49'. This major E-W Anomaly was flanked on both sides by magnetic highs.

A 3-D inversion technique was employed to interpret the "Dange magnetic Anomaly". A best-fit model was obtained which is represented by a prismatic body having dimensions (10.11 x 2.94 x 3.32) km^3. The causative body was interpreted as an intrabasement body made up of basic igneous rocks with a high magnetic susceptibility of 0.0730 (SI Units). It is concluded that the-geodynamic process of the emplacement of the body are penetration by diapiric intrusion of mantle rocks followed by ascention to the lower and upper crust which on cooling forced a downward deflection of the crust by virtue of its increased density.

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CHAPTER ONE

GENERAL INTRODUCTION

1.1 THE AEROMAGNETIC GEOPHYSICAL METHOD

As a result of radical improvements in instrumentation, field methods, and modern interpretation techniques, the use of airborne measurements of the magnetic fields has become widespread. Of particular importance is its various applications in the investigation of the structure of the earth, and in the search for metallic ores, industrial minerals, and raw materials for energy such as oil and gas.

Aeromagnetic survey of an area involves the use of very sensitive magnetometers. The measuring devices are mounted on an aircraft and flown at a certain height above the ground surface. The variations of intensities of magnetic fields (the geomagnetic field plus the field due to subsurface structures) with distance along flight lines over the area flown by the plane are recorded. The data so collected and compiled, are processed and reproduced in the form of regularly spaced contour lines; the end result being an aeromagnetic map of the surveyed area. The anomalies expressed by the magnetic contours are dependent on the variable magnetic intensities of the underlying rocks and may be due to conditions near the surface or deep down in the subsurface.

Aeromagnetic mapping is the most widely used geophysical method and is applicable for reconnaissance, confirming geological boundaries, mining exploration and oil prospecting (Paterson and Reeves, 1985). The method has the advantage of lower cost per kilometer of land coverage and higher speed of coverage than any other geophysical method. Also there are, in general, no operational problems associated with irregular terrain or accessibility of remote areas.

The major draw back of aeromagnetic surveying lies in the high cost of surveying small areas and its ineffectiveness where the anomalies of interest are shallow and of very limited extent (Telford *et al*, 1976).

The planning and execution of a national programme of aeromagnetic surveying is an important geophysical activity in most countries of the world. The Geological Survey of Nigeria (GSN) commissioned the airborne magnetic surveying of the entire Nigeria's land mass which was carried out in the early - and mid - 1970s. The resulting maps have since been published by the GSN and are now available in half-degree sheets mostly on a scale of 1: 100,000 with contours of total magnetic field intensities in gammas. The contours are spaced at intervals of 5 gammas.

1.2 INTERPRETATION OF MAGNETIC ANOMALIES

No magnetic survey - ground or airborne - is complete without the data being presented as contour maps.

The contoured map is essential for the interpretation that follows. The interpretation of magnetic data is usually done in two stages, the first stage is qualitative and the second being quantitative.

The qualitative stage involves the visual inspection of the residual map of the surveyed area. In the hands of an experienced interpreter, subsurface structures such as uplifted basement fault blocks, intrusive plugs, lineaments, and geological boundaries stand out as a result of their magnetic signatures. Quantitative interpretation leads to the determination of the parameters of the causative body, such as depth to the top of the structure from the plane of observation, size, shape, dip, and magnetization. Basically, the process of quantitative interpretation of magnetic anomalies endeavours to determine a source distribution whose anomalous field matches as closely as possible the actual field on the surface of measurement (i.e. modeling process). This involves mathematical processing of data usually with the help of computers.

In the quantitative interpretation of magnetic anomalies, one can either analyze selected profiles taken across the investigated area (i.e. 2-D modeling) or consider the entire data over an area (i.e. 3-D modeling). The difference between the two is that profile analysis is based on the assumption that structures extending to infinity in a particular direction are responsible for

generating the observed anomalies. From the practical point of view of interpretation, a body is assumed to be 2-dimensional if the strike length is at least three times its width. The 3-D method imposes no such constraint.

Three-dimensional modeling of magnetic anomalies requires the analysis of data over an area. The vertical prism is a commonly used geometrical model for 3-D interpretation of magnetic anomalies. Structures such as intrusive plugs and uplifted basement fault blocks are usually approximated by prismatic models.

In the present study, the prism model along with the inverse modeling interpretation scheme was employed to interpret a prominent magnetic anomaly in Dange, near Sokoto.

1.3 THE SURVEY AREA

The survey area of the present study is located within the boundaries of the Sokoto Basin of Nigeria (Fig. 1.1). The Sokoto Basin forms the South-Eastern sector of a much larger, nearly circular Mesozoic basin known as the Iullemmeden Basin. The Iullemmeden Basin extends from Mali and the Western boundary of the Republic of Niger through Northern Benin Republic and North-Western Nigeria into Eastern Niger, covering an area of about 700,000 km^2 (Kogbe, 1981). The Nigerian sector of the Iullemmeden Basin is situated in the North-Western part of the country, between latitudes $10^0 30'N$ and $14^0 00'N$, and longitudes $3^0 30'E$ and $7^0 00'E$.

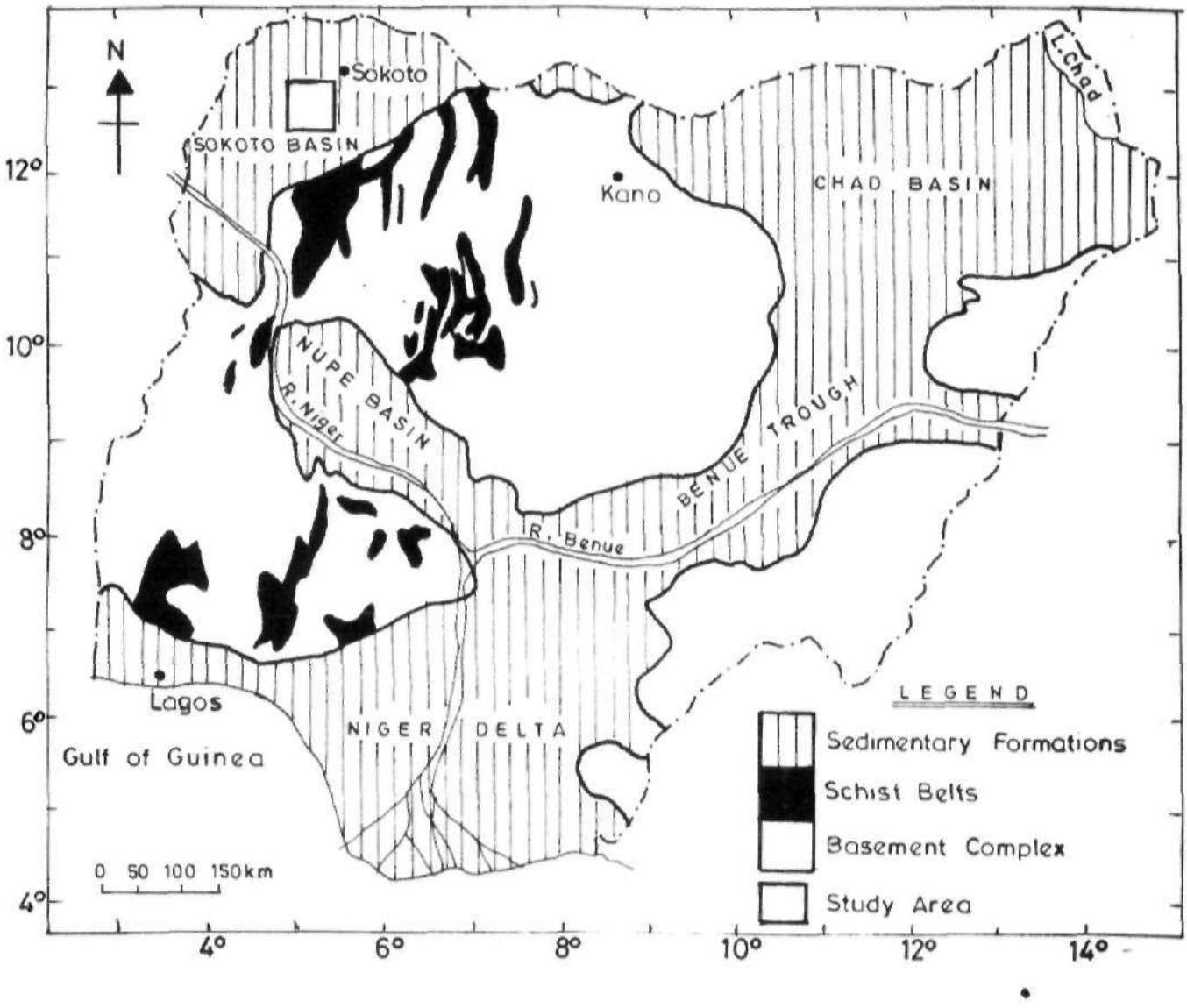


FIG. 1.1: SIMPLIFIED GEOLOGICAL MAP OF NIGERIA SHOWING THE STUDY AREA

This sedimentary basin in North-Western Nigeria consists predominantly of a gentle undulating plain with an average elevation varying from 250-400 meters above sea level (Kogbe, 1979). This monotonous plain is occasionally interrupted by steep-sided flat topped hills. A low escarpment which was named the `Dange Scarp' by the earlier workers is the most prominent feature in the basin and is closely related with the geology.

Due to its economic potential, many geological and geophysical investigations have been carried out to study its origin, evolution, structure, stratigraphy and the economic potentials of the basin. The geological works carried out in the area include those of Jones (1948), Parker (1961) and Kogbe (1979, 1981) among others; while Osazuwa (1985), Ananaba and Ajakaiye (1987), Umego (1990) and Sambo (1994) carried out some geophysical studies in different parts of the basin. The Geological Survey Department of Nigeria has also published aeromagnetic maps covering the Sokoto basin and other parts of Nigeria.

In the present study, the portion of the basin under consideration lies within latitudes $12^{0}30'$N and $13^{0}00'$N, longitudes $5^{0}00'$E and $5^{0}30'$E which corresponds to the aeromagnetic map of DANGE (Sheet 29) published by the GSN. The feature of interest is a prominent E-W trending magnetic low at the northeastern quadrant of sheet 29 (fig. 1.2) here termed the "Dange magnetic anomaly".

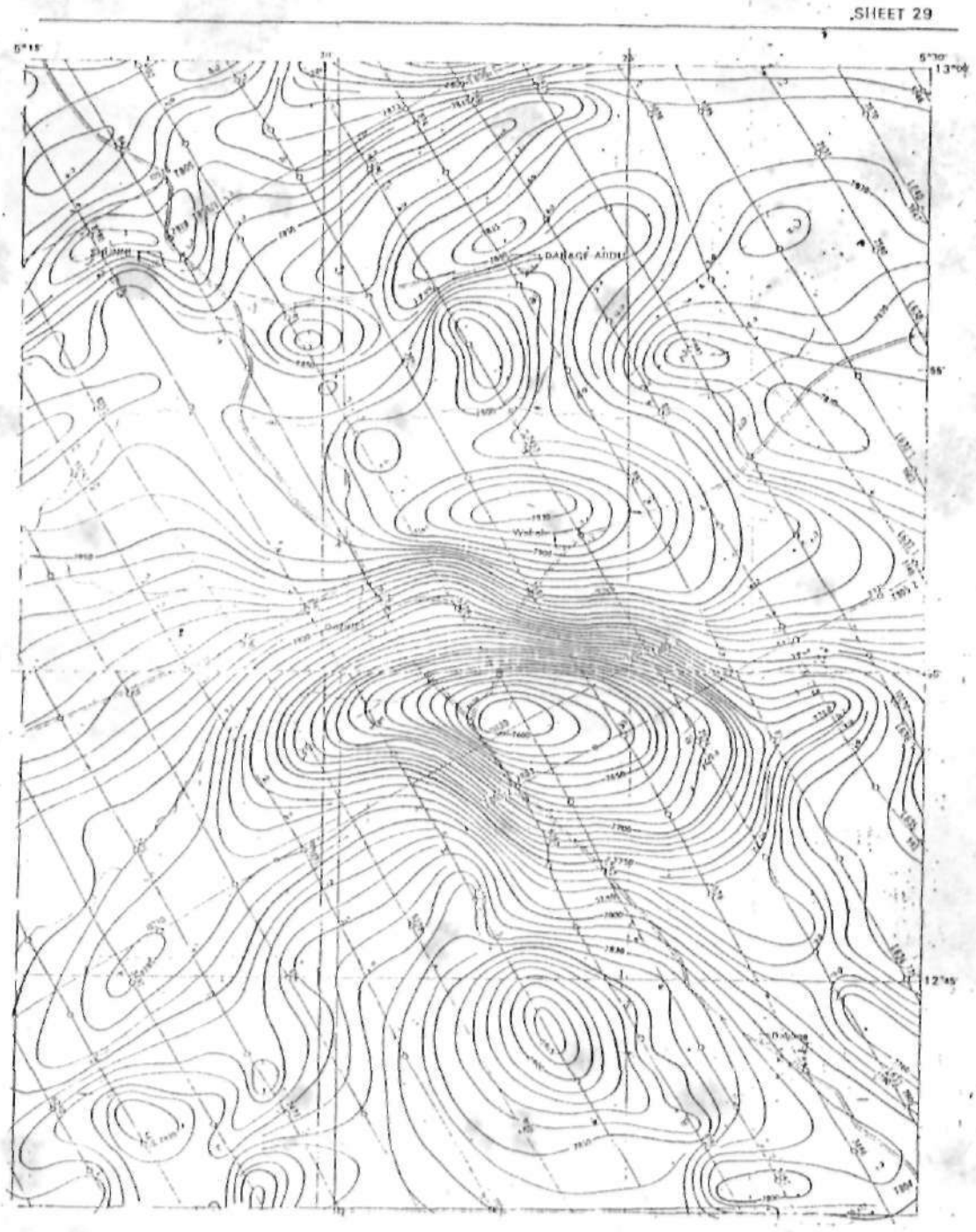


Fig. 1.2: Aeromagnetic Map of Dange (sheet 29) second quadrant.

1.4 PREVIOUS GEOPHYSICAL WORKS IN THE DANGE AREA

Apart from the geophysical investigation carried out in the Sokoto Basin as a whole (cited earlier), the only work specifically limited to the Dange area known to the Author is the ground follow-up radiometric survey of some radiometric anomalies carried out by Uwah (1984).

The radiometric anomalies in question were delineated from aeroradiometric survey commissioned by the GSN. In his work, Uwah focused attention on three locations with a total area of 1 km^2 in the vicinity of Dange village. The locations were considered to have the highest possibility of Uranium mineralization in the Sokoto Basin. The study concluded that the measured uranium concentration were lower than the level normally regarded to be of economic importance. However, Uwah also noted that the areas marked out as the most probable site of Uranium deposits coincide with a major magnetic low (Dange magnetic Anomaly) and wondered if there is a connection between the uranium mineral and the structures responsible for this magnetic low. He strongly recommended further investigation of this magnetic anomaly using magnetic methods.

The "Dange magnetic anomaly" with a magnetic relief of about 330 gammas also came to the notice of Umego (1990) and Sambo (1994) in the course of their investigations which made use of the same set of magnetic data but while Umego applied the Werner deconvolution technique to estimate the depths to the basement within the basin, Sambo

employed the spectral method for the same purpose. Umego estimated the depth to the top of the structure responsible for the "Dange magnetic Anomaly" as 2.0 km while Sambo obtained a slightly lower value of 1.85 km. Both, however, agreed that the depth to the basement at the anomaly site is 1.4 km implying that the structure is within the basement rocks. However, the model interpretations discussed above did not give information about other parameters besides the depth to the causative anomalous body.

1.5 SCOPE AND OBJECTIVE OF THE PRESENT STUDY

The objectives of the present study are as follows:

(a) To carry out a 3-dimensional interpretation of the "Dange magnetic Anomaly" with a view to deducing the shape, size, dip and magnetic susceptibility of the causative body from the interpreted model.

(b) To infer, as far as possible, from the interpreted parameters of the causative body, the possible mode of emplacement of the structure under investigation and its effect on the basin topography.

CHAPTER TWO

GEOLOGY

2.1 GENERAL GEOLOGY OF THE SOKOTO BASIN

The Sokoto Basin of Nigeria forms the South-Eastern sector of the Iullemmeden Basin - one of the young (Mesozoic - Tertiary) inland cratonic sedimentary basins of West Africa. The entire basin is believed to have developed by tectonic epeirogenic movements or stretching and rifting of tectonically stabilized crust during the Paleozoic (Kogbe, 1981; Wright *et al*, 1985). In the Sokoto sector, the rocks in the basin fall into two classes: a crystalline Precambrian Basement Complex and the overlying Cretaceous and Tertiary sediments (fig. 2.1).

The basement complex in Nigeria lies within the Pan-African mobile belt of West Africa and is believed to have a poly tecto - metamorphic nature (McCurry, 1976; Turner, 1983; and Rahman, 1988). Three major rock successions are distinguished and these are:

i) A crystalline complex of migmatites and gneisses which are the dominant rocks.
ii) The metasediments and metavolcanics which form the N-S trending schist belts; and
iii) The Older Granite series which intrude both the migmatite gneiss complex and the schist belts.

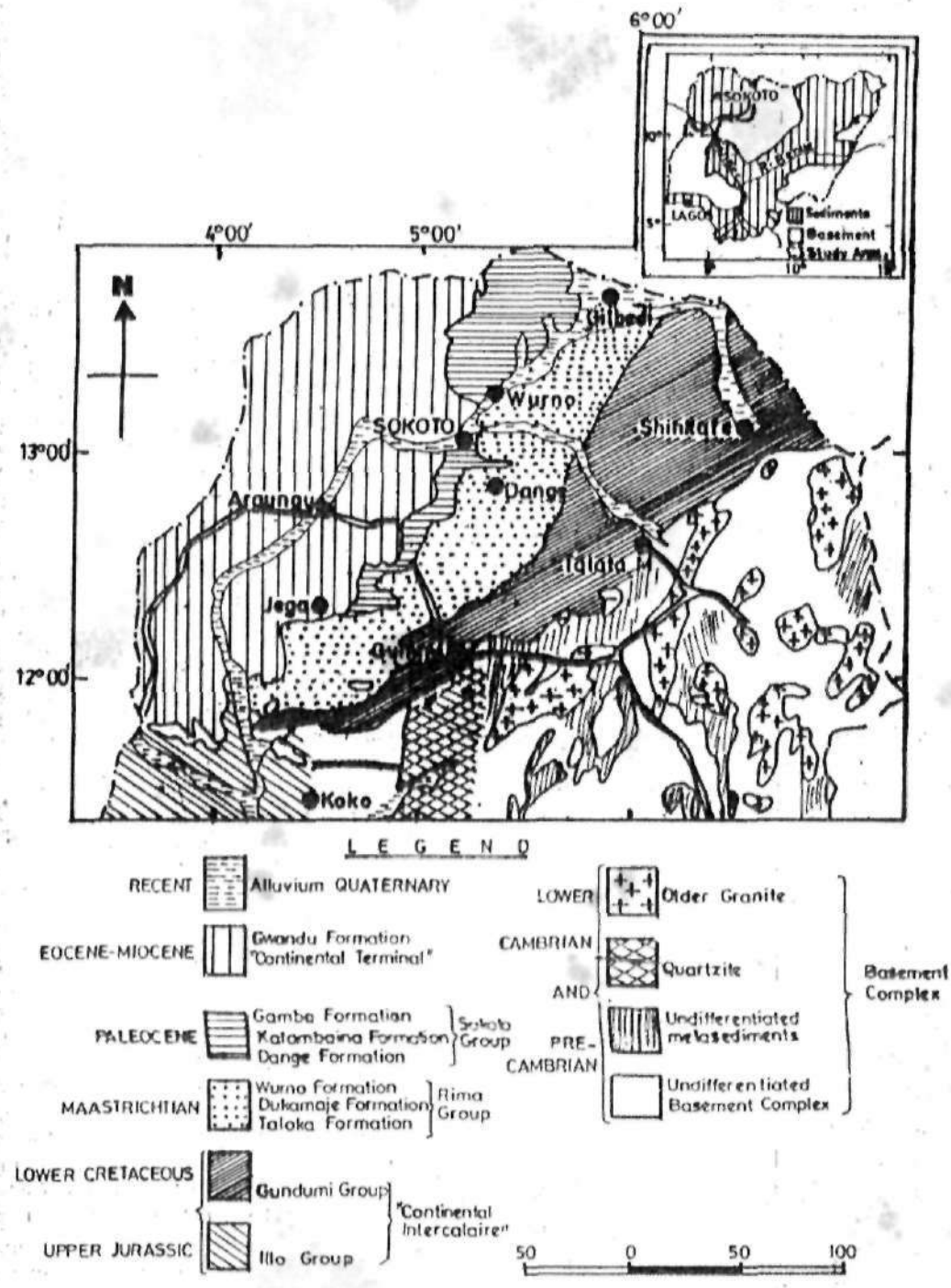


Fig. 2.1: Detailed geological Map of Sokoto Basin, North Western Nigeria. Location of the Basin is shown in inset.

Sediments began to accumulate during the lower Cretaceous comprising of a sequence of two continental phases separated by Cretaceous-Eocene marine transgression(s) (Kogbe, 1981). Overlying the Precambrian basement unconformably are pre-Maestrichtian continental deposits known as the Illo and Gundumi Groups. Both groups are lateral equivalents belonging to the upper part of the "Continental Intercalaire" of West Africa (Kogbe, 1981). The second phase in the depositional history started during the Maestrichtian when the marine Rima Group was deposited, and includes the late Paleocene marine sediments called the Sokoto Group. The Sokoto Group is overlain by the continental Gwandu Formation which is of Tertiary Age and has been attributed to a lacustrine environment (Kogbe, 1981). The sediments in the basin consist mainly of pebbly grits, sandstones and clays, with bands of shale, mudstone and limestone intercalations. Available geological evidence indicates that the sediments are generally shallow, attaining a maximum thickness of over 1,200 m near the frontier with Niger Republic (Kogbe, 1981; Wright, *et al*, 1985).

2.2 DETAILED GEOLOGY OF THE STUDY AREA (DANGE: SHEET 29)

2.2.1 Introduction

The geology described in this section covers an area of approximately 3,025 km^2 lying between latitudes $12^{0}30'N$ and $13^{0}00'N$ and longitudes $5^{0}00'E$ and $5^{0}30'E$. The essential geological features of this region are shown in

Figure 2.2, and comprise sedimentary rocks ranging in age from Middle Cretaceous to Quaternary. The sedimentary formations are underlain by gneisses, granites, phyllites and quartzites of Precambrian Age. The geology of this area is well documented by Parker (1961) and most of the information in this section have been derived from his work.

2.2.2 Physiography

The distribution of relief conforms quite closely to the various geological formations. The area is generally of low relief, with the highest elevation of about 364 m on one flat topped hill feature near Dange (Parker, 1961). The area is characterized by a monotonous landscape of gently undulating plains with an overall sandy mantle. The plain is broken in places by steep - sided, flat-topped mesas. The plains are surrounded to the West by a much incised and broken scarp, first described as the "Dange Scarp". Further to the West another low feature which marks the extent of a much varied topography which conforms to the outcrop of the Gwandu Formation (see STRATIGRAPHY) (Parker, 1961).

No major rivers traverses the study area, but the Gawan river flows from east to west across the southern part of the study area. Although it is perennial, it is characteristically bordered by swamp and marshy ground and is not free - flowing at the height of the dry season. Numerous small streams flow from a spring - line on the face of the Dange Scarp, but these are dry at the height of the dry season (Parker, 1961).

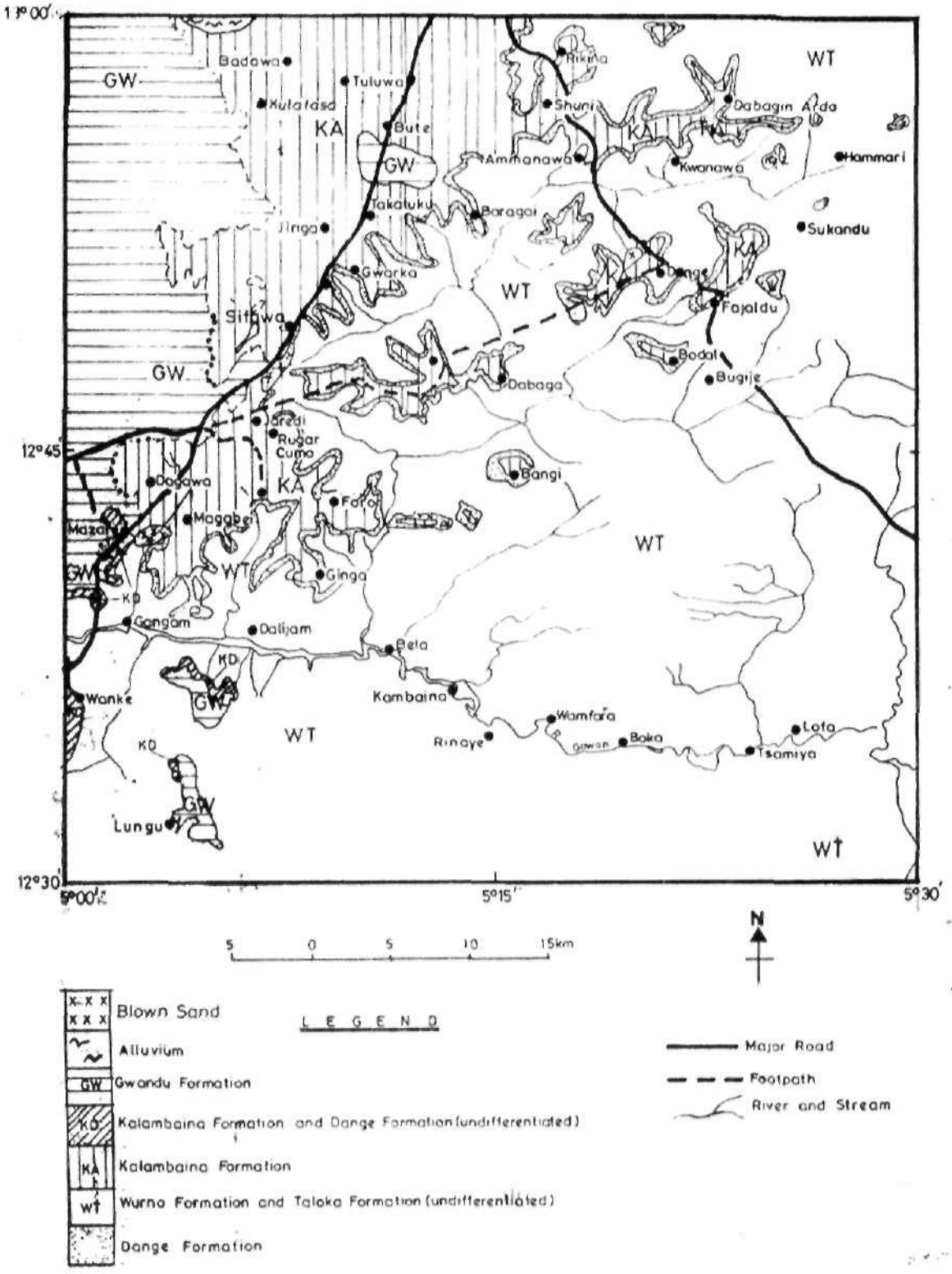


FIG.2-2:GEOLOGY OF DANGE (Sheet 29) (After Parker, 1961)

2.2.3 Stratigraphy

The study area conforms to the established sedimentary structure forming part of a shallow basin. The centre of which lies north of Niamey in Niger Republic. As a result of the drilling programme for limestone, the dip of the base of the calcareous formation has been calculated at 17 ft per mile at a bearing 60^0 west of true North (Parker, 1961).

A Pre-cambrian complex of gneisses, granites, phyllites and quartzites form the foundations of the Dange area but it does not outcrop anywhere within the study area.

Parker (1961) reported that the sedimentary rocks were free from faulting but Kogbe (1981) observed some minor WSW-ENE trending faults in the vicinity of Dange village. The sediments in this area (Dange, Sheet 29) were deposited during three main phases of deposition (see STRATIGRAPHICAL SUCCESSION, Table 2.1). Pre-Maetrichtian, Maestrichtian to Paleocene and Tertiary phases.

The Pre-Maestrichtian in the Dange Area belong to the Gundumi Formation. The formation is of middle Cretaceous age (Parker, 1961). The Gundumi Formation is underlain unconformably by the Basement Complex and consists of clayey grits, clays, sandstone and pebble beds of lacustrine and fluviatile origin with a basal conglomeratic level containing silicified wood (Kogbe, 1979).

Table 2.1: General Stratigraphical Succession in the Study Area (After Parker, 1961)

AGE	FORMATION	GROUP
Recent	Blown Sand	—
Mio-Paleocene	Gwandu Formation	Gwandu Group
	Unconformity	
Paleocene	Calcareous Formation	Sokoto Group
	Dange Formation	
	Unconformity	
Upper Cretaceous	Wurno Formation	Rima Group
	Mosasaurus Shales	
	Taloka Formation	
Middle Cretaceous	Gundumi Formation	Gundumi Group

The next stage in the depositional history of the Dange Area began during the Maestrichtian when the Rima Group was deposited unconformably on the Pre-Maestrichtian beds. The Rima Group was made up of three deposits: the Taloka Formation, Mosasaurus shales and Wurno Formation (Parker, 1961). The Mosasaurus Shales are referred to as the Dukamaje Formation by Kogbe (1979). The Taloka Formation consists essentially of white fine-grained friable sandstones and siltstones with thin intercalated mudstones and carbonaceous mudstones or shales. The Wurno Formation consists of pale coloured friables, fine-grained sandstones, siltstones and intercalated mudstones (Kogbe, 1979). The Rima Group is upper Cretaceous.

The Paleocene deposits belong to the Sokoto Group which lie unconformably on the Rima Group. The Sokoto Group contains two formations: the Dange Formation, and the Calcareous Formation (Parker, 1961). However, Kogbe (1979) split the Calcareous Formation into two, which he called the Gamba and Kalambaina Formations. The Calcareous Formation is made up of limestones, marls and shales.

Gwandu Formation is the deposition that occurred during the Tertiary phase and is Mio-Paleocene (Parker, 1961). The Gwandu Formation lies unconformably on the Sokoto Group. The formation includes locally indurated interbedded, thick grey, brownish black and red mudstones and fine to very coarse-grained white and brownish quartz sand (Kogbe, 1979).

Recent (Quartenary) deposits consisting of blown sand and old fixed sand dunes can be identified both in the field and from aerial photographs. Fairly extensive areas of blown sand obscures the geology some 800 m due north-west from Dange, between Jaredi and Rugar Cumo, and due east to Mazare.

2.3 ECONOMIC GEOLOGY OF STUDY AREA

The sediments in the Dange area contain some very important raw materials such as clays, ironstones, laterites, limestones, gypsum and gravels. Limestone deposits from the Paleocene Formation near Kalambaina (around Sokoto town) are already being utilized for the manufacture of cement by the Sokoto cement industry. The Rima Group of sediments is rich in gravel, lignite and salt deposits.

A report on water supply possibilities by Olowu (1940) on behalf of the Sokoto State Water Board concludes that the areas underlain by the Sokoto Group have good prospects for water supply.

CHAPTER THREE

INTERPRETATIONAL TECHNIQUE AND DATA COLLECTION

3.1 MODELING OF POTENTIAL FIELDS

The process of quantitative interpretation of both gravity and magnetic anomalies endeavours to determine a source distribution whose anomalous field matches as closely as possible the actual field on the surface of measurement.

Two methods are generally used to obtain the models; one method involves the generation of type curves for several simple geometric shapes under different possible conditions for curve matching with anomalies obtained in gravity and magnetic surveys. In the other method, the magnetic or gravity effect of a simple geometric body is computed and compared with observed anomaly; modifications are then made to the model, based in some way on the disagreement between previously calculated anomaly and the observed anomaly until a suitable fit is obtained.

In the later method, the observed data used for the analysis could be the whole data set obtained in the survey in which case three-dimensional (3-D) bodies are interpreted (Rao and Babu, 1991; Gerald and Debeglia, 1975). Selected profiles intelligently chosen, could also be used for modeling the potential field anomaly (2-D modeling). This involves only a part of the data collected in the survey (e.g. Corbato, 1965; Mao, 1965; Johnson, 1969; Won, 1981; Ojo, 1990; Umego, 1990).

In all cases of potential fields modeling there is one central problem; that several solutions are mathematically possible to a given problem but some could be geologically untenable. Because of this problem, constraints are introduced in the form of simplifications of geometry, limits to size or depth, range limits on density or susceptibility, and whatever other parameters may seem justified in the light of what is known or can be reasonably inferred about the geologic environment.

3.2 FORWARD AND INVERSE MODELING

The rigorous analytic method of modeling magnetic bodies earlier mentioned, can be effected either as a `forward' or `inverse' modeling. Forward modeling consists of the following steps (Patersons and Reeves, 1985):

i) Human estimation of an initial model, compatible with what is known of the geology;
ii) Computation of the exact theoretical anomaly for model;
iii) Comparison of the observed and calculated anomalies;
iv) Judicious adjustment of the model by human interaction and within geologically reasonable limits in the hope of improving the fit of the calculated data to the observed points;
v) Return to stage (ii) and so on; and
vi) Stop at stage (iii) once the fit is acceptable.

Inverse modeling on the other hand, pursues the following course:

i) Choice of a geometric model type and estimation of initial values;
ii) Computation of the theoretical anomaly for the model;
iii) Measurement (on some mathematical basis such as least first-power or least squares) of the quality of the fit between the observed and calculated anomalies.
iv) Investigation (e.g. through partial derivatives) of the effect of variation of individual model parameters on the quality of fit;
v) Estimating the increments to all modeled parameters to revise the model in a way designed to bring the most efficient convergence between the observed and calculated anomalies in the next iteration;
vi) Back to step (ii) with the revised model;
vii) Stop at step (iv) when changes in the model parameters can no longer improve the fit.

The main difference between the procedures is that, the inverse modeling procedure forbids further human interaction once the initial model is decided. The remaining steps enumerated above are automatically executed by the machine. The forward modeling procedure allows for human judgement at every iteration. On the whole, forward modeling is time consuming being a trial-and-error process. There is also no guarantee that any improvement will be obtained at stage (iv). However, the technique has merit in

being programmable on microcomputers with graphic displays and, because of the human interaction at every iteration, the model always retains geologic credibility in the hands of an experienced interpreter.

Inverse modeling is relatively faster in producing an acceptable model because the fit is mathematically defined and the iteration ceases once further improvement is impossible. Also, from a practical point of view, user interaction would not be possible where exceedingly large numbers of interpretations - such as all anomalies encountered along aeromagnetic profiles - have to be carried out. The geologic plausibility of derived models, is however less certain. The uncertainty can be remedied or at least minimized by constraining certain model parameters within some specified limits informed by the geology or otherwise (Paterson and Reeves, 1985).

In the present study, the inverse modeling procedure was adopted because of its advantages over the forward modeling process.

3.3 DATA SOURCE AND TREATMENT

For this study, the data set used was taken from the aeromagnetic data base of the Sokoto Basin compiled by Umego *et al*, (1992). The data for the Dange area (sheet 29) was extracted, and appropriate N-S profiles which cut across the anomaly of interest were chosen. The data was regridded and contoured and the regional field removed to

produce figure 3.1 which represents the residual magnetic map of the second quadrant of Dange (Sheet 29).

3.3.1 Regional - Residual Separation

The interpretation of potential field anomalies frequently begins with some procedure which eliminates or attenuates unwanted field components in order to isolate the desired anomaly targeted for interpretation.

There are many methods in use for such an operation. According to Nettleton (1971) regional - residual separation techniques in the analysis of potential fields data may be grouped into graphical, spectral and polynomial fitting methods. For the purpose of this study, the polynomial fitting method is utilized.

The polynomial fitting method assumes that a polynomial surface adequately models the regional field whose smoothness is controlled by the polynomial order (Beltrao *et al*, 1991). A least squares operation is usually carried out which determines a potential surface which is fitted to the observed data. The polynomial could be of first order or above but is usually of low order. In the present study the regional field was removed from the observed aeromagnetic data by fitting a first order polynomial.

The expression for the regional surface over the study area is given as:

$$F = 8234.1 - 31.787\,x - 20.469\,y \quad \ldots\ldots \quad (3.1)$$

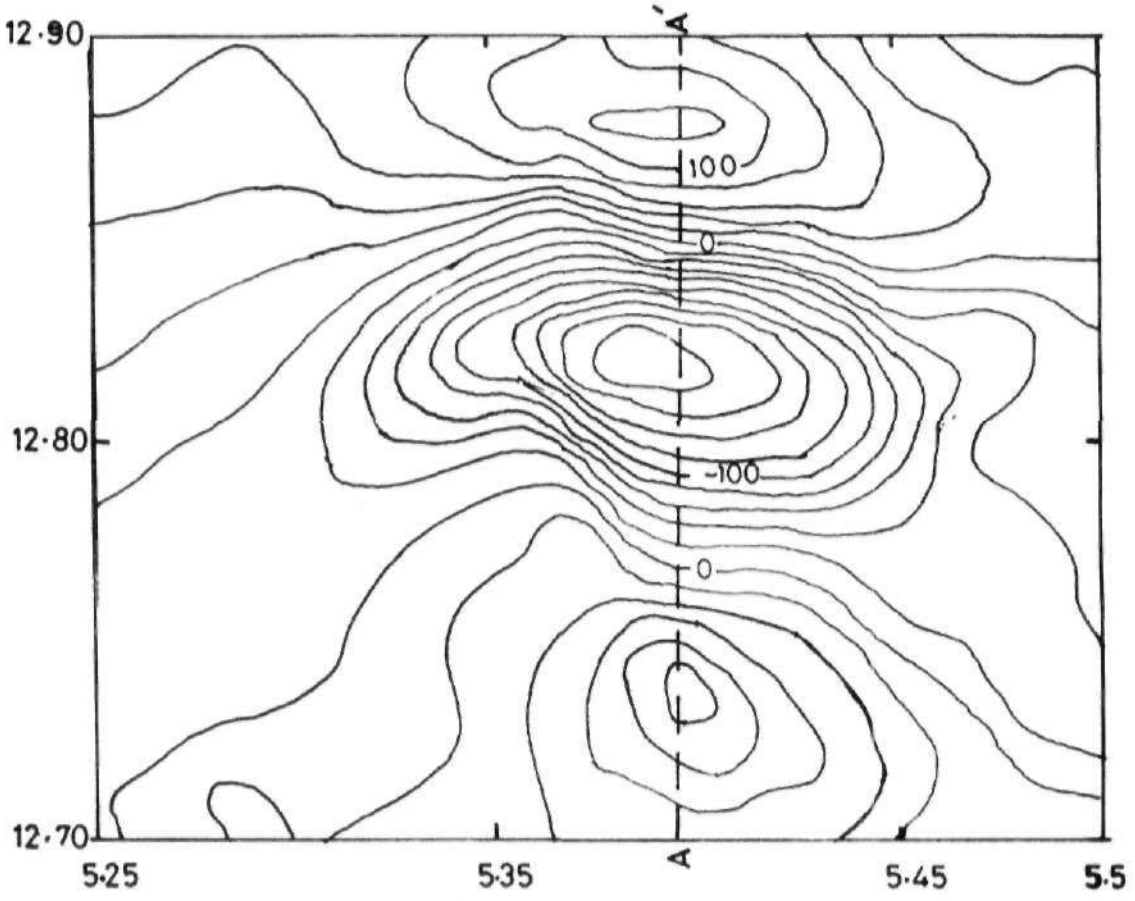


FIG. 3.1: RESIDUAL MAGNETIC FIELD OF PART OF DANGE (Sheet 29)

where x and y are grid Co-ordinates in kilometers, which describe the position of the data points with respect to the origin of the two axes of the data array. The Coefficient and the constant term were derived by Sambo (1994), who also used the first order surface to remove the regional from the aeromagnetic data covering the entire Sokoto Basin of which the present area of study (Dange) is only a part. The use of a first order regional field derived from the data set of the much larger area is justified by the fact that the present area of study is relatively small and a regional field derived from such a limited data set would be greatly influenced by local or near-surface anomalies.

The regional trend was subtracted from the observed aeromagnetic data to obtain the residual anomalies. The residual contains the components of the field which, presumably, are caused by the geological features of interest.

A new data set comprising a total of 546 data points covering an area 27.6 km by 22.08 km at grid intervals of 1.1 km was generated. The data was then re-arranged to suit the main program MAGINVI (Kankgolo, 1994) used for the interpretation. The data extracted was again machine contoured (Fig. 3.1) and inspected to ensure that it correctly represents the Anomalous magnetic low targeted for interpretation (Fig. 1.2).

CHAPTER FOUR

COMPUTATIONAL PROCEDURE FOR THREE-DIMENSIONAL MODELING OF MAGNETIC DATA

4.1 INTRODUCTION

3-D modeling requires the analysis of data over an area. Many computerized interpretation schemes on the inversion of magnetic fields due to prismatic bodies have been reported in the literature (e.g. Whitehill, 1973; Coles, 1976; Bhattacharyya, 1980; Rao and Babu, 1991; and others).

Most of these methods employ variations of the optimization process derived from the classical Gauss's method for solving non-linear equations (Won, 1981). In the present study, the anomalous magnetic field under investigation is assumed to be caused by an isolated prism-shaped body inferred from the elliptically shaped closed contours (Dobrin, 1976) and the characteristic magnetic signature observed for such bodies.

The steps for inverse modeling were mentioned earlier and are henceforth used as guide in describing the method employed in the present study.

4.2 THE ANOMALY EQUATION

Steps (ii) through (vii) of the inverse modeling technique of section 3.2 together make up the computer programme MAGINVI (Kangkolo, 1994) used for the inversion of the observed magnetic field. The program was run on an

IBM PC/AT. The algorithm used to develop the program MAGINVI is based on Rao and Babu (1991).

Let the point O on the observation plane be taken as the origin of the coordinate system and the observation be taken at grid points laid parallel to x- and y- axes. Then the analytic expression for the total field magnetic anomaly at any point P(x,y,O), (see fig 4.1) due to a uniformly magnetized vertical prism whose sides are parallel to the coordinate axes is given by Rao and Babu (1991) as:

$$\Delta T(x,y,0) = G_1 \ell n F_1 + G_2 \ell n F_2 + G_3 \ell n F_3 + G_4 F_4 + G_5 F_5 \quad .. \quad (4.1)$$

where the G's are functions of the inclination and declination of the geomagnetic field and those of the prism and the F's are functions of the coordinates of the fields and those of the prism given as follows:

$$F_1 = \frac{(R_2+\alpha_1)(R_3+\alpha_2)(R_5+\alpha_1)(R_8+\alpha_2)}{(R_1+\alpha_1)(R_4+\alpha_2)(R_6+\alpha_1)(R_7+\alpha_2)},$$

$$F_2 = \frac{(R_2+\beta_1)(R_3+\beta_1)(R_5+\beta_2)(R_8+\beta_2)}{(R_1+\beta_1)(R_4+\beta_1)(R_6+\beta_2)(R_7+\beta_2)},$$

$$F_3 = \frac{(R_2+h_1)(R_3+h_1)(R_5+h_1)(R_8+h_2)}{(R_1+h_1)(R_4+h_2)(R_6+h_2)(R_7+h_1)}$$

$$F_4 = \arctan\frac{\alpha_2 h_2}{R_8\beta_2} - \arctan\frac{\alpha_1 h_2}{R_6\beta_2} - \arctan\frac{\alpha_2 h_2}{R_4\beta_1}$$

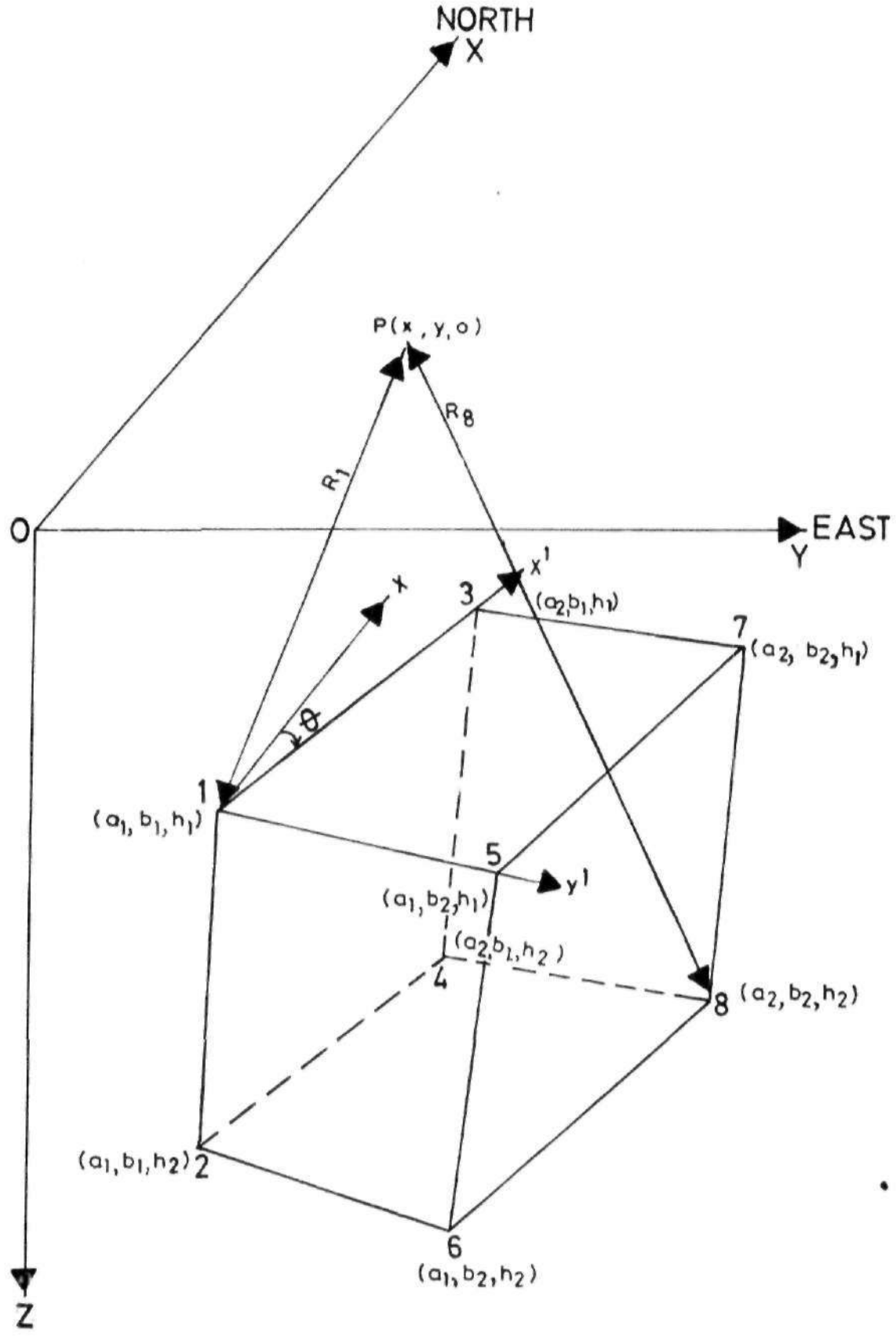


FIG.4.1: THREE DIMENSIONAL RECTANGULAR PRISM SHOWING THE DISPLACEMENT OF THE CORNERS OF THE PRISM BODY WITH RESPECT TO A POINT OF MEASUREMENT ON THE SURFACE (After Rao and Babu, 1991)

$$+\arctan\frac{\alpha_1 h_2}{R_2\beta_1}-\arctan\frac{\alpha_2 h_1}{R_7\beta_2}+\arctan\frac{\alpha_1 h_1}{R_5\beta_2}$$

$$+\arctan\frac{\alpha_2 h_1}{R_3\beta_1}-\arctan\frac{\alpha_1 h_1}{R_1\beta_1},$$

$$F_5=-\arctan\frac{\beta_2 h_2}{R_8\alpha_2}-\arctan\frac{\beta_2 h_2}{R_6\alpha_1}-\arctan\frac{\beta_1 h_2}{R_4\alpha_2}$$

$$+\arctan\frac{\beta_1 h_2}{R_2\alpha_1}-\arctan\frac{\beta_2 h_1}{R_7\alpha_2}+\arctan\frac{\beta_2 h_1}{R_5\alpha_1}$$

$$+\arctan\frac{\beta_1 h_1}{R_3\alpha_2}-\arctan\frac{\beta_1 h_1}{R_1\alpha_1},$$

$$R_1=\sqrt{\alpha_1^2+\beta_1^2+h_1^2},\quad R_2=\sqrt{\alpha_1^2+\beta_1^2+h_2^2},$$

$$R_3=\sqrt{\alpha_2^2+\beta_1^2+h_1^2},\quad R_4=\sqrt{\alpha_2^2+\beta_1^2+h_2^2},$$

$$R_5=\sqrt{\alpha_1^2+\beta_2^2+h_1^2},\quad R_6=\sqrt{\alpha_1^2+\beta_2^2+h_2^2},$$

$$R_7=\sqrt{\alpha_2^2+\beta_2^2+h_1^2},\quad R_8=\sqrt{\alpha_2^2+\beta_2^2+h_2^2},$$

$$\alpha_1=a_1-x',\quad \alpha_2=a_2-x',\quad \beta_1=b_1-y',\quad \beta_2=b_2-y'.$$

$$x'=x\cos\theta+y\sin\theta\quad \textit{and}\quad y'=-x\sin\theta+y\cos\theta$$

$G_1 = EI\ (Mr + Nq)$, $G_2 = EI\ (Lrt\ Np)$,

$G_3 = EI\ (Lq + Mp)$, $G_4 = EI\ (Nr-Mq)$,

and $G_5 = EI\ (Nr-Lp)$.

EI is the intensity of magnetization, L,M,N, are direction cosines of magnetization, and p,q,r are the direction cosines of the geomagnetic field.

4.2.1 Choice of an Initial Model and Estimation of Initial Parameter

The model type was assumed to be a prismatic body, uniformly magnetized. The body is characterized by as many as eight parameters. Six of the parameters are the horizontal and vertical coordinates a_1, a_2, b_1, b_2, h_1, h_2 (Fig. 4.1) of the prismatic body and the remaining are the intensity of magnetization (EI) and orientation of the prismatic body with respect to the geographic North (θ).

There are many standard methods of obtaining approximate values of the parameters (e.g., McGrath and Hood, 1970; Rao *et al* 1973, Telford *et al* 1976;).

In this present study, the initial values for the horizontal dimensions (a_1, a_2, b_1, b_2) and the orientation of the prism (θ) were assumed based on the minimum and maximum closures of the contour map of Dange (Rao and Babu, 1991). The depth to the top of the prism shaped body h_1, was estimated by Peters' method (Telford *et al*, 1976) and h_2 was assumed based on the magnitude of the anomaly. Table 4.1 shows the starting values for the various parameters of the prismatic body used to model the anomaly.

Table 4.1: Modeling Parameters for the Prismatic body

Starting Parameters	
Parameters	Values
a_1	09.50 km
a_2	16.40 km
b_1	09.00 km
b_2	21.60 km
h_1	01.20 km
h_2	06.00 km
EI(CGS)	0.00200
θ	5^0

The Field Parameters	
Parameters	Values
Inclination (I)	-4.5^0
Declination (D)	0.0^0
Ambient Magnetic field strength (T)	33,000 nT

4.2.2 Inversion Technique

Given an initial estimate of the parameters of the prismatic body, a method is hereby described which will simultaneously improve all the unknowns by using a non-linear inversion technique developed by Marquardt (Rao and Babu, 1991). The technique is a combination of differential correction and non-linear least squares method.

We start with an initial model and iterate on the parameters in order to minimize the objective function defined by (Rao and Babu, 1991):

$$f = \sum_{i=1}^{M_x} \sum_{j=1}^{M_y} [\Delta T'(i,j) - \Delta T''(i,j)]^2 \qquad (4.2)$$

where $\Delta T'$ and $\Delta T''$ are the observed and calculated anomalies respectively, and M_x and M_y are the number of observation points in the x- and y - directions, respectively.

The expression for ΔT (equation 4.1) is non-linear with respect to the body parameters. ΔT is expanded in a first order Taylor series about initial values of the body parameters to obtain an approximation of equation (4.2). The approximate sum of the squares is minimized for the changes in the parameter values, these are then corrected and the process is iterated with the hope of minimizing the objective function f. The least squares values of the parameter changes are given by N linear equations (Rao and Babu, 1991):

$$\sum_{k=1}^{N}\sum_{i=1}^{M_x}\sum_{j=1}^{M_y}\left(\frac{\partial}{\partial P_l}\Delta T(i,j)\right)\left(\frac{\partial}{\partial P_k}\Delta T(i,j)\right)(1+\delta_{kl}\lambda)\,dP_k$$

$$-\sum_{i=1}^{M_x}\sum_{j=1}^{M_y}[\Delta T'(i,j) - \Delta T''(i,j)]\frac{\partial}{\partial P_l}\Delta T(i,j) \qquad (4.3)$$

where $l = 1.....N$, and $\delta_{kl} = 1$ for $k = l$

$= 0$ otherwise

P_k represents one of the parameters a_1, a_2, b_1, b_2, h_1, h_2, EI, and Θ. dP_k represents the increment or decrement of the kth parameter. The parameter λ controls the convergence rate and the direction of the change in the parameter hyperspace at each iteration.

Although in the present work a single Prism source is considered, it is possible to adapt the programme for multiple prism solutions by simply adding some computation loops in the program.

Once equation (4.3) is solved for the unknown differential correction vector (dP_k), improved values P_k'are obtained such that (Won, 1981):

$$P_k' = P_k + dP_k \qquad (4.4)$$

By replacing P_k with P_k' the process can be iterated until the root-mean-square error is minimized.

It is found through experiment (Won, 1981) that this method has one occasional problem: equation (4.4) is based on the assumption that values of dP_k are small compared with P_k. Therefore, when P_k is grossly wrong, equation (4.4)

will produce a large dP_k' which, depending upon the present rate of change of P_k, may violate the assumptions of differential correction and, consequently, the process may not converge. To avoid such a problem, certain allowable limits are imposed on each parameter. The choice of such limits may be informed by geological information or other practical considerations, for example, the magnetic susceptibility, depths and horizontal dimensions may be constrained to remain positive.

4.3 COMPUTATIONAL PROCEDURE

The fortran program MAGINVI (Kangkolo, 1994) was employed for the modeling of the Dange Anomaly. The program requires the initial values of the unknown parameters of the causative body to be assumed. These initial values were estimated (Table 4.1) and constitute the input data to the program along with the anomaly and the field parameters, i.e. the inclination, declination and ambient magnetic field strength.

The parameter λ (equation 4.3) controls the convergence rate and the direction of change in parameter hyper space at each iteration. The objective function f_0 as defined by equation (4.2) was found for the initial model (zero iteration). A value of 0.5 was initially given to λ and the increments dP_k are solved for. The increments are added to the initial parameter values and the objective function f_i is again calculated using these values.

If $f_1 \leqslant f_0$, then the step is a success and the value of λ is decreased by a factor of 0.5 and the value of f_1 is assigned to f_0. The method was iterated until some convergence criterion was met. If $f_1 > f_0$ at any stage, the search is unsuccessful, λ is doubled and equation (4.3) is again solved for the increments. The objective function f_1 is again calculated and compared with f_0. This procedure is repeated until $f_1 \leqslant f_0$. The convergence criterion is that the value of the objective function remains practically at the same value or the increments of the various parameter values are negligible (Rao and Babu, 1991). In some investigations (e.g. Rao and Babu, 1991; Won, 1981), the objective function, f_1 decreases monotonously until it reaches a certain value at which the program terminates. However, it is possible for the f function to decrease monotonically only over an initial interval, after which, f increases with increasing number of iterations, or in some cases oscillates (Cordell and Henderson, 1968).

In the present study, the f function decreases from 2,620,330.0 to 412,529.3 after three iterations, and thereafter it oscillates. The program was then adjusted to terminate at the least value of f reached before oscillation commences.

CHAPTER FIVE

RESULTS, DISCUSSION AND CONCLUSIONS

5.1 INTRODUCTION

In Chapter Four the iterative computer method for fitting models to magnetic anomalies has been described. The Dange anomaly data was fed to the computer and a `best-fit' model was obtained. The interpreted model parameters are presented in this chapter.

In any potential field interpretation technique, the ambiguity problem is always present and this study is not an exception. The inadequate geological information makes the interpretation more difficult. Effort has been made to explain the interpreted model in light of the available information.

5.2 INTERPRETED MODEL PARAMETERS

The iterative inversion program MAGINVI commenced with an f function having a value of 2,620, 333.0 and continuously decreased to 412,529.3 at the end of three iterations. The final values of the parameters of the interpreted model were as follows:

a_1	=	14.40	km
a_2	=	17.34	km
b_1	=	09.24	km
b_2	=	19.95	km
h_1	=	01.63	km
h_2	=	04.95	km
EI	=	0.0445(SI units)	
θ	=	4.5^0	

These parameters describe a rectangular prism with horizontal sides 10.71 km x 2.94 km and a height of 3.32 km. The magnetic susceptibility of 0.0730(SI units) deduced for the interpreted model (a value of 0.02349 SI which is the average for basement rocks in the study area is added to the magnetic contrast to get the absolute magnetic susceptibility for the interpreted body) falls between range of values for average basic rocks and basalts as shown in a similar work done by Ojo (1990) and also reflected by Gerkens' table of rock susceptibility (Gerkens, 1989). Although it is generally not possible to identify a rock type from magnetic information alone due to the large range of variation in the magnetic susceptibilities of rock materials (Dobrin, 1976; Lidiak *et al*, 1987), the causative body being interpreted in the present study is probably of basic igneous composition. The root-mean-square error, which gives the mean deviation of calculated field values from those of the observed field is 27.4 gammas.

5.3 GOODNESS OF FIT BETWEEN OBSERVED AND COMPUTED ANOMALIES

In order to assess the quality of the final model, the theoretical magnetic intensity of the model was computed using equation (4.1) and computer contoured to produce fig 5.1. A comparison of this figure with fig. 3.1 reveals a remarkable similarity between features of the observed anomaly map and the interpreted anomaly map.

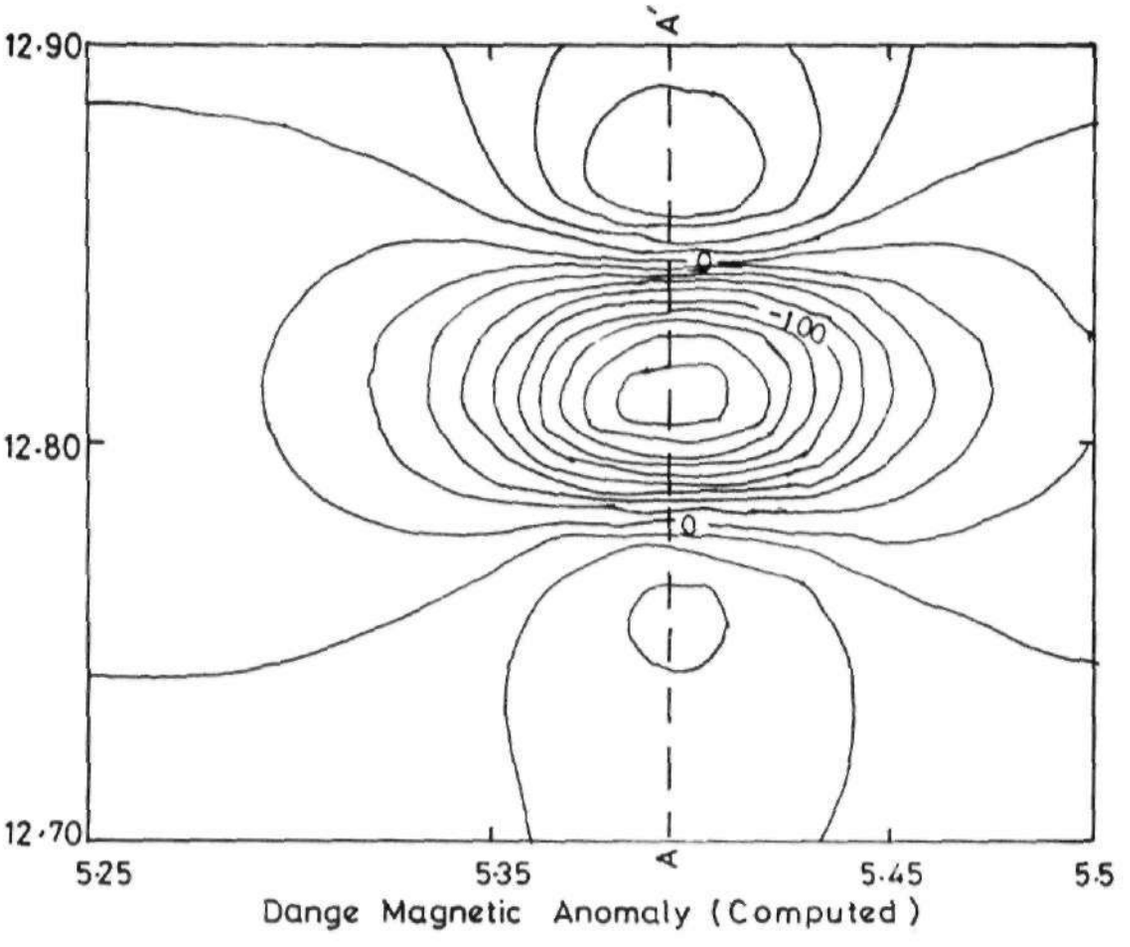


FIG.5.1:MAGNETIC FIELD OF THE INTERPRETED MODEL FOR THE DANGE MAGNETIC ANOMALY

Also, plots of profiles AA' across both figures are presented in fig 5.2 and show a good correlation between the two. The minor departure of the interpreted field from the observed field could be attributed to various factors. These include the fact that the causative body was assumed to be due, exclusively, to induced magnetization but may actually be a combination of induced and remanent magnetization. Another possible source of error could be that the anomaly might have been caused by more than one body. An attempt to accommodate the effect of other interfering bodies in the model resulted in larger discrepancies between the observed and the computed fields, and this was then abandoned. A third source of differences between the observed and computed anomaly is the assumption that the causative body is of regular prism shape. This is unlikely to be strictly true and the body is most likely to be an irregularly shaped body only approximated by the prism model.

Umego (1990) and Sambo (1994), estimated the depth to the top of the structure responsible for the Dange anomaly to be 2 km and 1. 85 km respectively, using the same set of magnetic data but employing different methods of interpretation. Their estimates compare well with the value of 1.65 km obtained in the present study.

5.4 DISCUSSION

In their investigations, both Sambo (1994) and Umego (1990) estimated the sedimentary thickness under the

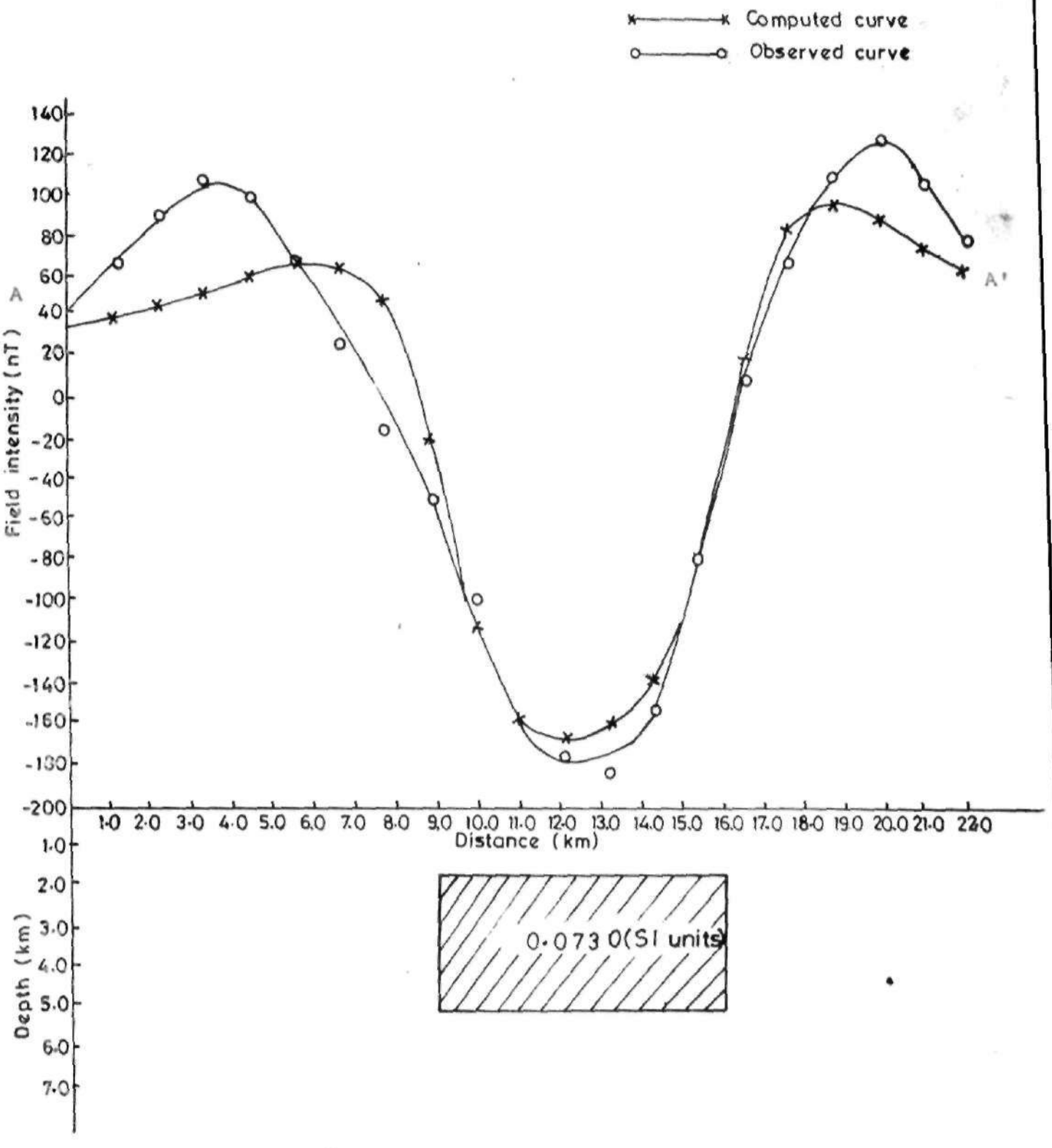


FIG.5.2: PROFILE AA' ACROSS DANGE AEROMAGNETIC ANOMALY SHOWING A/C ROSS-SECTION OF THE MODEL

Dange magnetic anomaly to be 1.4 km. This suggest that a depth of 1.65 km to the top of the causative body places the body within the basement.

As stated earlier, the causative body is probably of basic igneous composition inferred from the high magnetic susceptibility deduced from the interpreted model. Since basic rocks are essentially mantle-derived (Ojo, 1990), their probable occurrence beneath the Sokoto Basin may indicate the presence of deep fissures in the crust beneath the basin. This further suggests that the causative body probably occurred through magmatism with subsequent magmatic emplacement.

The geodynamic process of the emplacement of the Dange anomalous body is not certain. However, a proposition similar to the one proposed by Haxby *et al*, (1976) in explaining the mode of formation of the Michigan basin may be put forward thus: the lithosphere beneath the site of the Dange magnetic anomaly was penetrated by diapiric intrusion of mantle rocks. The diapir ascended to the lower and upper crust, and on cooling, forced the downward deflection of the crust by virtue of its increased density. This could account for the local depression at the site of the Dange anomalous body reported by Sambo (1994).

The problem of the origin and nature of the Dange Anomalous body cannot be finally resolved from this study due to its limited scope, and lack of detailed geological data of the basement underlying the study area. However,

this study should serve as an impetus for further investigations to cover the entire magnetic anomalies in the Sokoto Basin using the 3-D modeling interpretation technique so as to resolve the issuer raised herein.

5.5 SUMMARY AND CONCLUSION

Digital magnetic data extracted from existing half-degree aeromagnetic map of DANGE (sheet 29), within the Sokoto Basin has been used to investigate the structure of the basement beneath the sediments. The sheet is characterized by a prominent E-W negative anomaly occurring in the North-Western sector of the sheet and aligned along latitude $12^{0}49'$. This major E-W anomaly was flanked on both the northern and southern sides by magnetic highs (fig.1.2).

A three-dimensional inversion technique was employed in interpreting the Dange anomaly. The technique use an iterative scheme that combines the least squares and differential correction methods to improve on the initial estimates of the anomaly parameters by inverse modeling process.

Starting with an f function having a value of 2,620,333.0, the modeling process converged rapidly to a minimum rms error of 27.4 gammas after three iterations. The final result gave the horizontal dimensions of the causative body as (10.71 x 2.94) km^2 and 3.32 km in depth. The causative body was interpreted as an intrabasement body

made up of basic igneous rocks with a high magnetic susceptibility of 0.0730 (SI units).

The three-dimensional inverse modeling method used in the present study has proved effective in determining the shape, size and susceptibility of the causative body that is characterized on the surface by elliptically closed magnetic contour lines. The main advantage of this method of interpreting magnetic data over the other methods is the relative economy of the time factor. Given trial estimates of the parameters of the body under investigation, the interpreted parameter values can be obtained in minutes depending on the number of bodies and parameters sought.

Considering that the present anomaly investigated is only one of many others in Sokoto Basin there is need for a much wider coverage of the magnetic anomalies in the Basin using the inverse modeling technique. This will not only shed more light on the accuracy of the present work, but could also bring about a new understanding of the processes that bring about the evolution of the Sokoto Basin. The economic viability of the rocks in the basin could also be assessed.

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