"CORRELATION OF LANDSAT, GRAVITY AND AEROMAGNETIC ANOMALIES WITH MINERAL DEPOSITS IN NIGERIA".

BY

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A thesis submitted to the Post-graduate School, Ahmadu Bello University, Zaria in partial fulfilment of the requirements for the degree of Master of Science, Applied Geophysics,

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DECLARATION

I declare that this thesis has not been submitted in whatever form to any other institution, organization or body other than Ahmadu Bello University, Zaria Nigeria for the award of any degree. All inclusions from others have been duly acknowledged and referenced.

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CERTIFICATION

This thesis entitled - Correlation of Landsat, gravity and aeromagnetic anomalies with mineral deposits in Nigeria by S. O. Ayinde 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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DEDICATION

This thesis is dedicated to

my father,

Hameed Ayinde

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ABSTRACT

In this study, the structural control of mineral deposits in Nigeria north of 8^0 latitude is investigated by the correlation of some mineral occurrences with Landsat, gravity and aeromagnetic anomalies. The study involves a comparative analysis of mineral deposits that are associated with fracturing and other mineral "indicators" such as lineaments, Bouguer and aeromagnetic anomalies, and certain geologic environment.

Preliminary correlation of available data shows that there is an element of correlation between the distribution of mineral occurrences and the so-called indicators. Mineralization zones correlate relatively well with zones of high lineament density ($\rho_L \geqslant 0.00014$ km/km^2) having a NE-SW and NW-SE orientation; with gravity lineaments and zones of large to low negative Bouguer anomalies (-90 to 0 mgals); with magnetic lineaments and zones of high intensity of magnetization ($I > 32780\gamma$); and with certain rock types. Preliminary analysis indicates that 45% of the mineralization zones are within 14 km of lineaments. The mineralised Landsat lineaments have lengths in the range of 0 - 490 km, of which the 70 - 210 km range are predominant. Minerals that show some correspondence with these structural features are gold, bismuthinite, columbite, molybdenite, kyanite, wolframite, copper ores, lead, zinc, cassiterite and sillimanite; while iron ores, feldspar, baryte and uraninite show no conspicuous correlation.

Furthermore, most of the potential field anomalies correlate well with mineral occurrences but a few of these anomalies show no conspicuous correlation in some cases. The non-correlation of these few potential field anomalies is ascribed to the fact that they might have been caused by lithological changes rather than structural ones. Thus the localization of mineralization zones along linear features, where epigenetic mineral occurrences or deposits of a particular paragenesis are found suggests the existence of a structural relationship. Therefore, the deposition of the chosen minerals are structurally controlled.

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ABBREVIATIONS

γ	....	Gamma
I	....	Intensity of magnetization
Landsat	....	Land resources technology satellite
ρ_L	....	Lineament density
Magsat	....	Magnetic resources technology satellite.
Mgals	....	Milligals

CHAPTER ONE

INTRODUCTION

1.1: General Introduction:

Nigeria is blessed with enormous mineral resources. The major minerals include metallic minerals: uranium, thorium, manganese, wolfram, niobium, tin titanium, iron, zircon, gold, silver, lead and zinc; industrial minerals: talc, glass - sand, barytes, abrasives, gemstones, limestone and marble; ceramic minerals: clays and feldspars; metallurgical and refractory minerals: fluorspar and graphite, and mineral fuel: coal, oil and natural gas among others (Federal Surveys, 1978). The earlier methods employed for the exploration of these minerals were on the basis of visual examination of the exposures and outcrops supplemented by deep drilling. In some areas, neither the size nor the nature of the deposits favoured their exploitation.

The aim of this study is therefore to determine the structural control of mineral deposits in Nigeria by the correlation of some known mineral occurrences with Landsat, gravity and aeromagnetic anomalies. This approach is also secondarily being used as a possible means of directly detecting undiscovered mineralization zones. The study involves a correlative study of some minerals whose occurrences are mainly localized to fracture zones and to some areas with "mineral indicators" such as Landsat lineaments, Bouguer and aeromagnetic anomalies, and the geologic environment (i.e. rock type). The last three indicators are used here to supplement the Landsat lineaments in order to substantiate the correlation. Much emphasis is placed on minerals that have been found associated with fracture zones. This type of approach has long been employed in the United States of America to aid mineral exploration. For instance, in Central Colorado, areas with high concentrations of intersecting lineaments coincide or are immediately adjacent to mineralization zones (Nicholais, 1974).

The entire work is restricted to the area north of 8^{o} latitude (fig. 1.1) because the data available covers this area and for the fact that the crystalline rocks are more pronounced in the area. The indicator maps adapted are those of Oluyide and Udoh (in press) for lineament and geological maps; Ajakaiye and Burke (1973), Ajakaiye and Verheijen (1977) and Ojo (1984) for Bouguer anomaly maps, and Geological Survey of Nigeria (1975) and Ajakaiye et al (1986) for the aeromagnetic map. Although all these maps have been given general regional interpretations by their respective compilers, they have been re-interpreted in the light of the present objective.

1.2: Previous Work

The geological and geophysical studies on Nigeria are numerous and variable in content. Most of these studies are

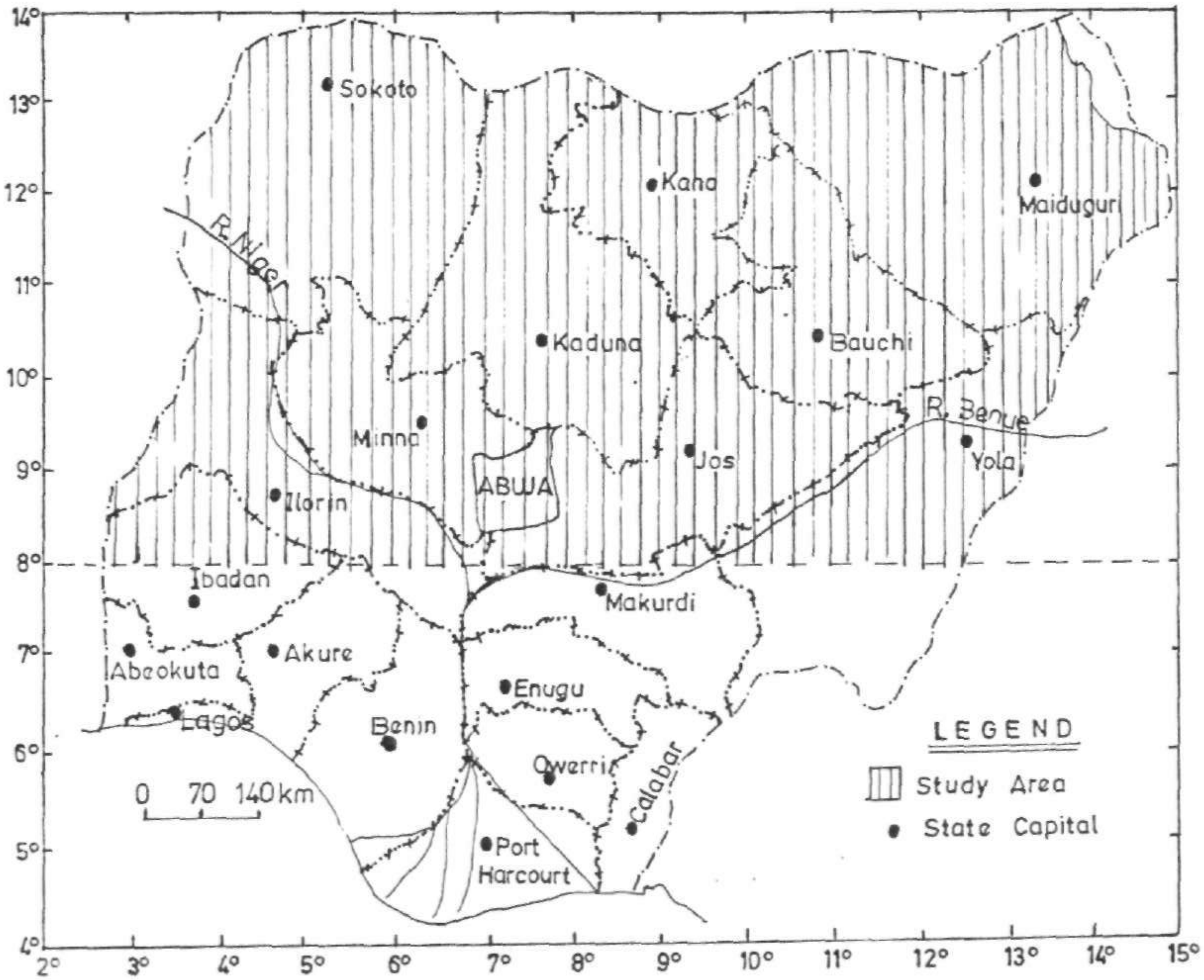


FIG.1.1: MAP OF THE STUDY AREA

regional in nature and they include mapping of Landsat lineaments, potential fields, surface geology, drainage patterns, mineral occurrences among others. Only those aimed at mineral exploration within the study area are further discussed.

Prior to 1919, mineral exploration based on geological mapping, geochemical analysis and drilling were carried out separately by the Mineral Surveys of Southern and Northern Nigeria. During the existence of these divisions, a considerable amount of studies were carried out in the exploration of minerals such as barium, columbite, gold, tin, graphite, iron, lead and zinc (Geological Surveys, 1957). The occurrences of gold, sillimanite and kyanite have been associated with the amphibolites and schists of the basement complex (De Swardt and Van Coppenhagen, 1947; Pargeter, 1958). Lead, zinc and barium occur in the Benue trough environ (Ford, 1981). Columbite, tantalite, wolframite, cassiterite, copper ares and molybdenite are associated with the alluvial deposits of the Younger granites and in some Older granite pegmatites (Rockingham, 1950; Cole, 1956; Turner, 1965). Pastor and Turaki (1985) have however recognized two basic genetic types of primary mineralization in these areas; dissemination of cassiterite in biotite-granites or cassiterite + columbite and other minerals in various combination and the vein controlled hydrothermal mineralization. The occurrences of iron in numerous localities in the country have been reported (Dada, 1981). A great abundance of feldspars are found in granitic rocks (Federal Surveys, 1978). Also some geological studies aimed at ascertaining the mineral potentials of the Schist belt have been reported (Olade, 1976; Adekoya, 1981; Matheis and Caen-Vachette, 1981).

Some work have also been done in area of gravimetric prospecting aimed at establishing Kaolin deposits (Ebifegha, 1977) and locating saltdomes around some brine lakes in Nigeria (Umego, 1978; Ajayi, 1986). Studies have also been carried out in areas of magnetic and radiometric prospecting aimed primarily at locating magnetic and radiometric minerals respectively (Geological Survey of Nigeria, 1975; Uwah, 1984; Dewu, 1986). A considerable amount of studies as distinct from mere prospecting have been undertaken by some mining companies with special exclusive prospecting licences to search for minerals like lead, zinc, cassiterite, columbite, gold, iron, uranium, etc. Some of these companies include Amalgamated Tin Mines, Associated Ores Mining Company, Nigerian Mining Corporation, Nigerian Uranium Mining Company, National Steel Council among others. The methods employed by these companies include electrical, seismic, magnetic, gravity, radiometric, geochemical and well logging; to gain information about the rocks below the surface.

In Nigeria, the use of structural analysis for aiding mineral exploration has not been quite adopted. Instead it has been employed to study crustal features that might have experienced differing tectonic histories (Chukwu-Ike, 1977, 1981; Chukwu-Ike and Norman, 1977 ; Oluyide and Udoh, in press). However, Ananaba's (1983) structural study on Nigeria's landmass showed a relatively positive correlation with mineral occurrences. Mineralization zones are within areas with high lineament density; $\ell \geqslant 0.0300$ km/km^2.

CHAPTER TWO

GEOLOGY AND MINERAL OCCURRENCES

2.1: Geology of Nigeria

The geology of Nigeria shows that the rocks that make up the various units of geological succession vary from crystalline to sedimentary rocks (fig. 2.1). The crystalline rocks are composed principally of metamorphic and igneous rocks such as granites, amphibolites, gneisses and migmatites. In places, there are extensive occurrences of schists, phyllites, quartzites and marble, the metamorphosed representative of ancient sediments. These rocks are believed to have been subjected to polymetamorphism with the formation of mountain ranges that were eventually eroded with the original rocks highly migmatised and granitised (McCurry, 1973, 1976). The sedimentary rocks are made up of alluvium, sands, clays, mangrove swamps, grits, lignites, sandstones, shale and limestone.

2.1.1: Crystalline Rocks

The crystalline rocks are divided into three groups on the basis of their age; the Basement Complex, the Younger granites and the Tertiary deposits. The Basement Complex is made up of Precambrian to early Paleozoic crystalline rocks which are considered to be the floor on which subsequent accumulation were laid down. Within it, three lithological units are distinguishable: polymetamorphic migmatite - gneiss - quartzite complex, low grade sediment dominated

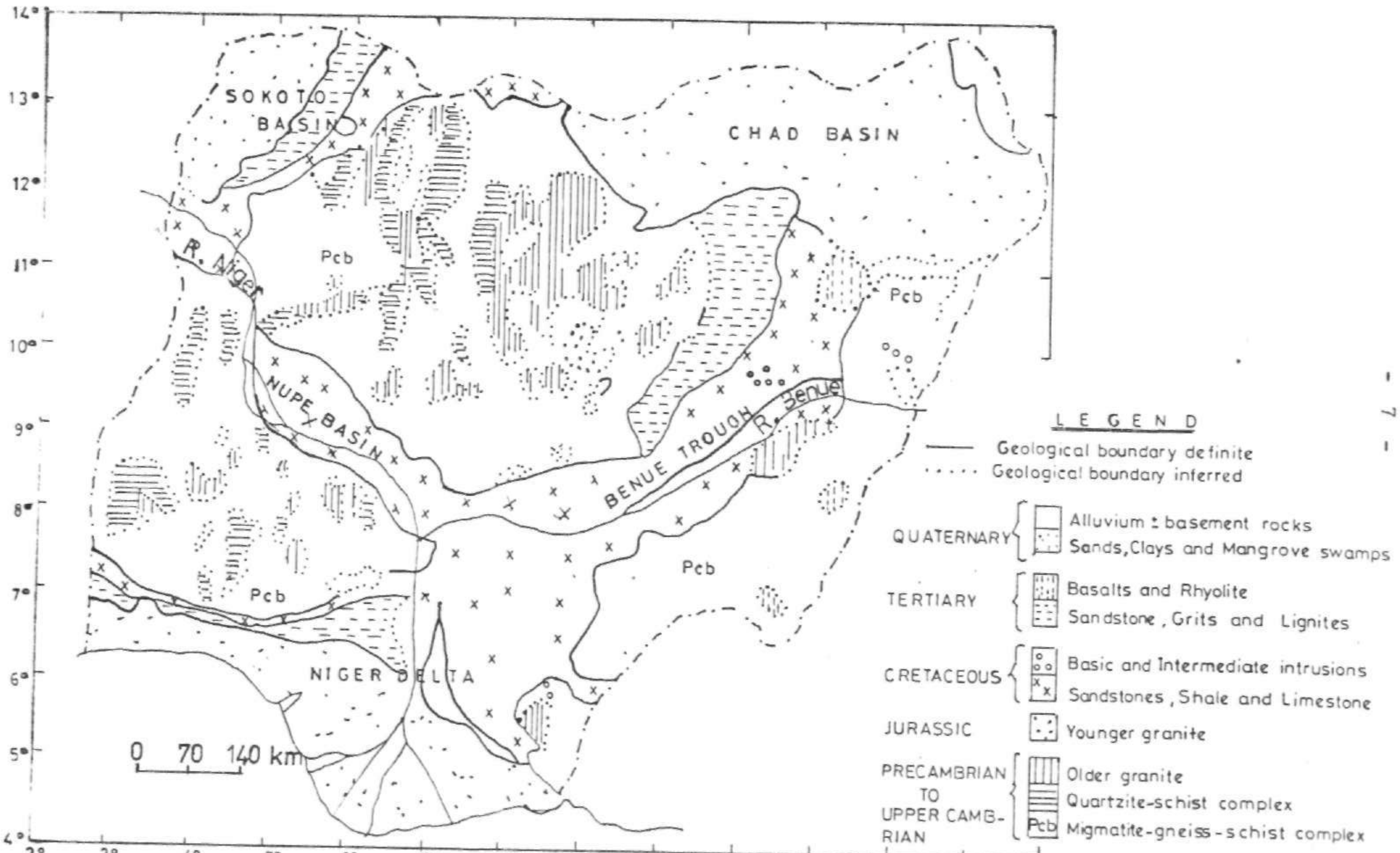


FIG.2.1: GEOLOGICAL MAP OF NIGERIA (From Oluyide and Udoh, in press)

schist belts and the Older granite suite which cuts through both the latter (Rahaman, 1975; McCurry, 1976; Rahaman and Ocan, 1978). The schist belts are variously regarded as small ocean basins (Rahaman, 1981), in filled rift structures (Olade, 1976)or synclinal remnants of an extensive supracrustal cover (McCurry, 1976). They are composed essentially of fine grained clastic pelitic schists, phyllites, banded iron formation, carbonate rocks and mafic metavolcanic (Turner, 1983). The Older granite suite range in composition from tonalite, diorites through granodiorites to granites and syenites (Tubosun et al, 1984). The Younger granites which are high level discordant intrusions of a series of anerogenic, alkaline shallow subvolcanic intrusives in the basement complex are made up of rhyolite, granite - porphyries, quartz - porphyries and granites (Jacobson et al., 1963; Bowden et al., 1984; Pastor and Turaki, 1985). Several geological and geophysical studies have been carried out on the Nigerian Younger Granites (Ajakaiye, 1968, 1970, 1974; Oyawoye, 1968; Ike, 1979; Ajakaiye et al., 1986; etc). The Tertiary deposits are products of volcanic activities and are made up of basaltic rocks (Fargher, 1961; Adefila, 1966). They have been classified as Tertiary to Recent by Burke et al. (1971).

2.1.2: Sedimentary Rocks

There is a long gap in the geological history of Nigeria between the PreCambrian and the Cretaceous sediments. Early in Cretaceous time, tectonic dislocations gave rise to of diagenesis (Furor, 1963). These sediments are preserved in major depressions (basins) which are today identified as the Benue trough, the Chad basin, the Niger delta, the Nupe basin and the Sokoto basin. A structural and stratigraphical relationship has been suggested to exist between these basins (Kogbe, 1981) but the non-uniformity in the level of studies in all the basins made it impossible to establish a definite correlation. However, borehole geophysical data revealed that the sedimentary sequence is thickest in Southern Nigeria (Kogbe, 1981). Of these basins only the Benue trough is further discussed here because of its tectonic relevance to the present study. All the basins are shown in figure 2.1.

The Benue trough is believed to be a rift system which developed during the break-up of Gondwanaland which was subsequently filled mainly with Cretaceous sediments (Pugh and King, 1952; Uzuakpunwa, 1974; Wright, 1976). The sediments are in some places strongly folded, the folding follows the structural gain of the flanking basement (Wright, 1976). At its southwest and northeast ends, younger rocks overlie the older formations. The stratigraphical and structural conditions are essentially continuous from the southwest to the northeast through the entire length of the Valley (King, 1950; Short and Staub1e, 1967; Artsybaschev and Kogbe, 1974; Offodile, 1976).

2.2: A Review of Metallic Minerals

Metallic minerals are of two kinds; the abundant and the scarce metals. These metals have versatile properties such as malleability, ductility, and high thermal and electrical conductivities. The abundant metals include iron, aluminium, titanium and magnesium while the scarce metals are copper, lead, zinc, tin, tungsten, chromium, gold, silver, platinum, uranium, mercury, and molydenum. When these metals form deposits, the minerals in them have distinctive properties and composition. On this basis they can be grouped into three categories; sulphide minerals (i.e. copper, lead, zinc, nickel, tin, mercury, molybdenum and bismuth), native metals (i.e. gold, copper and platinum), oxide and silicate minerals (i.e. tungsten, tantalum, tin, niobium, beryllium and uranium). Although some overlap occurs, the number of metals concentrated principally in sulphide deposits is larger (Park and MacDiarmid, 1970 ; Skinner, 1976). Some metals such as iron, titanium, nickel, lead and copper are produced from ores worked solely or mainly for these metals; others are recovered as co-products from ores that contain more than one valuable metal (for example lead-zinc, copper-zinc, zinc-lead-copper, iron-titanium-vanadium, and nickel-copper); yet others are only recovered as by - products from the processing of ores of other metals. Such by - products include manganese, gold, silver, cadmium, cobalt and mercury (Skinner, 1976).

Although a large number of metallic minerals exist, the most common ones are described here in their most general sense to illustrate the variations in the types of deposits, their various ore forms and geological association. These minerals include the ores of copper, molybdenum, tin, wolfram, gold, iron, tantalum, barium, lead, zinc and uranium.

COPPER

Major Forms: Cu, Cu_2S, $CuFeS_2$, Cus, Cu_5FeS_4, Cu_2O, $Cu_2(Co_3)(OH)_2$ $Cu_3(Co_3)(OH)_2$

Mode *of Occurrence:* The sulphides and oxides are associated with hydrothermal and contact metasomatic deposits while native copper is observed as microinclusions in basic igneous rocks altered by hydrothermal deposits.

MOLYBDENUM

Major Form: MoS_2

Mode of Occurrence: It is generally associated with acid intrusives and it occurs in pegmatite dykes. Deposits are associated with hydrothermal formation. Occurrences in quartz veins or silicified rocks are especially widespread. Paragenetic associates of this mineral include wolframite, chalcopyrite and sphalerite.

T I N

Major Forms: SnO_2, Cu_2FeSnS_4

Mode of Occurrence: The ores of tin are genetically associated with acid igneous rocks, mostly granites and occur in pegmatite dykes in association with niobium, tantalum, iron and other metals, quartz - cassiterite and sulphide cassiterite. Sulphide cassiterite occurs in hydrothermal tin ore deposit. Occurrences in rhyolite and alluvial deposits are also common.

W O L F R A M

Major Form: $(Mn, Fe)WO_4$

Mode of Occurrence: Occurs chiefly in quartz, hydrothermal and sulphide veins; quartz veins in granite masses. Occasionally associated with ores of tin, molybdenum, iron, etc. Also in small amounts in epithermal veins and in placer deposits.

G O L D

Major Forms: Au, (Au, Ag), $AuTe_2$, AuAgTe

Mode of Occurrence: Occurs in hydrothermal deposits genetically associated with intrusions of acid rocks in paragenesis with quartz, sulphides of iron and copper. In auriferous conglomerates and in placer deposits.

I R O N

Major Forms: Fe_2O_3, Fe_3O_4, $HFeO_2aq.$, $HFeO_2$, $Fe(Mg)Fe_2O_3$, $FeCo_3$

Mode of Occurrence: Occurs chiefly in extensive thick beds of sedimentary origin; also as an accessory mineral in igneous rocks; in vein deposits, often as gossan; as a sublimation product in lavas, in many metamorphic rocks; and in contact metasomatic formations especially contact of limestone with granite in association with chlorites, sulphides, calcite and other minerals.

NIOBIUM-TANTALUM

Major Forms: $(Fe,Mn)Ni_2O_6$, $(Fe,Mn)\ Ta_2O_6$

Mode of Occurrence: Occurs together in granitic pegmatites in association with albite, quartz, beryl, zircon, tourmaline, wolframite, cassiterite and other minerals; also in placer deposits in areas of pegmatites and granitic rocks.

B A R I U M

Major Forms: $BaCo_3$, $BaSO_4$

Mode of Occurrence: Occurrence is widespread chiefly in hydrotherma vein deposits, in sedimentary rocks as veins, lenses, cavity fillings, and in concretions; in residual clay deposits, in cavities in igneous rocks and as a hot springs deposit.

LEAD - ZINC

Major Forms: Pbs, $PbCo_3$, $PbSO_4$, Zns, $ZnCO_3$

Mode of Occurrence: Occurs chiefly in limestones, dolomites and other sedimentary rocks, in hydrothermal ore veins; in contact metasomatic deposits and rarely in pegmatites.

U R A N I U M

Major Form: UO_2

Mode of Occurrence: Occurs mainly in hydrothermal vein deposits, in association with arsenides of nickel, cobalt, bismuth, silver, argentite, and haematite; in granite and syenite pegmatites in paragenesis with the ores of thorium, niobium, and tantalum. It is widespread in smaller amount in a large variety of environment.

The above descriptions were summarised from books on ore deposits (Park and MacDiarmid, 1970; Roberts et al., 1974; Skinner, 1976).

2.2.1: Geological Processes of Mineral Formation

All mineral masses which are formed as a result of some geologic processes fall into two basic genetic groups (endogenous and exogenous processes), depending on the source of energy to which they owe their formation. The deposits formed as a result of endogenic (magmatic deposits;

gravitational segregation, magmatic injection, disseminated, late magmatic, pegmatite and hydrothermal deposits) depend on the internal energy of the earth, and are products of magmatic activities (Sinkankas, 1966). Those formed as a result of exogenous processes occur in the upper part of the earth's crust. These deposits include contact metasomatic deposits, sedimentary deposits (i.e. placer and clorite deposits) and secondary enrichment deposits; residual and supergene enrichment deposits (Sinkankas, 1966). Some of the deposits are however related to fracturing because of their genesis. Thus only those that are controlled by fracturing are further discussed.

When a magma begins to crystallize after upward intrusion into cooler portions of the crust, several mechanism may lead to deposits associated with the resulting igneous rocks. If the early formed minerals should be much more dense than the parent magma, they may sink rapidly and form concentrations by magmatic segregation on the floor of the magma chamber. When the entire magma has crystallized to an igneous rock, the segregated layers of heavy minerals may prove to be rich ores. Ore deposits which become concentrated by the various differentiation processes may be injected into openings in the surrounding country rocks to form a magmatic injection deposit or may become concentrated in large or very small amounts to form disseminated deposits. Magmatic injection deposits cut across or transect the structures of the country rock taking the form of dykes or irregular bodies in accordance with the dominant opening available. Pegmatite deposits are formed in high pressure regions around the margins of magma chamber or just outside the margins in available openings. They take up any shape, but apparently most are dyke-like or lens-like. Contact metasomatic deposits are formed when early formed minerals in a cooling magma tend to be anhydrous and free of volatiles. As crystallization continues, the residual liquid becomes enriched and saturated in volatile components. Eventually the volatile start to escape and alter the rocks surrounding the magma chamber. Finally the escaping hydrothermal fluid may follow well-defined flow channels and, as they cool deposit any dissolved matter they carry into hydrothermal deposits (Park and MacDiarmid, 1970; Skinner, 1976).

2.2.2: Mineral Occurrences of Nigeria

Although Nigeria is blessed with enormous mineral resources, the mineral production is not remarkable because they have not been fully exploited. Many other small deposits and occurrences of several types are recorded. Most of these minerals occur in their various ore forms and they are unevenly distributed probably as a result of the plate tectonic theory of crustal evolution (i.e. differing nature of the depositional environments). The mineral belts are linear zones along which epigenetic mineral occurrences and deposits of a particular paragenesis are found (Woakes, in press). Numerous faults have been recognised in some areas where mineral occurrences are evident (Chukuwu-Ike, 1977; Chuku, 1981; Ananaba, 1983). Petroleum is of major economic significance but because of its genesis it will not be further discussed. Figure 2.2 shows the distribution of

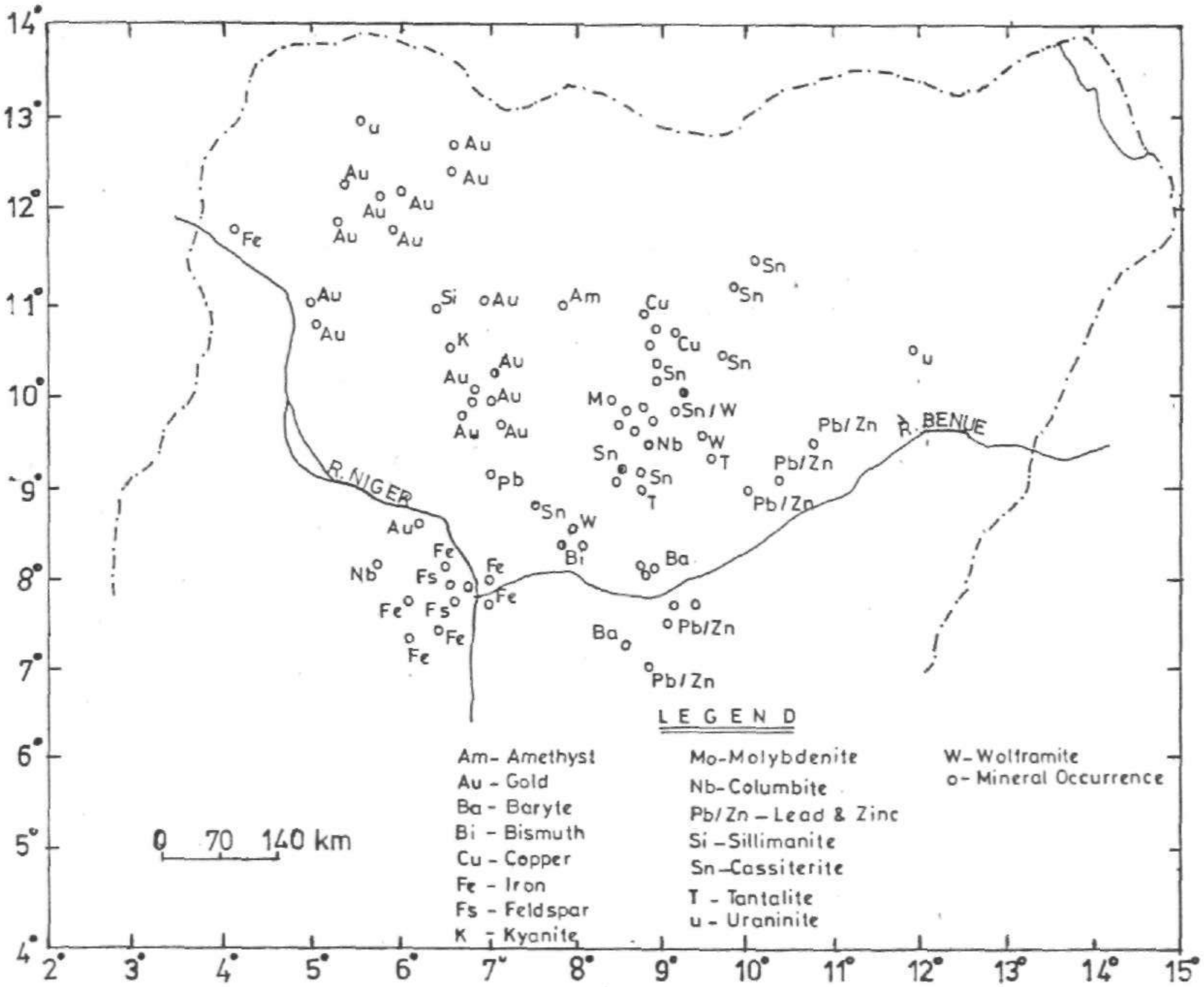


FIG-2.2: MINERAL OCCURRENCES MAP OF NIGERIA (From Federal surveys 1978 and GSN publications) the chosen minerals in the study area. Some of the occurrences are further discussed below.

Uranium is not currently mined in Nigeria but some occurrences have been found in the Sokoto basin, the Liruei hill, the Jos Plateau and in some granitic bodies in the basement complex where they are associated with pyrochlore (African Technical Review, 1986). Cassiterite, the ore of tin and columbite are found in the alluvial and eluvial deposits associated with the Younger granites and Older granite pegmatites with tantalite, wolframite and bismuthinite widely disseminated on the cupola zones of the biotite-granites in the younger granites. Iron ore occurs in numerous localities within the country, some occurences are confined to basic and ultra basic igneous rocks while others to sedimentary rocks. Feldspar is abundant in igneous rocks and are mostly found in pegmatite bodies in the lead and zinc lodes of the Benue trough and in certain veins associated with the Younger granites. Sulphides of lead and zinc, locally associated with quantities of copper, cadmium, barytes and other secondary minerals, sulphides, carbonates and oxides occur in lodes and veins filling open fractures of the Benue trough. In the Middle-Benue, there are numerous mineral veins and lodes predominating barytes. The barytes occur with quartz and the carbonate of iron, calcium and magnesium and occasionally sulphides of lead and zinc in vein systems filling fissures in earlier brecciated fracture zones. Graphite, kyanite and sillimanite are confined to the schists and gneisses and to quartz veins. Traces of gold are found in modern alluvial deposits and quartz vein mineralization in some basement rocks containing varying amount of silver. Schist and amphibolite are the source rocks of all the gold found in Nigeria (Geological Survey of Nigeria, 1957; Federal Surveys, 1978; Ford, 1981; Woakes, in Press).

Although some parts of the basement complex are barren of economic minerals, the others are nevertheless important as local source of such minerals discussed above. Since there is no clear distinction between mineral occurrences and deposits, the areas with mineral occurrences should be viewed in this context as just mineralization zones.

CHAPTER THREE

MINERALS INDICATORS AND INDICATOR MAPS

3.1: Mineral Indicators:

The physical characteristics of mineral deposits or occurrences depend on their composition. For example density, magnetic susceptibility, resistivity and radioactivity are related to composition. These properties vary from point to point and with the direction within the depositional environment. The configuration of the structures (spaces) containing the minerals depend on the stress history of the host rocks. Spaces are created in rocks either by mechanical or chemical processes. The obvious mechanical process is fracturing of rocks. When a rock mass is deformed there will be some part subjected to tension; mechanical failure will allow extension of openings which may eventually contain some minerals. The creation of spaces by chemical process takes place in serveral ways; one mineral in a rock may be replaced by another in reaction with a solution, if the newly formed mineral occupies less volume than the original one, space is made (Park and MacDiarmid, 1970).

A mineral indicator is therefore defined as any physical or chemical phenomenon which correlates with known deposits or occurrences (Rubin, 1979), for example Landsat lineaments, surface, geobotanical and potential field anomalies. Of these indicators, Park and MacDiarmid (1970) have observed that structural studies have unquestionably led to the discovery of more ores than has any other directed effort. This is because the movements of fluid underground is controlled by permeability, a function of the original character of the rock plus the elements of superimposed structure. This chapter therefore, gives a brief description of these indicators and how they are recognised. Their compilation is beyond the scope of this study.

3.1.1: Lineaments

These are character lines of the earth's physiognomy and they reveal the hidden architecture of the basement rocks. A lineament is defined as a mappable simple or composite linear feature of a surface, whose parts are aligned in a straight or slightly curving relationship, and which differs distinctly from the patterns of adjacent features and presumably reflects a subsurface phenomenon (O'Leary et al., 1976). Their presence often indicate the occurrences of faults/fractures. The surface features which make up a lineament may be geomorphic or tonal. Lineaments may be continuous or discontinous. In discontinuous lineaments, the separate features are aligned in a consistent direction and are relatively closely spaced. Ground checks on many Nigerian lineaments confirmed that they are dominantly negative topographic features containing silicified mylonites and blastomylonites (fault indicators) over the basement (Chukwu-Ike, 1981).

They offer convenient passage ways along which all the deposition products of deep-seated magmatic hearths rise filling the entire volume of the fissures. Areas of maximum lineament intensity and lineament intersections are good prospecting targets. Prospectors and mining geologists have long realised that in many mining provinces, mining districts occur along linear trends (mineralization zones) and have established many mines by exploring along the projections of such trends. Minerals found associated with the occurrence of lineaments include cassiterite, columbite, sillimanite, wolframite, molybdenite, amethyst, barytes, gold, tantalite, uraninite and kyanite among others (Park and MacDiarmid, 1970). Moreso, it is generally believed that a correspondence exist between mineral occurrences or deposits and the occurrences of lineaments, thus the mapping of this indicator is a major exploration technique for these minerals (Pascucci et al., 1973; Nicholais, 1974; Kowalik and Gold, 1975; Offield et al., 1977; Ananaba, 1983). Information pertaining to the recognition and compilation of Landsat lineaments are described in textbooks on remote sensing (Barret and Curtis, 1977; Sabins, 1978; Barry and Gillespie, 1980).

3.1.2: Geobotanical Anomalies

Vegetation growing in mineralized soil may have a higher metal content in its tissue than those in normal or background soil. Geobotanical features such as vegetation anomalies are often used in the temperate and humid climate zones where mineral deposits are concealed beneath a cover of soil and vegetation (Sabins, 1978). The following criteria have been employed by Sabins (1978) to recognise such concealed ore deposits, viz:

(i). Lack of vegetation due to concentration of metals in the soil that are toxic to plants.

(ii). Presence of some species (indicator plants) that grow preferentially on outcrops and soil enriched in certain elements e.g. Acrocephalus Roberti in copper zones

(iii). Presence of physiological changes in plants such as abnormal size, shape, etc due to high metal concentration.

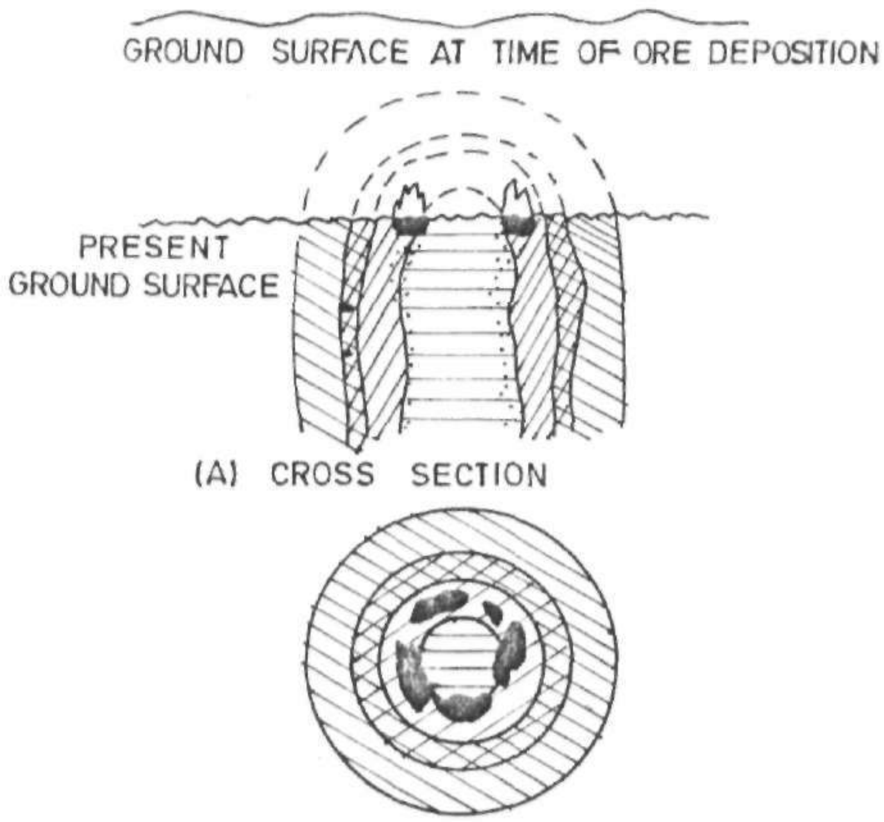
3.1.3: Surface Anomalies

These are anomalies associated with igneous intrusions when they give rise to hydrothermal solutions. When these solutions invade the country rock, ore bodies could be deposited in hydrothermal veins such as joints and fractures. These solutions could also interact chemically with the adjacent country rock thereby altering the mineral composition quite beyond the site of ore deposition (Sabins, 1978). Later uplift and erosion may expose successively deep alteration zones and eventually the ore body itself. Hydrothermally altered zones are noticed in the field by the presence of pegmatites, dykes and aplites. The zoning is due to changes in temperature, pressure and chemistry of the hydrothermal solution at progresively greater distances from the ore body (Sinkankas, 1966; Sabins, 1978). These zones are valuable indicators of possible deposits. Minerals that are found in hydrothermal zones include some metallic sulphides and oxides. Typical alteration zones and their mineral assemblages are shown in figure 3.1.

Some surface anomalies are in the form of the geologic environment (i.e. rock type). Some rocks are known to be constituted of some certain minerals. Table 3.1 shows the rock-mineral relationships that could be used to aid mineral exploration. The table is divided according to the three principal rock types and some minerals commonly found in them.

3.1.4: Potential Field Anomalies

These are anomalies or irregularities in the earth's potential fields caused by changes in the physical properties of subsurface rocks. Gravity, electrical, electromagnetic and magnetic methods rely very much on the existence of such irregularities. They are obtained by mapping the configuration of the basement rocks where structural features like lineaments are evident. Lineaments are recognised on Bouguer anomaly and aeromagnetic maps by the presence of aligned highs and lows, steep contour gradient and aligned offset of trends. On the aeromagnetic maps, favourable indications of mineralization zones are high magnetic values exhibiting characteristic criss-crossing patterns which



(B) MAP VIEW OF PRESENT GROUND SURFACE

LEGEND

- UNALTERED ROCK
- PROPYLITIC ZONE
  Epidote, Calcite, Chlorite
- ARGILLIC ZONE
  Quartz, Kaolinite, Montmorillonite
- PHYLLIC ZONE
  Quartz, Sericite, Pyrite
- POTASSIC ZONE
  Quartz, Sericite, Biotite, Potassium, Feldspar
- ORE ZONE
  Chalcopyrite, Molybdenite, Pyrite
- GOSSAN
  Limonite from weathered ore

(Propylitic, argillic, phyllic and potassic zones: ALTERATION ZONES)

FIG-3.1: MODEL OF HYDROTHERMAL ALTERATION ZONES ASSOCIATED WITH PORPHYRY COPPER DEPOSITS (After Lowell and Guilbert, 1970)

Table 3.1: Summary table of Rock-Mineral associations

(From Sinkankas, 1966)

Rocks	Deposits and Minerals	Examples of Occurrences
Igneous group		
Rhyolite	Tin ores in fissures: cassiterite, topaz, tourmaline	Jos - Nigeria
Trachyte	Fissures: Kaolinite, minor sulphides, cavities: Opal	Mexico
Basalt	Amygdaloidal: Native Copper and Silver, quartz calcite, zeolite.	Michigan, U.S.A.
Diabase	Seams and fissures: Gold, Copper, cobalt-Nickel	Ontario, Canada
Granites	Veins, seams and altered zones: Cassiterite, wolframite, bismuthinite, molybdenite.	Great Bear Lake, Canada.
Granitic pegmatites	Vein like shape: Feldspar, quartz, mica, beryl, tourmaline, garnet, columbite, tantalite, topaz.	Pegmatite regions of California, Maine, Brazil, Nigeria.
Syenite	Vein: Quartz, gold, sulphides	Ontario
Nepheline-Syenite	Distinct crystals (Phenocrysts): Corundum, Zircon	Ontario, Maine
Granodiorite	Disseminated: Porphyry copper ores	Southwest United States.
Monzonite	Altered zone: Molybdenite	Jos Plateau-Nigeria, California.
Diorite/ Gabbro	Veins: Native metals and sulphides Large masses: Magnetite, Ilmenite, pyroxene copper, nickel and iron sulphide	Colorado, California, Jos Plateau - Nigeria.

Table 3.1 (cont'd)

Rocks	Deposits and Minerals	Examples of Occurrences
Anorthosite	Large coarsely crystalline masses: Labradonite, magnetite, ilmenite	New York, Iron mountain Wyoming, Labrador.
Peridotite	Masses: Chromite, nickel ores with olivine, platinum, magnetite, single crystals: Garnet, diamond.	New Caledonia, Eastern Pennsylvania, Africa.
<u>Metamorphic group</u>		
Gneiss	Disseminated pods, single crystal, lenses, stringers: almandite, graphite, corundum, mica, kyanite, sillimanite, andalusite, ilmenite	Gore Mountain, New York, Swiss Alps.
Schist	Disseminated pods, single crystal, lenses stringers: Garnet, graphite, talc, Serpentine, chlorite, magnetite, mica.	Appalachian Mountain, Alpine regions, California.
Serpentine	Disseminated and vein like bodies: Chromite, magnesite, Cinnabar	Oregon and California, Barrens of Maryland.
Quartzite	Cavities: Quartz	Numerous localities
Slate	Cavities: Quartz Veins: Quartz with gold and sulphides scattered crystals: Pyrite	Numerous localities
Phyllite	Scattered crystals and pods: Andalusite and kyanite	
Marble	Scattered crystals, pods, lenses: Sulphides,mica, graphite, corundum, garnet.	New Jersey, Southern New York Marble belt.

Table 3.1 (cont'd)

Rocks	Deposits and Minerals	Examples of Occurrence
Sedimentary group		
Conglomerate	Copper, silver, gold and diamond	Brazil, Ontario, Nigeria, South Africa.
Sandstone	Disseminated: Uranium - vanadium ores, Cavities: Quartz crystals Seams; Veins and disseminated: Cinnabar, galena, sphalerite, barite, calcite, gypsum, anhydrite	Colorado Plateau Hot spring region, Arkanas, Benue trough - Nigeria.
Shale	Seams, cavities: Boron minerals, sulphates and carbonates, strata and seams: gypsum anhydrite.	Searles lake, California.
Limestone	Sulphide veins and disseminated deposits: Sulphides of lead, copper and zinc, seams and geod-like openings: barite, fluorite, minor sulphides	Mexico, Clay Centre, Ohio
Chert	Breccia openings, seams, veins: Lead, Zinc and Iron sulphides, calcite.	Oklahoma, Kansas, Missouri
Saline rocks	Strata: Halite, gypsum, anhydrite	New Mexico, New York, Germany.

reflects fracturing and subsequent mineralization in the fracture system (Grant and West, 1976).

Although both the methods adopted here (i.e. gravity and aeromagnetic) involve mapping of structures favourable for mineral accumulation, the significant parameters are different. The aeromagnetic method takes into cognisance variations in magnetic susceptibility of rocks; rocks with high susceptibility are potential areas for iron - rich minerals. On the other hand, the gravity method detects and measures changes in the vertical component of the earth's gravity field due to lateral variations in the density of the subsurface rocks. Many geologic structures such as mineralized lineaments give rise to disturbances in the normal density distribution within the earth which cause diagnostic anomalies in the gravitational field. These anomalies are of great interest in mineral exploration. However, high density minerals are particularly favourable prospect for gravity exploration because of their distinct density contrast (Dobrin, 1976). Tables 3.2 and 3.3 list densities and susceptibilities for some of the chosen minerals and their host rocks respectively. In everycase, the susceptibility of the rocks and minerals depend on the amount of ferrimagnetic mineral present, the grain size and mode of distribution (Parasnis, 1972), while the densities depend on their respective mineral constituents. Information on the preparation and interpretation of potential field maps are discussed in standard textbooks on exploration geophysics

Table 3.2: Densities and susceptibilities of some minerals

(From Telford et al., 1976)

Minerals	Density Range Kgm^{-3}	Susceptibility x 10^{-3} (S.I. Units)
Bismuthinite	6500 - 6700	
Cassiterite	6800 - 7100	90
Chalcoite	5500 - 5800	
Chalcopyrite	4100 - 4300	32
Copper		
Cuprite	5700 - 6150	
Galena	7400 - 7600	
Gold	15600 - 19400	
Haematite	4900 - 5300	550
Ilmenite	4300 - 5000	1.5×10^5
Magnetite	4900 - 5200	5×10^5
Malachite	3900 - 4030	
Marcasite	4700 - 4900	
Molybdenite	4400 - 4800	
Pyrite	4900 - 5200	130
Pyrrhotite	4500 - 4800	125,000
Rutile	4180 - 4300	
Silver		
Sphalerite	3500 - 4900	60
Stannite	4300 - 4520	
Uranimite	8000 - 9970	
Wolframite	7100 - 7500	

Table 3.3: Densities and susceptibilities of some igneous and metamorphic rocks (From Telford et al., 1976).

Rocks	Density Range (Kgm^{-3})	Susceptibility Range $\times 10^{-3}$ (S.I. Units)
Anorthosite	2640 - 2940	
Basalt	2700 - 3300	20 - 14500
Diabase	2500 - 3200	80 - 13000
Diorite	2720 - 2990	50 - 10,000
Gabbro	2700 - 3500	80 - 7200
Gneiss	2700 - 2900	10 - 2000
Granite	2500 - 2810	0 - 4000
Granodiorite	2670 - 2890	
Marble	2600 - 2900	
Nepheline-syenite	2530 - 2700	
Phyllite	2600 - 2900	
Quartzite	2500 - 2700	
Rhyolite	2350 - 2700	20 - 3000
Schist	2390 - 2900	25 - 240
Serpentine	2400 - 3100	250 - 1400
Slate	2680 - 2800	0 - 3000
Syenite	2600 - 2950	
Trachyte	2420 - 2800	

such as Parasnis (1972), Dobrin (1976), Telford et al (1976), and others.

It should be noted that in the potential field maps, the mineralization zones are not identified immediately because the anomalies being sought are usually not a direct indication, only mineralization zones at small depths under the earth's surface are occasionally the immediate cause of some local potential field anomalies. The potential field method could be used more effectively as a direct indicator when the mapping equipments are logged through wells. Although this approach is expensive, it is nevertheless reliable as it detects distinct variations in the physical properties of subsurface strata.

3.2: Indicator Maps

The indicator maps comprise the lineament and lineament density maps, Bouguer anomaly, total field aeromagnetic and geological maps. Although most of these maps have been given regional explanatory and quantitative interpretations by their compilers, a brief outline of each of them especially in relation to mineral occurrences are discussed here. The lineament map has been further analysed for ease of correlation. The geological map has already been discussed in the previous chapter (i.e. chapter two).

3.2.1: Lineament and lineament density maps

The lineament map (fig.3.2) shows that the rocks in the country's landmass have been subjected to differing intensities of deformation throughout their geological period. Consequently, the lineaments have a variety of structural trends: N-S, NE-SW, NW-SE and E-W (Oluyide and Udoh, in Press). The lineaments are of sufficient prominence and length and they cut across both basement and sedimentary rocks. The basement areas have high occurrences of lineaments than the sedimentary region. The Jos Plateau is unique for its ring structures, cauldron subsidence and emplacement of anerogenic granites. In the Benue trough (see fig.2.1), the lineament patterns in the northern part is however more complex than in the southern part. *The large dotted circles on the map (fig. 3.2) are* selected exploration targets. These areas have a high concentration of intersecting lineaments.

Lineament analysis particularly in relation to mineral occurrence is best achieved by first computing the lineament densities (ℓ) at grid interval over the study area and subsequently presenting the data in a map form. Lineament density is the summed length of lineaments within a specified grid per unit area of the grid (Karcz, 1978). This approach has been employed to further analyse and interprete the lineament map. Firstly, the project area was divided into seventy-eight (78) $1^{\circ} \times 1^{\circ}$ cell with each having an average area of approximately 12321 km^2. The summed length in

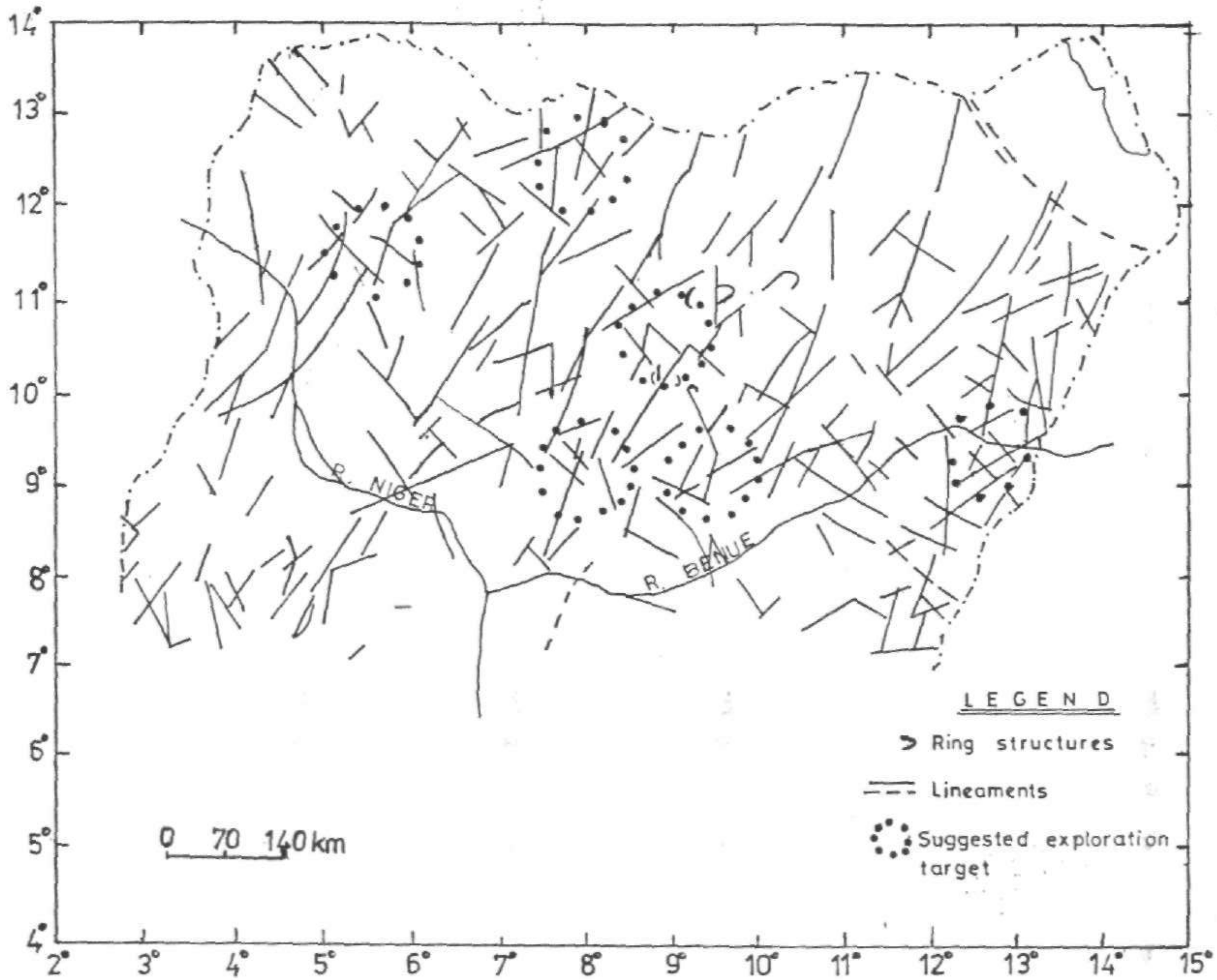


FIG. 3.2: MAJOR LANDSAT LINEAMENTS OF NIGERIA (From Oluyide and Udoh in press)

kilometres of the lineaments within each cell was plotted at the centre of the cell. The exercise was carried out for all the cells and the data contoured at 0.0025 contour intervals as shown in figure 3.3. On this map, states within the central basement (i.e. Bauchi, Benue, Gongola, Kaduna, Plateau and Sokoto States) have a high lineament density ($\rho_L \geq 0.00014$ km/km^2) while those in the sedimentary regions (i.e. Borno and Niger States) are characterized by a low lineament density ($\rho_L \leq 0.00007$ km/km^2).

3.2.2: Bouguer Anomaly Map

The Bouguer anomaly maps (figs. 3.4a-c) indicate variations in the density of rocks caused by geologic or lithologic changes. The maps cover some parts of the central basement, Chad basin and Benue trough (fig. 3.4a); Nupe basin (fig. 3.4b); and the Quaternary-basement area of Kano State (fig. 3.4c). The trends of the anomalies are NW-SE in the central basement, Nupe and Chad basins, and NE-SW in the Benue trough, Chad basin and the Quaternary basement area of Kano State. The dashed lines on these maps are lineaments while the others are subtle lineaments. Both represent either aligned gravity highs or lows.

There is a general negative Bouguer anomaly within the central basement of Northern Nigeria; the Younger granite areas are characterized by largely negative Bouguer anomalies (-90 to -60 mgals) with moderately negative Bouguer anomalies (-60 to -30 mgals) on either side. In the Chad basin, there

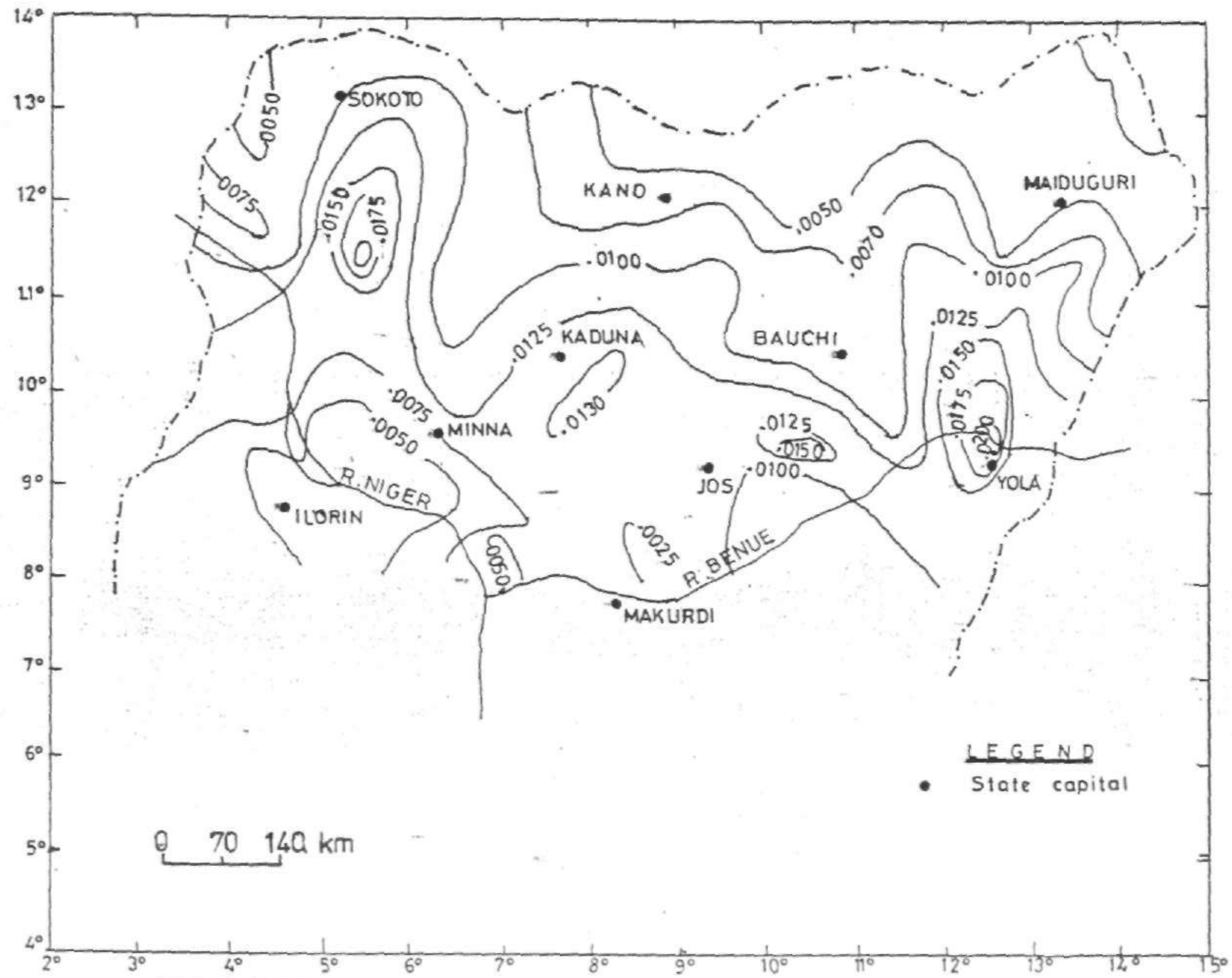


FIG.3.3 LINEAMENT DENSITY MAP OF NIGERIA (Compiled from fig.3.2)
(Actual density is obtained by multiplying the values by 0.014)

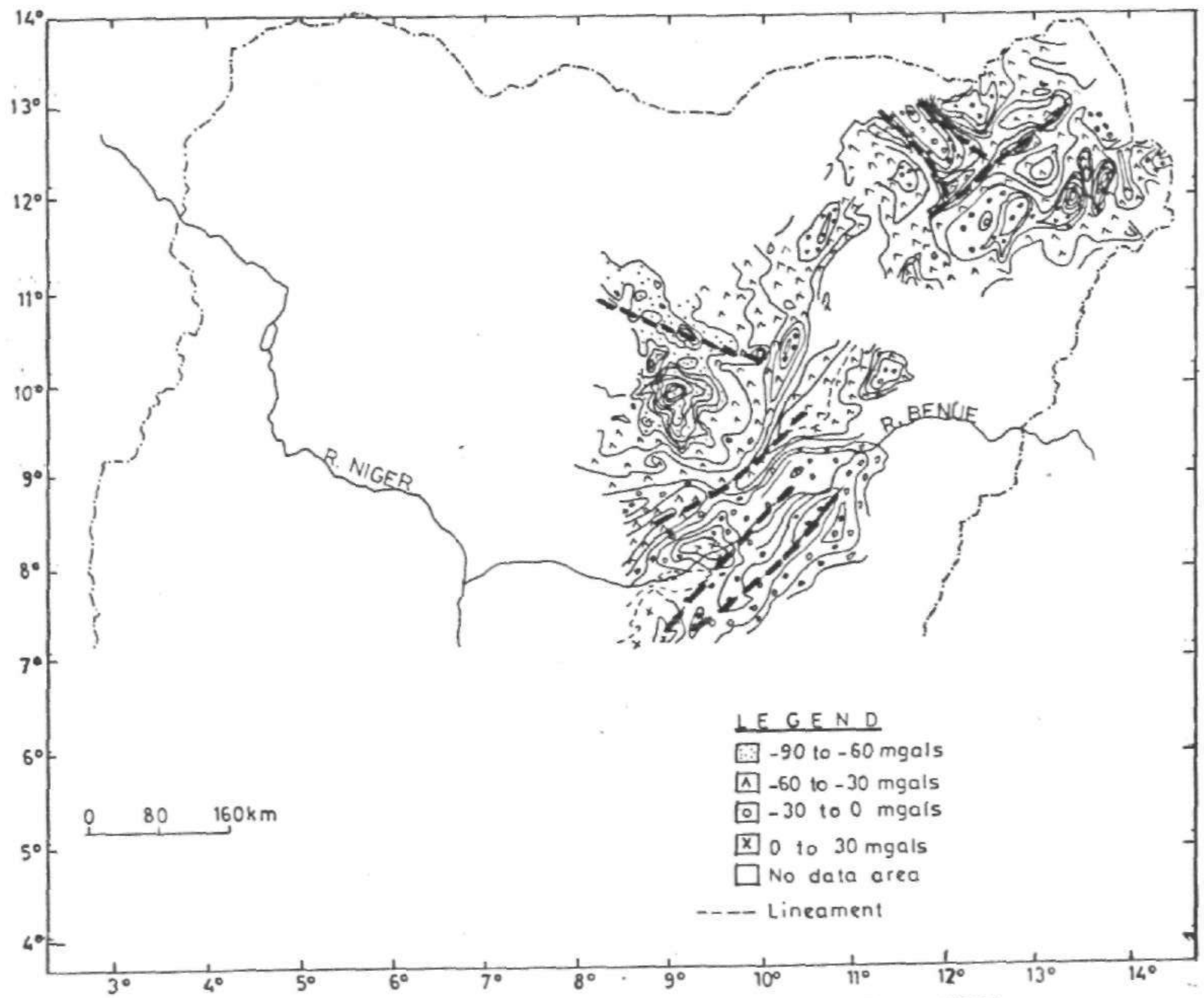


FIG.3.4a ; BOUGUER ANOMALY MAP OF NIGERIA (From Ajakaiye and Burke, 1973)

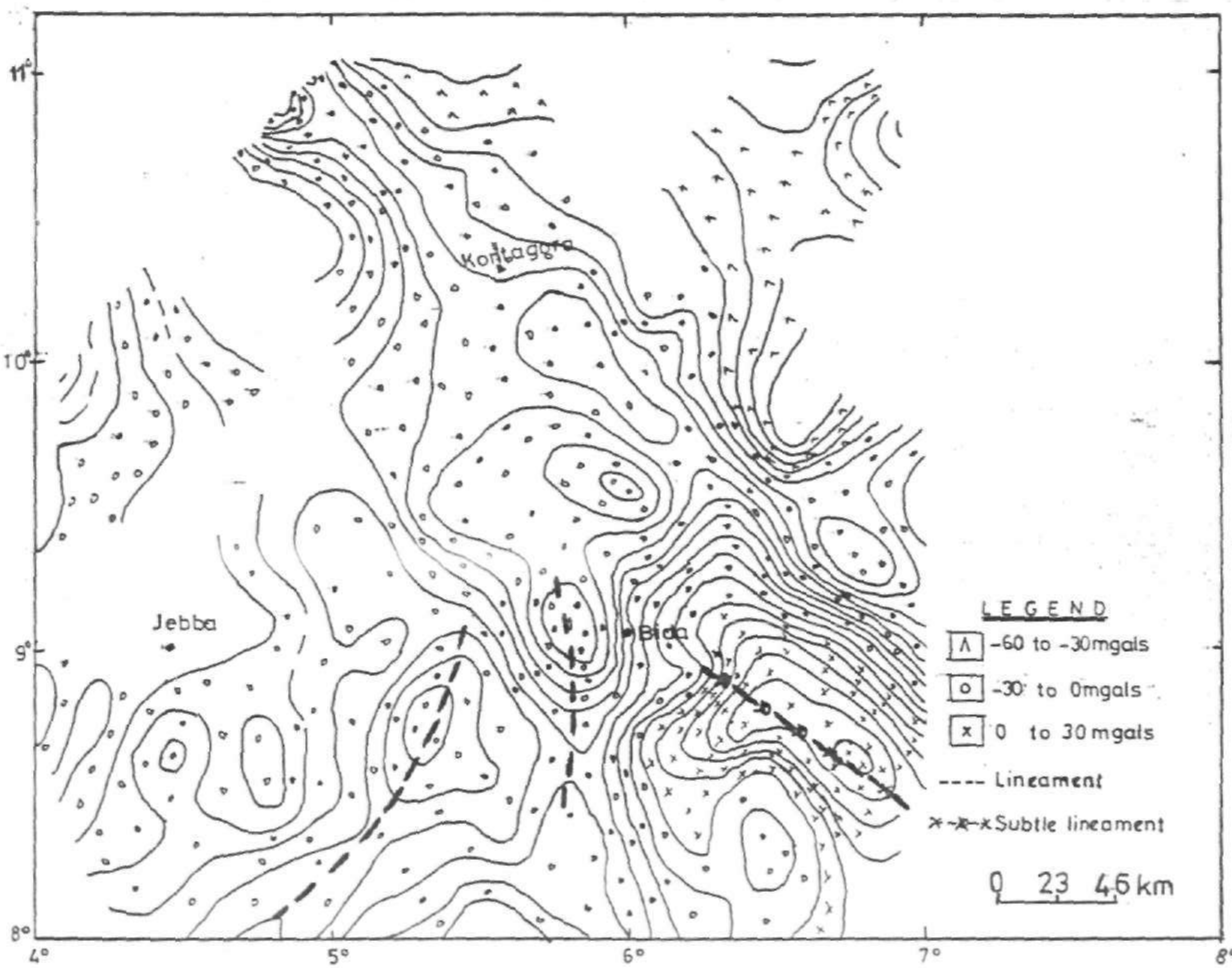


FIG. 3-4b : BOUGUER ANOMALY MAP OF NUPE BASIN (From Ojo, 1984)

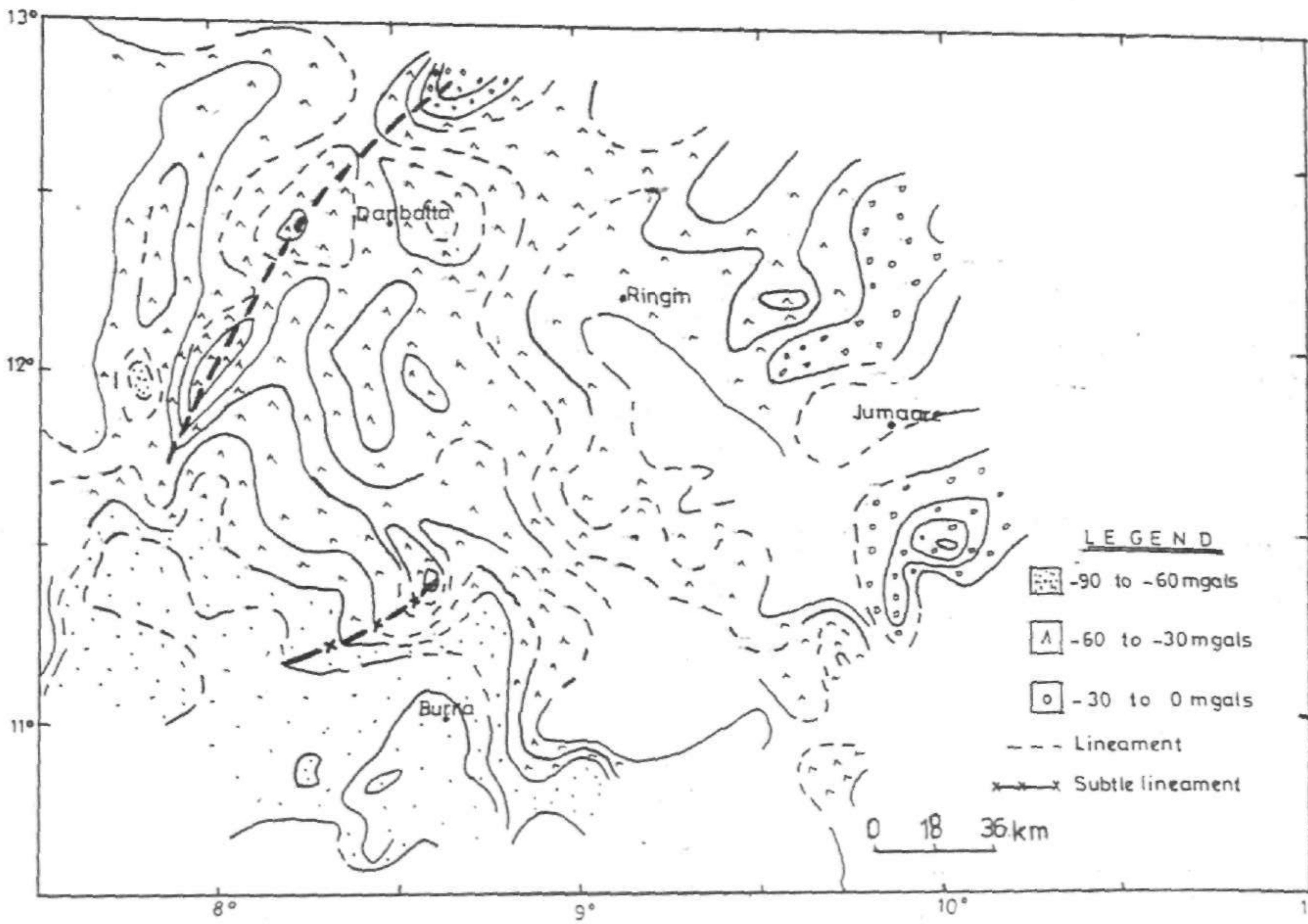


FIG. 3·4c : BOUGUER ANOMALY MAP OF THE QUATERNARY BASEMENT AREA OF KANO STATE
(From Ajakaiye and Verheijen, 1977)

are moderately negative and low negative (-30 to 0 mgals) Bouguer anomalies with the former predominating. The Nupe basin and the basement complex south of it are characterized by a central low positive Bouguer anomaly (0 to 15 mgals) with low negative Bouguer anomalies on either side. In the Benue trough, there are also low positive Bouguer anomalies within the vicinity of low negative Bouguer anomalies.

The large negative Bouguer anomaly with a very high gravity gradient in the Jos Plateau environ (fig. 3.4a) is attributed to the presence of relatively low density granites in this area. However, the low positive Bouguer anomalies in Benue trough (fig. 3.4a) and Nupe Basin (fig. 3.4b) may be attributed to large scale thinning of the crust with a relatively small thickness of sediments overlying it or be due to the presence of marine crust, a characteristic of areas where marine regression had taken place. Folding in the trough is indicated by aligned gravity highs (0 to 30 mgals), while shift in the courses of rivers Niger and Benue corresponds to bends in the gravity contours. This therefore suggests that the courses of these rivers are along negative topographic features. The presence of the Benue trend in the Chad basin may be due to the extension of Cretaceous sediments in the Benue trough beneath the Quaternary sediments of the Chad basin. Furthermore, the high gravity gradient in the area south of longitudes 13^{o} - 14^{o}E and latitude 12^{o}N (fig. 3.4a) could be associated with igneous intrusions

3.2.3: Aeromagnetic Map

An aeromagnetic map essentially displays variations in the magnetic properties of crustal rocks expressed in units called gammas. High intensity of magnetization is typical of mafic rocks such as basalts that have high concentrations of the mineral magnetite. In addition to showing the presence of magnetite rich rocks, it also portrays the configuration of the crystalline basement rocks.

The aeromagnetic data in this study consists of a total field aeromagnetic map that extends from longitudes 5^{o} - 12^{o}E and latitudes 8^{o} - 12^{o}N (fig. 3.5). The coverage is restricted to this area because of its high mineral density. The area between longitudes 7^{o} - 12^{o}E and latitudes 7^{o} - 12^{o}N was published by Ajakaiye et al (1986), while the rest was compiled by sampling the aeromagnetic maps released by Geological Survey of Nigeria at 3 km interval with the results contoured and finally matched with the area previously published. The total magnetic field has values ranging from 31640 γ to 33250 γ and an average value of 32445 γ. The areas with high intensity of magnetization ($I > 32780\ \gamma$) extend over a wide region and they encompass areas with low intensity of magnetization ($I < 32780\ \gamma$). One of the most striking features is a series of magnetic anomaly belts (lineaments) mostly trending NE-SW. Those within the previously published area

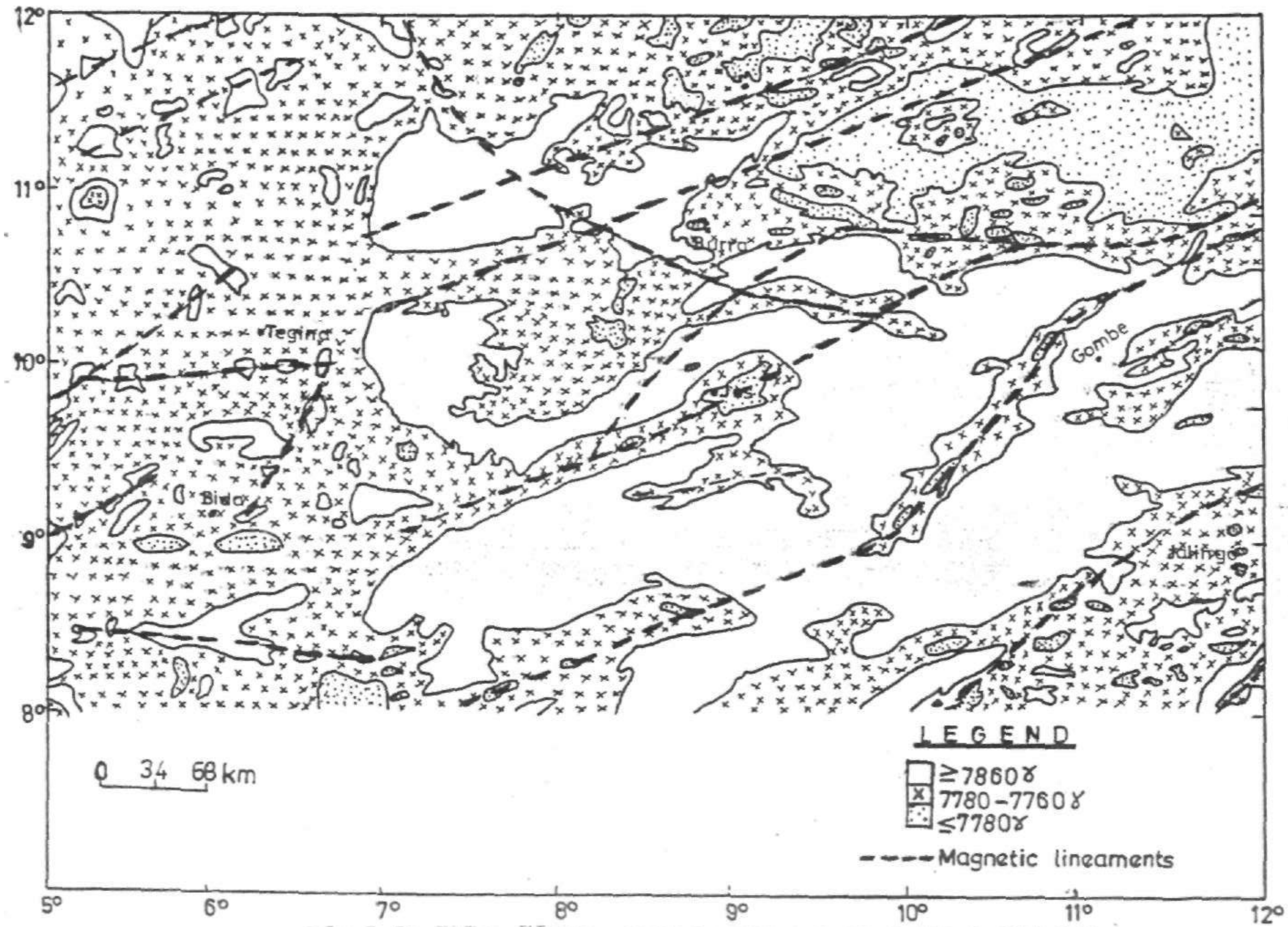


FIG.3.5: TOTAL FIELD AEROMAGNETIC MAP OF CENTRAL NIGERIA
(A value of 25000γ was subtracted from the actual magnetic field values)

were inferred by Ajakaiye et al (1986) and they are alignments of magnetic lows while those in the remaining part are alignments of magnetic highs. Both indicate the structural trend of the basement rocks.

However, there is a reason to believe that the behaviour of the magnetic field is such that describes the undulation of the basement topography. Where the basement rocks are deeply buried beneath a thick sedimentary cover, the intensity of magnetization is lower than in areas where the sedimentary cover is thin.

CHAPTER FOUR

CORRELATIONS

4.0: Introduction

A broad correlation is made in this chapter between the indicator maps and the mineral occurrence map. The correlation is on the basis of the parameters earlier enumerated. Also an attempt has been made to cross-correlate the structural features in the indicator maps in order to ascertain and substantiate the correlation.

4.1: Correlation

The superimposed map of Landsat lineaments and mineral occurrences (fig. 4.1a) show the occurrence of some minerals in the vicinity of fracture zones. A preliminary analysis indicate that 45% of the mineralization zones occur within 14 km of the lineaments. Minerals that correlate well with this indicator include lead and zinc, tantalite, cassiterite, columbite, wolframite, bismuthinite, copper ores, gold, molybdenite, kyanite and sillimanite while areas with barytes, feldspars, uraninite, iron and some gold show no conspicuous correlation. The mineralized lineaments have lengths in the range of 0 - 490 km of which the 70 - 210 km range are predominant (fig. 4.1b). Mineralization zones have a high lineament density; $\rho_L \geq 0.00014$ km/km^2 (fig. 4.1c) and they fall on or along lineaments with NE-SW and NW-SE trends. Of the six selected target areas (fig. 4.1a) only four targets

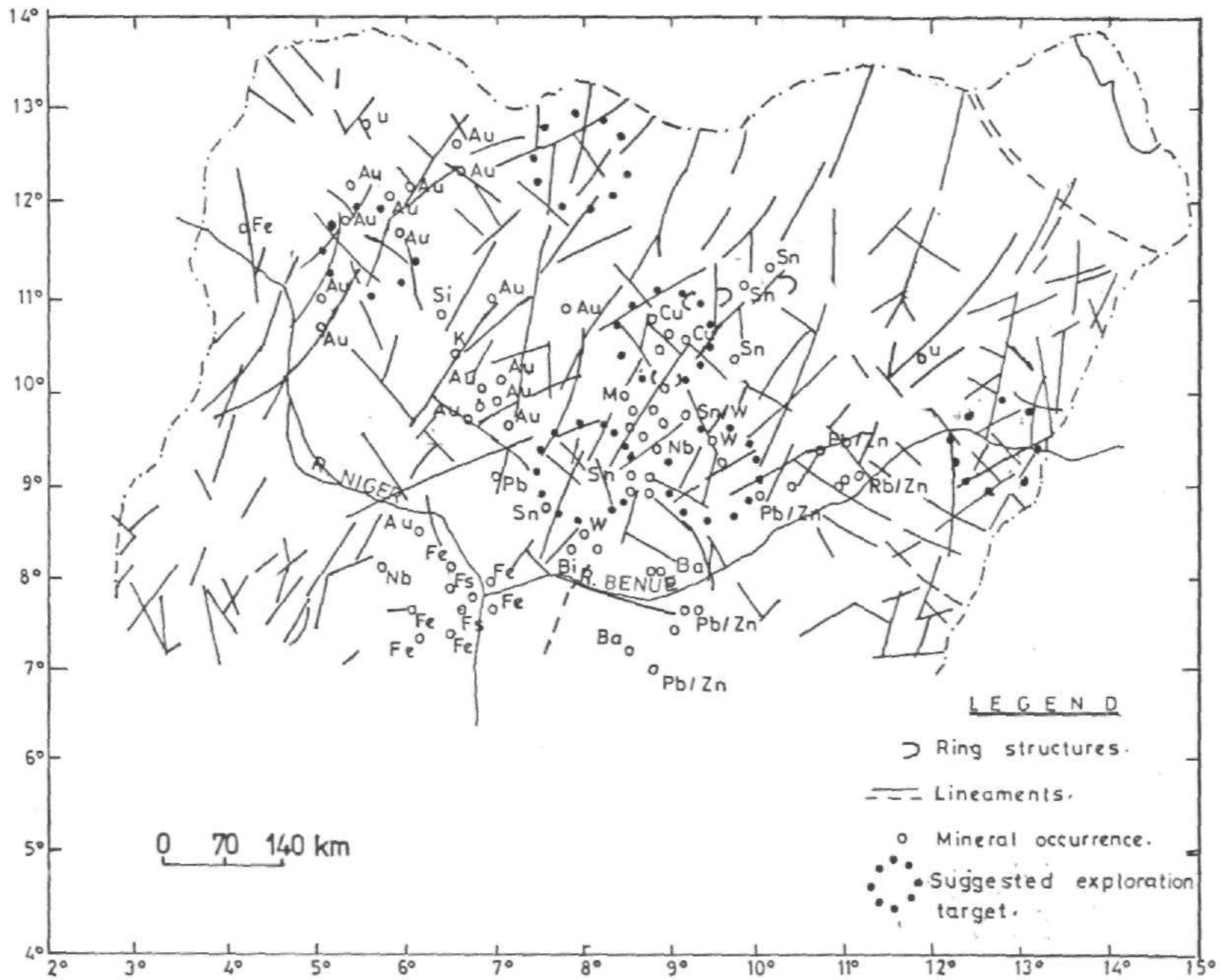


FIG. 4la: A CORELATION MAP OF LANDSAT LINEAMENTS AND MINERAL OCCURRENCES (From figs 2.2 and 3.2)

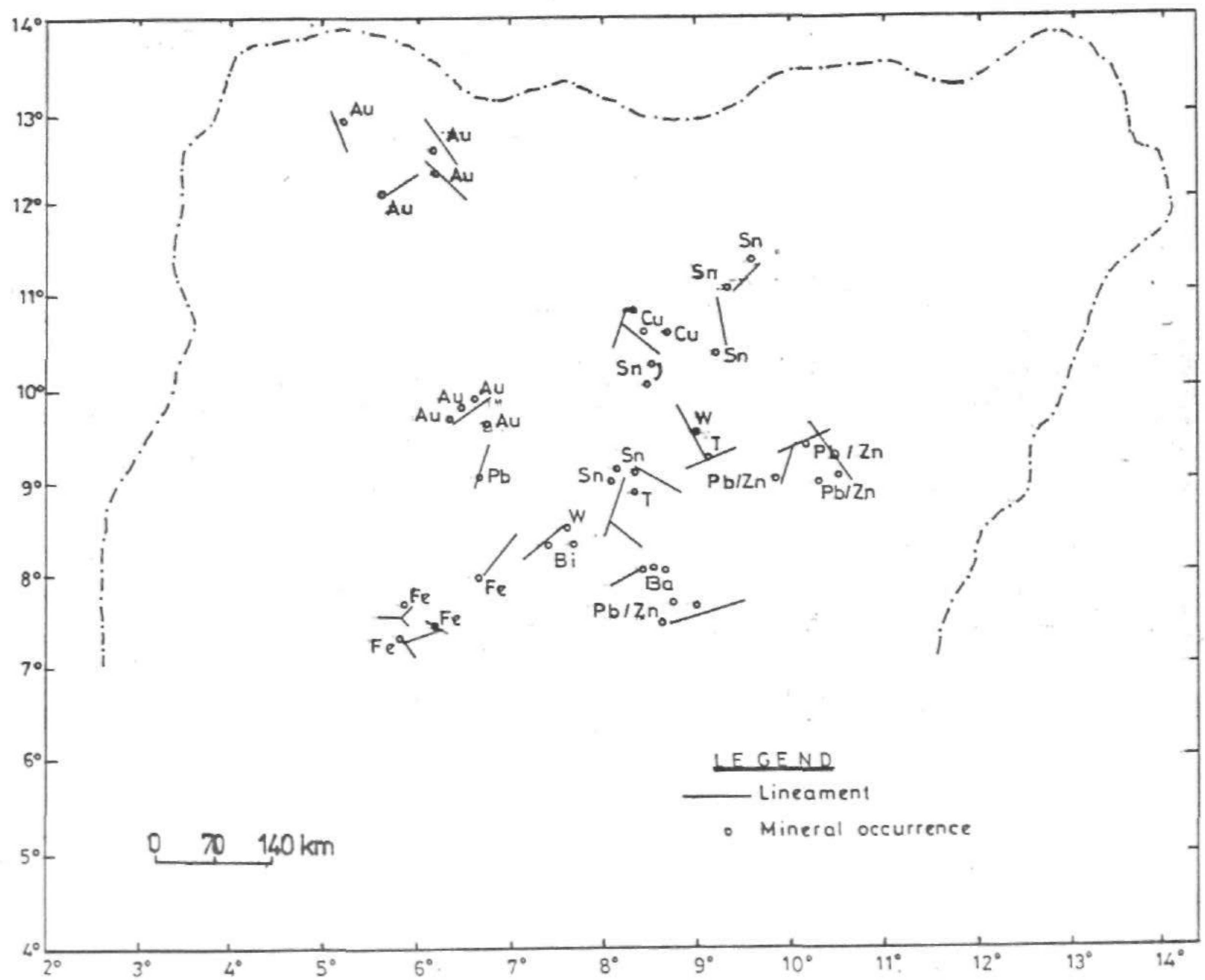


FIG 4.1b MAP OF PREDOMINANT MINERALIZED LINEAMENTS (From fig. 4.1a)

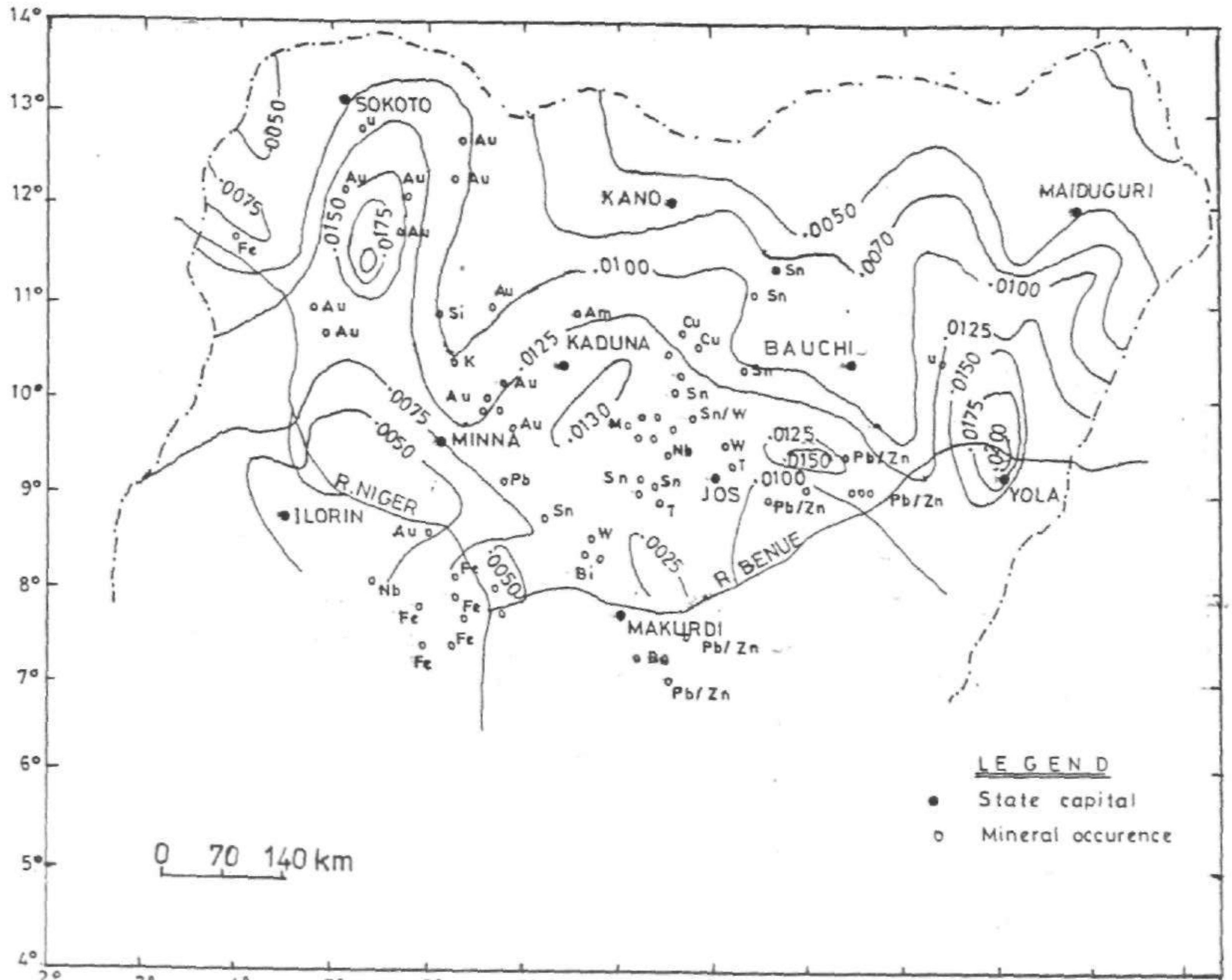


FIG.4.1c: A CORRELATION MAP OF LINEAMENT DENSITY AND MINERAL OCCURRENCES
(From figs. 2.2 and 3.3)
(Actual density is obtained by multiplying the values by 0.014)

coincide with mineralization zones. The other two targets without known mineralization may be the site of undiscovered ore deposits.

A comparative analysis of the Bouguer anomalies and mineral occurrence maps (Fig. 4.2) indicate some correspondence between Bouguer anomalies and mineral occurrences. Minerals like columbite, copper ores, cassiterite, wolframite, and molybdenite occur in areas with largely negative Bouguer anomalies (-90 to -60 mgals). The moderately negative Bouguer anomalies (-60 to -30 mgals) are within areas with cassiterite, tantalite, lead and zinc mineralization while the low negative Bouguer anomalies (-30 to 0 mgals) correspond to areas with baryte, gold, columbite, lead and zinc. Although most of the lineaments inferred on this map show no conspicuous correlation with mineral occurrences, minerals like copper ores, barytes, cassiterite, lead and zinc tend to show a correspondence with a few of the lineaments. As a corollary to this, a structural relationship appears to exist between lead and zinc mineralization and the axial gravity highs in the Benue trough.

The correlation map of mineral occurrences and total field aeromagnetic intensity (fig. 4.3) reveal that most of the mineralization zones are within areas with high intensity of magnetization. Minerals like cassiterite, columbite, baryte, wolframite, tantalite, copper ores, molybdenite, lead and zinc, gold, kyanite and sillimanite are within areas having their intensity of magnetization greater than or equal

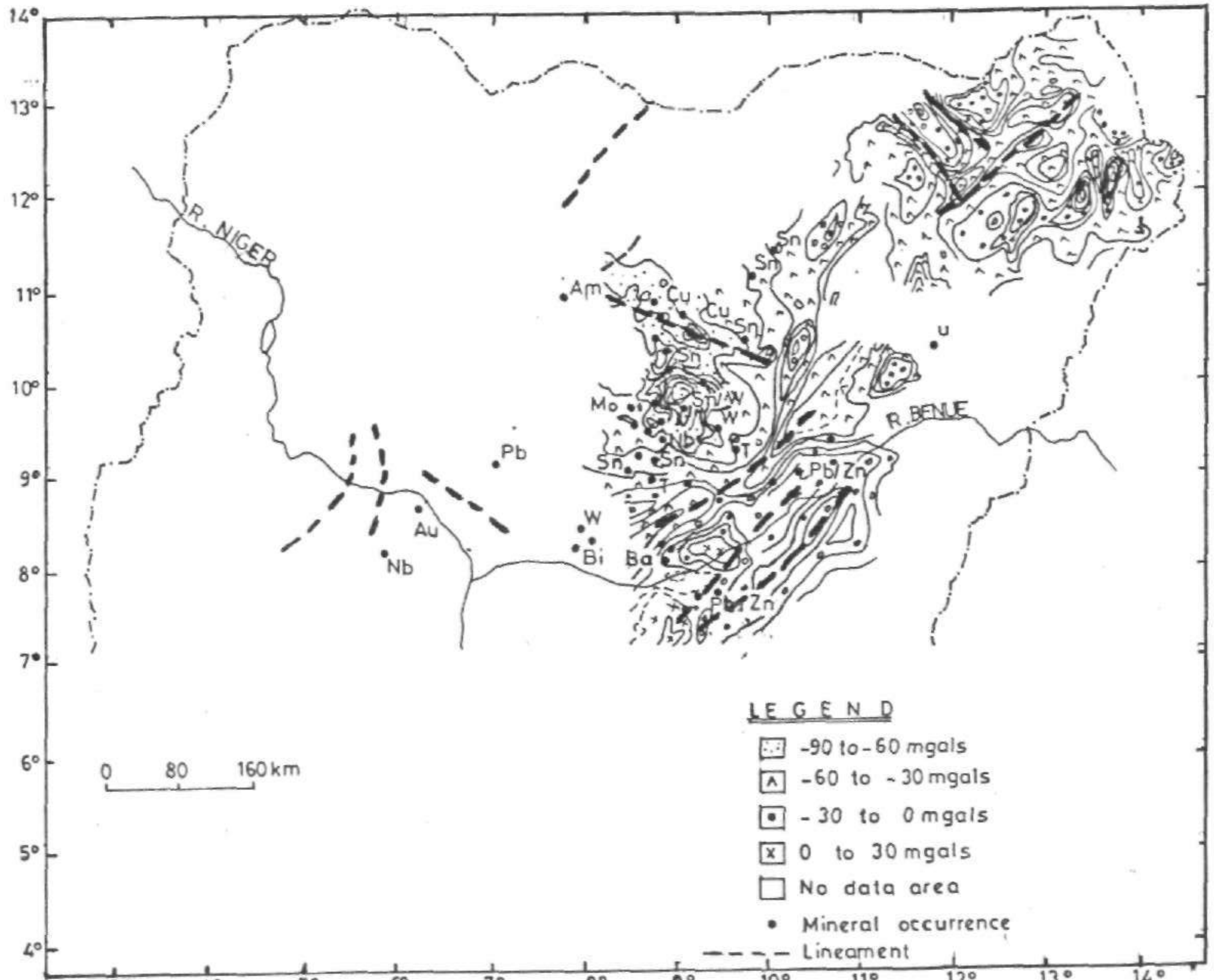


FIG. 4.2: A CORRELATION MAP OF MINERAL OCCURRENCES AND BOUGUER ANOMALIES
(From figs. 2.2 and 3.4a–c)

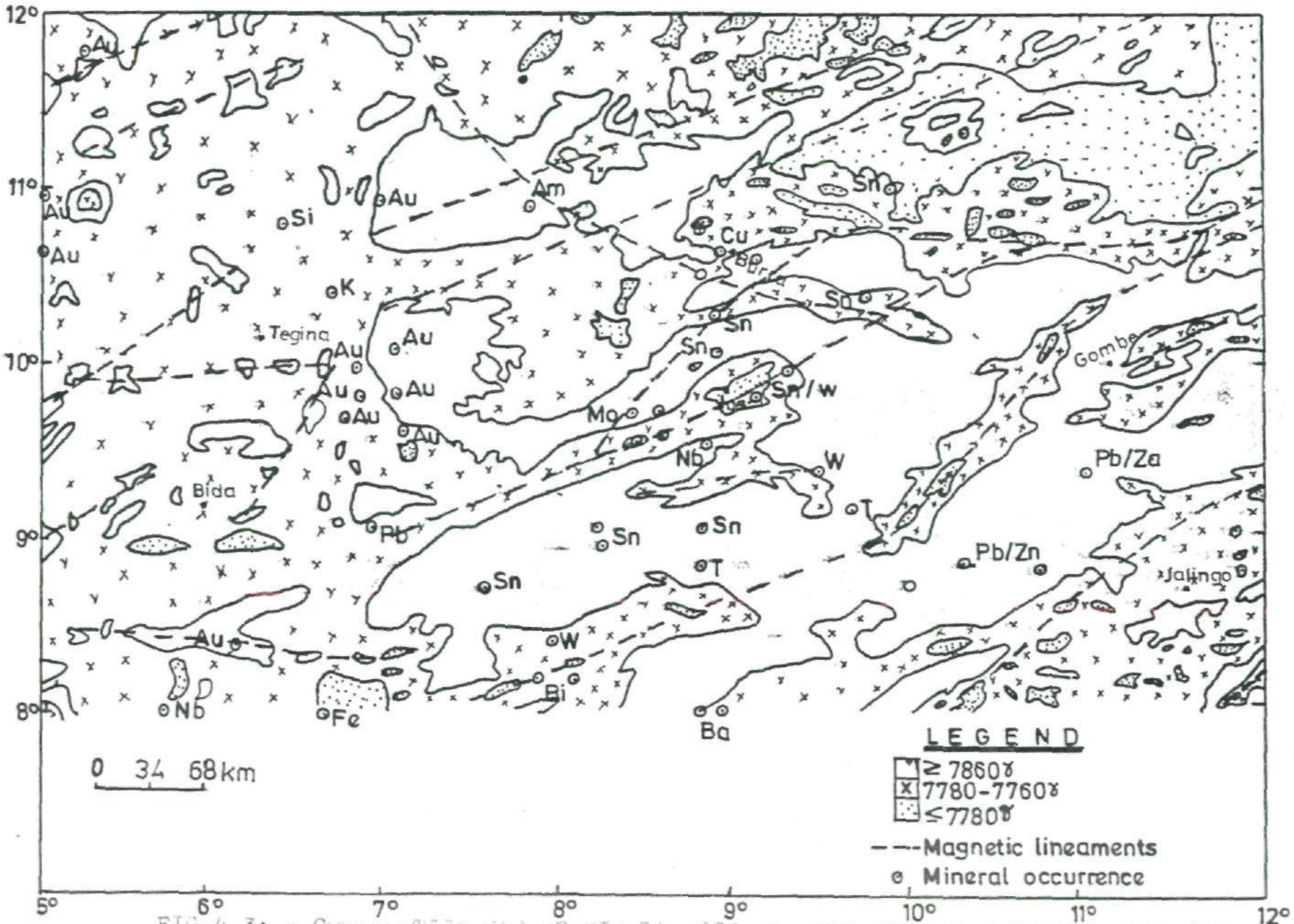


FIG.4.3: A CORRELATION MAP OF MINERAL OCCURRENCES AND AEROMAGNETIC ANOMALIES
(From Figs.2.2 and 3.23)
(A value of 25000 γ was subtracted from the actual total magnetic field values)

to 32780 γ. The magnetic lineaments show a correpondence with gold occurrences in the schist belt, and the cassiterite, wolframite and molybdenite mineralization zones in the Younger granite environ. On the other hand, the correlation map of mineral occurrences and geological environment (fig.4.4) indicate the confinement of metalliferous minerals to the basement areas. The mineral density is higher in the Younger granite province than any other area of the basement complex. Furthermore, some minerals are restricted to a specific geologic environment as it is with gold, kyanite and sillimanite in the schist belt; lead, zinc, baryte and bismuth in the Benue trough; molybdenite, wolframite, tantalite, columbite, cassiterite and copper ores in the Younger and Older granites; uraninite, iron, feldspars and some gold in sandstone regions. Finally, the configuration of the present known deposits especially in the ring complexes (Pastor and Turaki, 1985) are in consonance with those compiled by Sinkankas (1966). Table 4.1 shows the mineralization in the Nigerian ring complexes and their associated configuration.

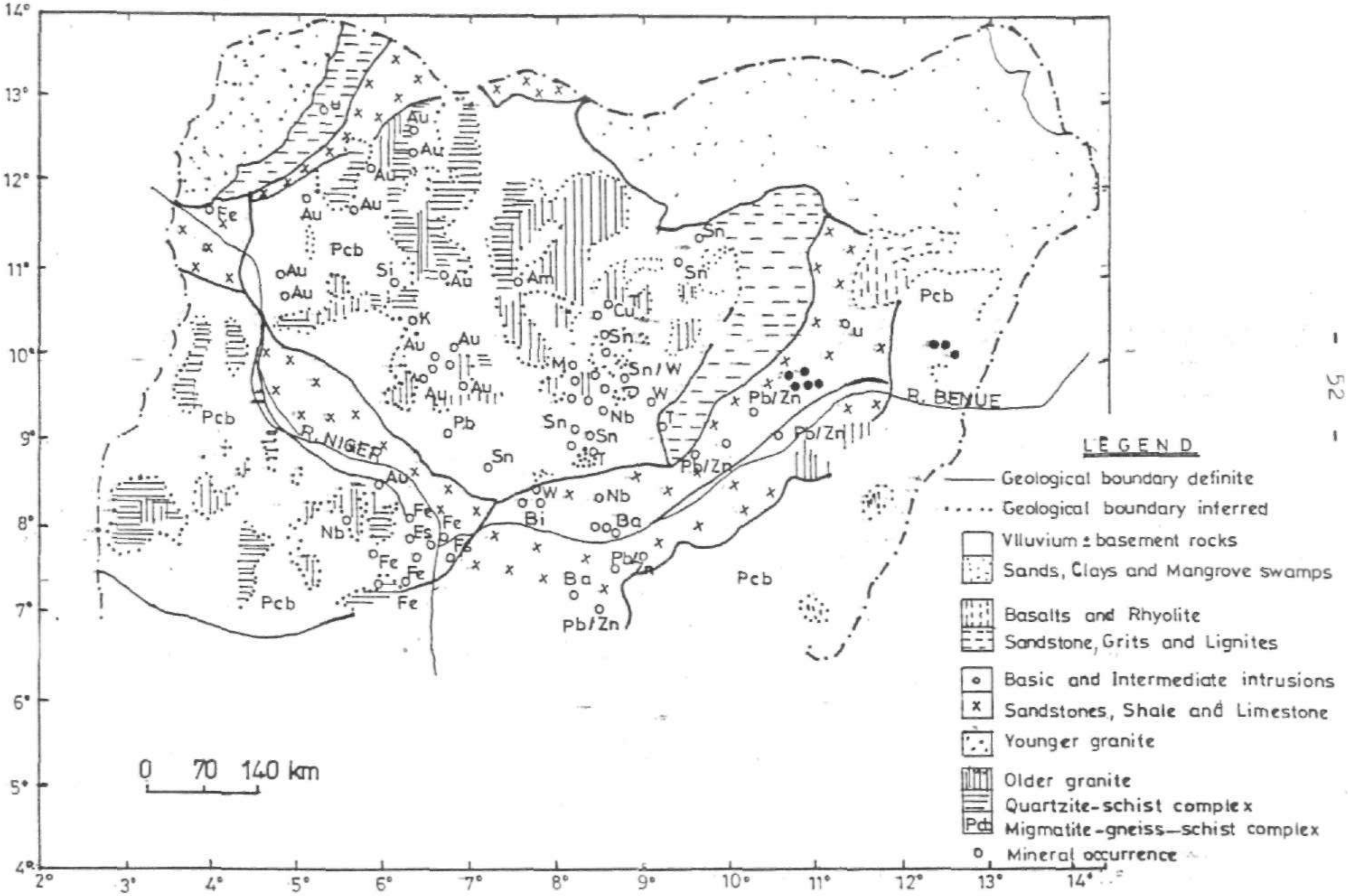


FIG. 4.4: A CORRELATION MAP OF MINERAL OCCURRENCES AND GEOLOGY (From figs. 2.1 and 2.2)

Table 4.1: Primary mineralization in Nigerian Ring Complexes

(From Pastor and Turaki, 1985).

Stage	Mineral	Shapes of mineralized body	Process
Early Cassiterite	Cassiterite, ilmenite, Zircon, magnetite ± columbite ± minor sulphides ± minor wolframite.	Dissemination of irregular shapes	Late magmatic to early post magmatic.
Greisen	Quartz, Chlorite, sericite, topaz, trioctahedral micas, fluorite, cassiterite, wolframite	Vein-like greisen bodies	
Sulphides	Sphalerite, galena, chalcopyrite, pyrite, stannite, arsenopyrite, bismuthinite, molybdenite, pyrite, marcasite, pyrrhotite, ilmenite, cassiterite, wolframite, quartz, cubanite.	Fissure - filling veins and veinlets	Hydrothermal
Late Quartz - Cassiterite-wolframite	Quartz, Cassiterite, Wolframite, ilmenite ± columbite ± minor sulphides	Comb textured veinlets, stringers, rarely veins.	

In conclusion, the mineralization zones are along linear zones along which epigenetic mineral occurrences or deposits of a particular paragenesis are found. The behaviour of both potential fields within some of the mineralization zones are such that suggests the occurrence of negative topographic features (i.e. fractures).

4.2: Cross-correlation

Despite the fact that there is a correspondence between mineral occurrences and Landsat lineaments, the predominant mineralized lineaments show no conspicuous correlation with those of their potential field analogues (fig.4.5). This could mean that the potential field lineaments are mere geophysical trends that may not necessarily be associated with structural features. However, a correspondence is evident between magnetic and gravity lineaments. Moreso, most of the selected exploration targets occur in areas where potential field lineaments are evident. Therefore, one should not necessarily dismiss the possible relevance of these trends to mineral occurrences.

The above therefore suggest a positive correlation between exploration targets and potential field lineaments and a correspondence between gravity and magnetic lineaments.

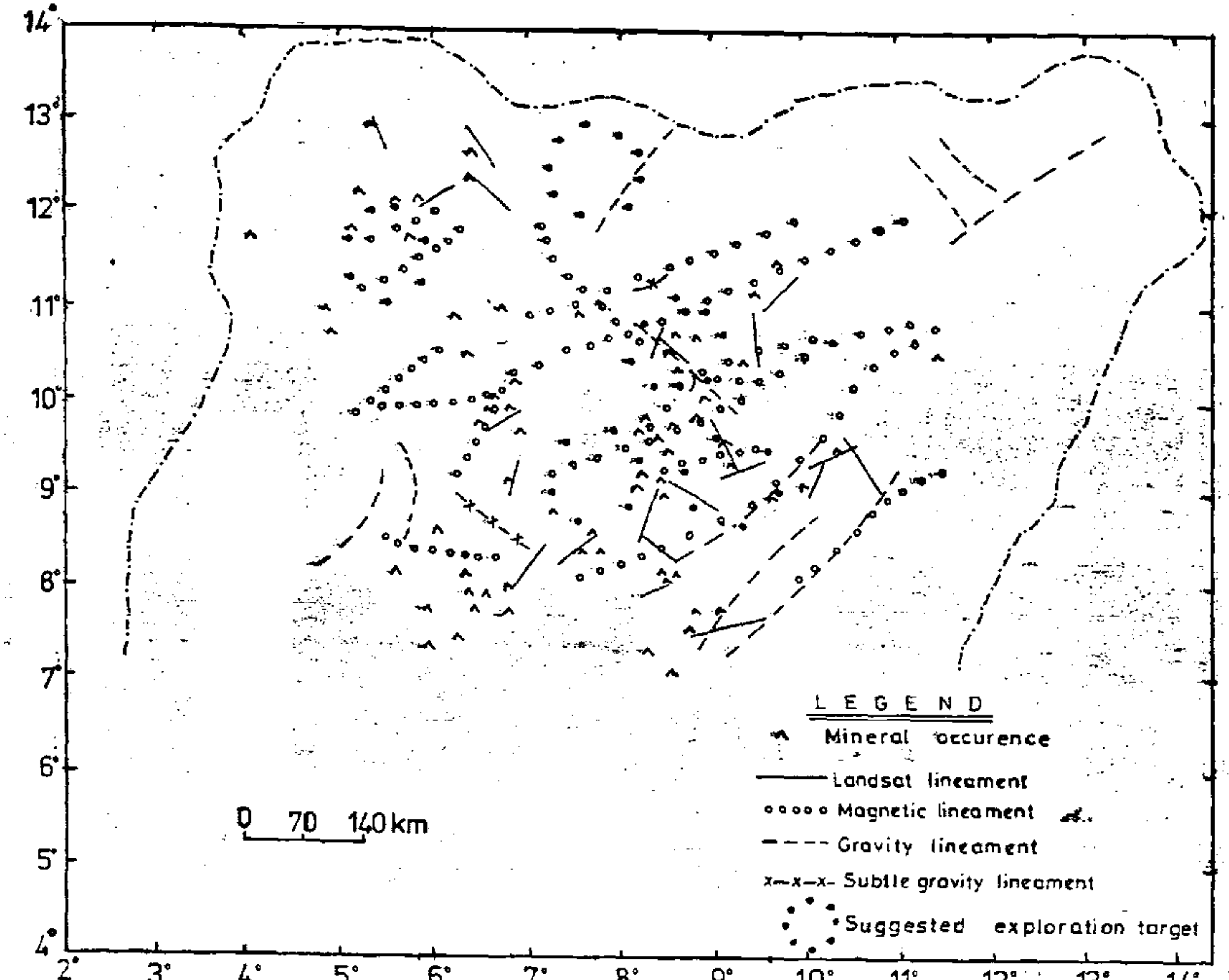


FIG. 4.5: CROSS—CORRELATION MAP OF POTENTIAL FIELD LINEAMENTS AND PREDOMINANT MINERALIZED LINEAMENTS.

CHAPTER FIVE

DISCUSSIONS, CONCLUSIONS AND RECOMMENDATIONS

5.1: Discussions

This study illustrates the reconnaissance use of structural features in ascertaining the structural control of mineral deposits. The minerals chosen for the correlation are those that have been found associated with fracturing. These minerals are apparently related to deep-seated structural features such as lineaments which might have acted as heat/fluid passage ways leading to the mobilization of these minerals in the crust. As a result, the structural features (i.e. lineaments) should not be viewed only as indicators of fundamental boundaries indicating blocks that might have experienced differing tectonic histories but also as pathways for mineral movements and foci for their concentration. The other three indicators were employed so as to integrate their results with those of lineament analyses in order to substantiate the correlation, and determine if a correlation exists between them and the mineralization zones. However, no attempt has been made to classify the lineaments either as joints or faults; only field checking can distinguish between them.

The lineament map adopted (fig. 3.2) represents macro-structures only, likewise the lineament density map (fig. 3.3). The latter correlated relatively well with that of Ananaba's (1983) except that areas with known mineral occurrences have their lineament density $\rho_L \geqslant 0.00014$ km/km^2 in the present study and $\rho_L \geqslant 0.0300$ km/km^2 in that of Ananaba (1983). The discrepancy in the density might be as a result of mapping macro and micro structures in the latter. It is however not known what might have been responsible for a variety of Landsat structural trends. Ball (1980) attributed the N-S trend to a product of brittle deformation and the others (i.e. NW-SE, NE-SW and E-W) to have resulted from transcurrent movements. The occurrence of these lineaments in both sedimentary and basement regions and their extension from the former to latter or vice versa supports the suggestion of McCurry (1973) that most parts of Northern Nigeria are underlain by the basement rocks. Moreso, the relatively high lineament density (i.e. $\rho_L \geqslant 0.00014$ km/km^2) in the target areas and the area south of latitude 11°N (Figs. 4.1a and 4.1c) could be attributed to the occurrence of igneous activities as suggested by the geological map, while the presence of ring structures within the vicinity of Jos Plateau is associated with the emplacement of near-circular porphyritic intrusives (i.e. Younger granites). Minerals that do not show conspicuous correlation with lineaments (i.e. baryte, feldspars, uraninite, iron ores and some gold) may occur chiefly in sedimentary regions. Furthermore, the occurrence of mineralization zones within 14 km of lineaments supports Woakes' (1986) deduction that mineral belts are along linear structures.

Although the significant parameters in both the potential field maps are different, a correspondence appeared to exist between them. Both maps are congruous with: undulation of the basement topography and outline of the ring complexes (Ajakaiye, 1970; Ajakaiye and Burke, 1973). Moreso, folding in the Benue trough as suggested by the gravity field is in line with Wright's (1976) hypothesis that the trough is strongly folded. Bends on the gravity contours as a result of shift in the courses of rivers Niger and Benue suggest a structural control of drainage patterns. These observations could not be made from the aeromagnetic map because of its coverage and high contour interval (80γ). Moreso, the coverage of the Bouguer anomaly map in Nupe basin (Fig. 3.4b) is not enough to indicate whether the subtle gravity lineament is continuous along the whole central basin. Furthermore, the non-correlation of the few potential field lineaments with mineral occurrences might be due to the fact that the geophysical trends are caused by lithologic changes. The Bouguer anomaly map (3.4a) showed that the Jos Plateau has a high concentration of granites (Ajakaiye and Burke, 1973) with a lower average density than their host rocks (Ajakaiye, 1970). The high concentration of minerals in this area could be attributed to the reactivation of deep-seated fractures coupled with mobilization of mineral rich magmatic hearth during and after the Pan-African Orogeny (Bowden, 1985) or be due to the known affinity of mineralization zones for volcanic necks, pipes, caldera, ring-dyke complexes, alteration zones around intrusive bodies and near-circular porphyritic intrusives as are evident in the Younger granite province (Woakes, personal communication).

Generally therefore, the occurrence of minerals in specific geologic environment conforms with the rock-mineral relationship given by Sinkankas, 1966 (Table 3.1). At present no general classification or theory of occurrence of minerals with respect to potential field anomalies has been presented. Each could therefore be studied individually in the context of its local setting. For example copper, kyanite, gold, sillimanite and uraninite are not magnetic, their occurrence in areas with high intensity of magnetization could be attributed to their existence with other magnetic minerals or their host rocks could be magnetic. Finally, it is likely that this study will have an increasing role to play in mineral exploration of underdeveloped areas where the existing data are scarce as in Gongola and Bauchi States. The difficult terrain and the problem of accessibility could also have contributed to the low level of detailed data available on these areas.

5.2: Conclusions:

The present study was aimed at determining the structural control of mineral deposits in Nigeria through the correlation of some mineral occurrences with the mineral indicator maps. The correlation maps (figures 4.1a-c, 4.2 - 4.4) show the occurrences of minerals in areas with high lineament density ($\rho \geqslant 0.00014$ km/km^2) with large to low negative Bouguer anomalies (-90 to 0 mgals) and with high intensity of magnetization ($I > 32780\gamma$). These regions also fall on or are immediately adjacent to Landsat lineaments with NE-SW and NW-SE tectonic trends (fig. 4.1a). The mineralized lineaments have lengths in the range of 0 - 490 km of which the 70 - 210 km range are predominant (fig. 4.1b). Minerals like lead, zinc, cassiterite, copper ores, columbite, wolframite, molybdenite, kyanite, bismuthinite, sillimanite and gold correlate well with the occurrence of these lineaments while baryte, feldspar, uraninite and some other gold occurrences show no conspicuous correlation. A preliminary analysis indicated that 45% of the mineralization zones are within 14 km of the mineralized lineaments. On the other hand, largely to low negative Bouguer anomalies (-90 to 0 mgals) are within areas with cassiterite, copper ores, molybdenite, columbite, lead, zinc, gold, wolframite, tantalite and baryte. The lineaments on this map showed a correspondence with occurrence of copper ores, cassiterite, baryte, lead and zinc mineralization. On the total field aeromagnetic map (fig. 4.3) minerals like cassiterite, columbite, baryte wolframite, tantalite, copper ores, molybdenite, lead, zinc, gold, kyanite and sillimanite are within areas with high intensity of magnetization ($I > 32780\gamma$). The magnetic lineaments showed a correspondence with the occurrences of gold in the schist belt, and cassiterite, molybdenite and wolframite mineralization zones in the Younger granite province.

Furthermore, most occurrences are restricted to specific geologic environment as it is with gold, kyanite and sillimanite in the schist belt; baryte, lead and zinc in the Benue trough; tantalite, wolframite, cassiterite, columbite, copper ores and molybdenite in the Younger and Older granites; uranium, iron ores, feldspars and some other gold occurrence in areas with sandstones (Fig. 4.4). Finally, the forms of the various known deposits especially in the ring complexes indicated that they were influenced as a result of the space creation. Also, the potential field lineaments showed a correspondence with the selected exploration targets.

In conclusion, the preceeding correlation therefore suggest the localization of mineral occurrences to areas with high lineament density; negative Bouguer anomalies, high intensity of magnetization, linear trends and specific geologic environment. Thus the occurrence of mineralization zones along linear features or within the vicinity suggest the existence of a structural relationship. On these bases, a correlation exist between these structural features and mineral occurrences. As a result, the deposition of the chosen minerals are structurally controlled.

5.3: Recommendations

The results obtained here form a working basis for further studies and are not necessarily definitive. Detailed ground truth studies are required to verify them. The following recommendations for future research are hereby suggested:

(i). Effort should be made to purchase colour composite Landsat images for areas along the Nigeria - Cameroon border and the two target areas without known mineralization in order to detect sharp intrusive contacts for possible mineralization.

(ii). Effort should be made to map out the economic mineral potentials of the Chad basin and areas along the Nigeria - Cameroon border in order to ascertain its structural relationship with the Benue trough.

(iii). Effort should be made to carry out more detailed ground geophysical surveys aimed at prospecting for minerals associated with igneous intrusives in the two selected targets without knwon mineralization.

(iv). Effort should be made to investigate the metallogenic characters of the Landsat lineaments in order to classify them in terms of their origin, mode of expression or size.

(v). Effort should be made to re-appraise the Bouguer anomaly and total field aeromagnetic maps by purchasing Magsat data for the entire country and by compiling a new Bouguer anomaly map whose observational points are all tied to a reference station.

(vi). Finally, while the study has dealt with area north of latitude eight degrees (8^{o}), effort should be made to extend this work to cover the entire country in order to make a broader correlation.

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