

REGIONAL PHOTOGEOLOGICAL INTERPRETATION
OF THE TECTONIC FEATURES OF THE CENTRAL
NIGERIAN BASEMENT COMPLEX:
A SATELLITE IMAGERY BASED STUDY

A Thesis submitted for the Degree of Doctor of
Philosophy of the University of London.

by

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ABSTRACT

This study is an evaluation of the potentials of satellite images in the regional tectonic studies of a poorly mapped Precambrian terrain. The Nigerian Basement Complex is used as a case study.

The research indicates that the amount and type of geological information obtainable from LANDSAT images depend on many subjective and objective parameters such as the sensor, climatological and human factors. The human factor include the geological background and experience of the interpreter. Generally, LANDSAT images supply data that are unique to the scale of the imagery.

Studies of the Nigerian Basement Complex show that there are many hitherto unrecognised fracture systems and faults, and indicate that these fracture systems probably control the Nigerian mineralisation. The research also shows that there are discrete fault-controlled ensialic low grade metasedimentary troughs in Nigeria, and that elongate porphyritic granites in Nigeria are controlled by these major faults.

Three episodes of folding are suggested by the Nigerian images. The oldest of these three appears luniform in shape on these images. Field checks on the luniform images suggest that they were originally flat-lying nappe-like folds.

The Nigerian low grade metasediments appear to have formed late in the evolutionary history of the Basement.

The research also indicates, for the first time, the locations and types of marginal fractures along the intra-cratonic and folded Benue trough. Data available in the thesis do not support the existing theories about the origin of the trough.

The study outlines the lineament systems of Nigeria. The regularly spaced North-South lineaments appear to be most extensive. Concentrically arranged lineaments considered to have originated from Archaean meteoritic impacts, are discussed in their regional settings. The wider tectonic implications of concentric lineaments are also examined.

LANDSAT images are considered useful in the study of tectonic trends and 'tectonic domains' of the Nigerian Basement and in elucidating the tectonic chronology of events of the study area.

Similarities and differences between the major tectonic elements of Nigeria, as seen from LANDSAT images, and those of the neighbouring West African countries are also discussed.

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P A R T I

CHAPTER ONE

BACKGROUND INFORMATION AND RESEARCH METHODS

1.1. INTRODUCTION

The present study examines the potential and usefulness of satellite images in the tectonic studies of a poorly mapped Precambrian terrain, exemplified by Central Nigeria. Conventional photo-interpretation technique was adopted. This method involved the observation of differences and changes in the grey levels, colours, textural characteristics and geometries of photographic elements. It is a visual-mental process of translating an image into geology. It is therefore obvious that the amount and type of information interpretable from photographs will depend not only on photographic and imaging factors but also on the experience, geological training and motives of the interpreter.

The study is restricted to regional tectonic features. "Regional features" are intended to cover geological features of any size visible on LANDSAT images. The term "tectonics" refers to the study of the major structural features of the Earth's crust. The emphasis in this study is on large scale features. It was conceived that by using small scale satellite images, it would be possible to identify large areas that apparently are

structurally homogenous in Central Nigeria.

The present research was motivated by the absence of co-ordinated geological data over much of the Nigerian basement as well as the occurrence of metasediments in discrete N-S troughs. In the early days of photogeology, Central Nigerian Basement Complex was used as a good area to illustrate some unique advantages of aerial photographs in elucidating structures of a metamorphic terrain (Allum, 1960). The existence of this photogeological research record of a part of Central Nigeria allows for a fair assessment of the types and amount of information obtainable from aircraft and satellite sensor platforms for imaging. Although much of the early photogeological work on Nigeria was localised and concerned primarily with lithological identifications under thick tropical soil developments, research records on fracture traces from air photographs carried out at Imperial College, London, form a useful basis for comparing the types and dynamics of structural features noticeable on satellite and air photographs. Initial results on the arrangement of shear fractures with respect to the principal deforming shear stresses as interpreted from orbital images, were found to agree in many respects with the pattern earlier deduced from air photographs. It was also observed that the geometries of fractures obtainable from the two platforms can be markedly different and that LANDSAT images afford a much more reliable way for inferring directions

of the last movements and relative ages of major structures.

Structural correlation in metamorphic terrains based on metamorphic grades, basement trends and fold orientation are often very unreliable (Park, 1969). Radiometric ages in polyepisodic metamorphic terrains also tend to be misleading because of the tendency for radiometric clocks to be reset by the latest period of metamorphism. An observation from the present study shows that although basement trends and folds could be misleading for correlation purposes, it is possible to divide a Precambrian terrain into tectonic provinces or domains, (Hepworth, 1967), based on the recognition of characteristic fold patterns, trend lines and major rock associations from orbital imagery. Since geological features observed on LANDSAT images are extensive, their characteristics are considered very diagnostic and more useful than outcrop-size structures for regional correlations in a terrain like Central Nigeria. Structural chronology established for Central Nigeria from LANDSAT data seem to throw new light on emerging radiometric ages of the area.

Tectonic features observed on LANDSAT images of Central Nigeria are not evident on published maps. This shows that in areas like Nigeria, where bed rock geology is largely concealed by soils and duricrusts, field geological mapping based on outcrops could be extremely

subjective. The field geologist handicapped by poor rock exposures tends to base his geological information on fragmentary data which in many cases may bear no relationship to bed rock geology. LANDSAT images of Nigeria show many hitherto unrecognised, systematic fracture zones, even in areas believed to be well mapped. These new structures are clearly significant in the correct interpretation of the stratigraphy of the Nigerian basement rocks.

Satellite images are therefore unique in the type of information they offer at their scale, and considering the resolution limitation at present, to one kilometer, they cannot be used for investigations less than that order. As the type and amount of information interpretable from LANDSAT photographs depend on many factors, it is suggested that geophysical information where available should form corroborative evidence of interpreted imagery features.

No sophisticated automatic image interpretation techniques were adopted for the study because automatic image interpretation was still at a very experimental stage.

A glossary of the more specialised technical terms used in this thesis appears at the end of the last chapter.

1.2. THE LANDSAT SYSTEMS

The name LANDSAT is now used instead of ERTS,

an acronym for Earth Resources Technology Satellite, launched by the United States of America on July 23rd, 1973. LANDSAT - 2 currently orbiting round the Earth, like LANDSAT - 1 before it, revolves in a sun-synchronous orbit at an altitude of about 900 kilometers above the ground. The satellite systematically images the Earth's surface once every 18 days acquiring repetitive imagery between latitudes 81°N and 81°S .

The payload of the satellites consist of the three Return Beam Vidicon (RBV) cameras, a Multispectral Scanning System (MSS) and a Data Collection System (DCS). For LANDSAT - 1 whose images have been employed extensively for this research, the RBV cameras became faulty soon after launch but the Multispectral Scanning System continued throughout the life of the satellite to provide high-quality imagery of the earth.

The MSS images the earth in four spectral bands simultaneously in four wavebands as follows:-

- MSS band 4, 0.5 - 0.6 microns wavelength (green)
- MSS band 5, 0.6 - 0.7 microns wavelength (red)
- MSS band 6, 0.7 - 0.8 microns wavelength (red/infra red)
- MSS band 7, 0.8 - 0.1 microns wavelength (infra red)

The MSS contains six detectors per band and scans the earth by means of an oscillating mirror. The ground coverage of each mirror oscillation from west to east, usually referred to as the cross-track swath width, is

185 kilometers. Each mirror oscillation is completed in 73.42 seconds within which the satellite has advanced some 474 meters along its track. The LANDSAT system of scanning is described as contiguous since no spaces are left uncovered between scan lines.

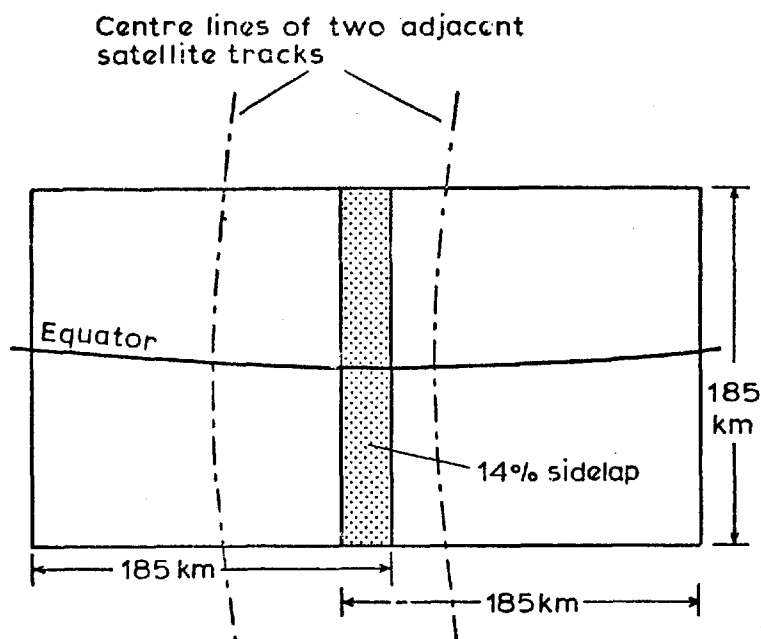
Each sensor detector records the light energy incident on it. This is multiplexed and encoded to form a digital bit stream which is then telemetered to the ground receiving station. When the satellite is far from a ground receiving station, the digital bit stream is recorded on the satellite's wide band tape recorders and subsequently transmitted on reaching a ground receiving station.

All the imagery used for the present investigation was obtained from the American National Aeronautics and Space Administration's (NASA) National Data Processing Facility, (NDPF). The NDPF apply geometric and radiometric corrections to each scene and issue them out to users as scene-corrected images or computer-compatible tapes. For this research, 70mm transparencies obtained from the NDPF were extensively used. These transparencies were used to make black and white paper prints using normal photographic printing processes. Colour composite transparencies and paper prints of areas of interest were also used.

The whole land surface of Nigeria from West to East is covered by nine N-S satellite tracks. The overlap between scenes of two adjacent tracks is about 14-15% (figure 1.). The percentage overlap of satellite images between adjacent tracks are known to increase towards the poles (Table 1.). Cloud cover problems have detracted from the usefulness of LANDSAT images in many parts of the world. It is very difficult, for example, to obtain a cloud-free image of Nigeria, south of latitude 6°N. North of this latitude, LANDSAT imagery coverage of Nigeria is considered very good.

1.3. A REVIEW OF THE LITERATURE ON THE USE OF LANDSAT IMAGERY FOR REGIONAL GEOLOGICAL WORK

Early workers on LANDSAT photographs very often looked at a couple of images and in an attempt to resolve local geological problems of interest. There has not been very proper evaluation of the many parameters, like climatic factors, soil developments and human factors affecting the amount of details extractable from satellite photographs. Opinions therefore vary between those who feel that minerals could be discovered directly from LANDSAT images and those who feel that orbital images are better "overseas". Publications assessing the merits or otherwise of satellite images for regional geological investigations are remarkably few while the literature on lineaments manifesting themselves on these images have grown into a torrent.



Imagery sidelap at the Equator

Figure 1.

The LANDSAT imagery sidelap between adjacent tracks near the Equator.

Table No. 1

The percentage overlap variation of adjacent LANDSAT swaths with Latitude. Data from NASA.

Latitude (degrees)	Image Sidelap (%)
0	14.0
10	15.4
20	19.1
30	25.6
40	34.1
50	44.8
60	57.0
70	70.6
80	85.0

Two notable early publications on the application of LANDSAT imagery for regional geological work are those of Viljoen and Viljoen (1973) and Isachsen (1973). Isachsen (1973) stated that varying degrees of bedrock geology, such as boundaries between major tectonic provinces, lithological contacts within tectonic provinces, foliation trends within massive gneisses, as well as lineaments could be regionally studied on LANDSAT images. Viljoen and Viljoen (1973, 1975), found LANDSAT images "ideally suited to the study of diagnostic macrostructures in Southern Africa." They were able to demarcate granite-greenstone contacts with their fringing mobile belts 'more closely'. Gee and Williams (1974) recognised the granite-greenstone terrains of Australia from LANDSAT imagery but stressed that satellite imagery studies would be an extra tool for the regional geologist that would complement rather than replace air photographs and other conventional regional exploration techniques. Viljoen and Viljoen (1975) felt that with an improved ground resolution of 10-30 feet, synoptic imagery from a satellite may compete or even supplant aerial photography.

Touminen et al. (1973) found a close relationship between geophysical data and satellite derived information of the Baltic Shield. Richards and Walraven (1975) also noted some important correlations between LANDSAT imagery and airborne geophysics of South Africa. Lathram and Albert (1976) observed that lineaments derived from

satellite images corresponded with deflections in gravity contour maps of Alaska. They also noted that different magnetic anomaly trends are separated by major satellite imagery lineaments. NASA (1973) has published papers of Symposia "On significant results obtained from the first Earth Resources Technology Satellite". The implications of these findings to the understanding of basement geology now appears on "Proceedings of the International Conference on the new Basement Tectonics," Hodgson and Gay edition (1976).

A significant finding from these publications is that most LANDSAT users make use of too few images. The writer has noticed that uncertainty often attends geological interpretations of only a few satellite images. As a result, most LANDSAT users try to impose current geological hypotheses like pure shear and simple shear dynamics (Moody and Hill, 1956, Sales, 1968) and the plate tectonic models (Hess 1965, Isaacks et al. 1968), while at the same time maintaining that these images reveal hitherto unknown and unrecognised features. No previously published information at the time of writing has considered some unique LANDSAT features outside the framework of the more popular tectonic hypotheses.

Numerous papers associate LANDSAT derived lineaments with ore deposits (Gregory and More 1975, Sisselman 1975). Lithological mapping and the differentiation of hydro-

thermally altered zones are generally difficult from LANDSAT. This is because the spectral reflectance differences between different rock types may be too small to be detected by these means. Rowan et al. (1975) reported that digital ratioing of MSS bands and subsequent stretching of the grey levels to increase the contrast of the images are a way of enhancing spectral differences between rocks and discriminating them. Goetz et al. (1975) agreed with this possibility but noted that various shades obtained from ratioing and stretching are not very consistent and require human eyes and brains to interpret the significance of the various shades rendered.

Despite these problems, there seems to be little doubt in the minds of researchers on LANDSAT imagery, that given the present ground resolution capabilities of the satellite sensors, ratioed and other enhanced images could bring out some poorly resolved geological information. It is also generally believed that careful analyses of satellite imagery can yield some significant geological information that may lead to the discovery of ore deposits and oil accumulations.

1.3.1. A review of the literature on air photographs as a tool for regional geological mapping

The importance of air photographs in regional geological studies is widely acknowledged. Considerable literature on the study of rectilinear elements on air

photographs has been reviewed earlier by Norman (1968) and recently updated (Huntington 1975, Zwain 1976). Fracture trace analysis or the study of linear geological information on air photographs as a subsurface exploration technique was pioneered by Blanchet (1957), and since then there has been notable contributions by Mollard (1957), Lattman (1958), Henderson (1960), Norman (1968, 1976) and Rumsey (1971).

While studies of fracture traces from air photographs have grown considerably over the years, systematic study of Precambrian structures using air photographs has again been relegated to the background. Spencer (1959) tried to apply fracture trace analyses from air photographs to Precambrian structures. He noted that field studies of joints and fractures alone would possibly not distinguish the major from minor fractures. His studies indicated some relationship between fractures and a 2.7 billion year old folding. Spencer (1959) however could not identify conjugate fracture sets from the Precambrian fractures interpreted from air photographs and so could not determine the stress field responsible for the fractures.

In the following year Allum (1960) published a systematic account of the use and superiority of air photographs in the study of a regionally metamorphosed terrain. The Nigerian basement was chosen as a typical area for illustrating this potential of air photography.

Allum (1960) stressed that air photo interpretation should be accorded a status in mapping and research because certain geological information obtainable from air photographs may not be obtainable in any other way. He also outlined techniques for differentiating some metamorphic structures like relic bedding and foliation, and syntectonic from post tectonic granites.

Hepworth (1967) indicated from photogeological studies of a large area in Uganda, that areas affected by the same tectonic episodes could be delineated. He found that the delineation of areas affected by the same tectonic episodes or "tectonic domains", is a useful guide towards understanding the tectonic chronology of a complex Precambrian basement. He also warned that features seen on this type of "broad-brush" study may not always corroborate detailed field work. Delineating areas of similar tectonic imprints in the manner suggested by Hepworth (1967) has been found useful in the interpretation of the Nigerian basement features and tectonic chronology from orbital images.

1.4. THE GEOGRAPHICAL SETTING OF THE STUDY AREA

The part of Nigeria covered by the present investigation is bounded in the West and East by 3°E and 13°E longitudes respectively and by latitudes 6°N and 12°N . The total area covered by the investigation is about 1 million square kilometers and about 960,000

square kilometers lie within Nigeria, (figure 2).

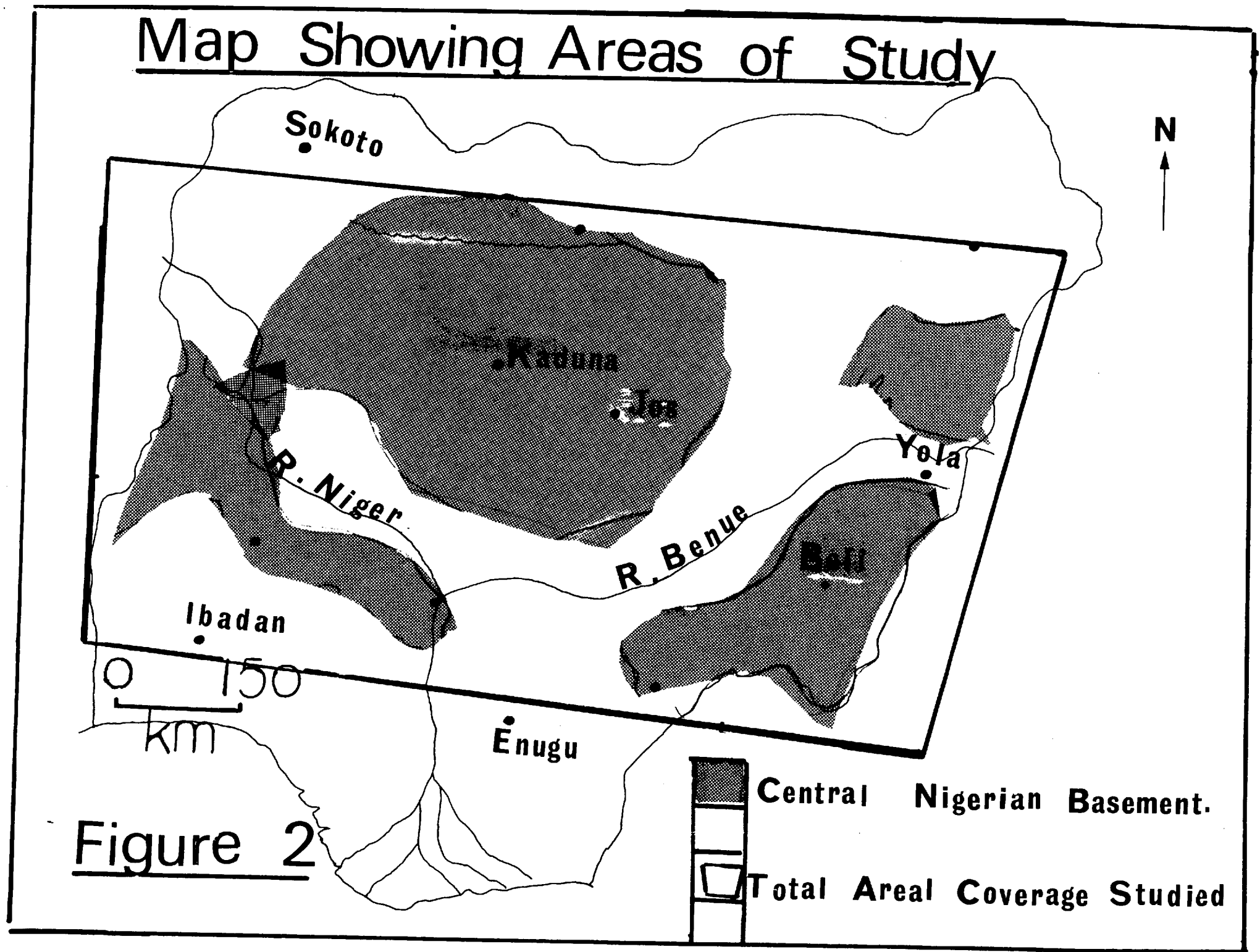
1.4.1. Rainfall

The study area lies well within the tropics. The amount of rainfall in Nigeria decreases from the coast inland. Over the investigated area, the highest annual rainfall of 90 inches is recorded around Jos. Evaporation from exposed bodies of water can reach 100 inches per year in the more northerly parts of the study area. The rainfall is monsoonal and falls mainly within the months of May to October.

1.4.2. Vegetation Zones

Vegetation zones tend to follow the amount of rainfall. Two broad divisions of the Nigerian vegetation into the forest and savannah zones are usually adopted. The forest zones occupy the coastal area, and mostly occur south of latitude 6°N . Subdivisions of the forest zone include the coastal saline swamp forest as well as the fresh water and the closed high forest zones each being progressively further inland. Lowe (1971) subdivided the high forest into two, depending on whether Precambrian or sedimentary rocks underlie the area.

The Savannah zones cover about $4/5$ of the land area of Nigeria, forming orchard bushes and open woodlands in which the main vegetation is grass. Most of the



investigated area lie in this belt. Patches of forest zones often occur within the Savannah. The Savannah is often subdivided into the Guinea, the Sudan and Sahel Savannahs. The Sudan and Sahel Savannahs occur progressively north of the Guinea Savannah and are characterised progressively by sparser vegetation. Figure 3 shows the close relationship between rainfall and vegetation zones of Central Nigeria.

1.4.3. Physical Features

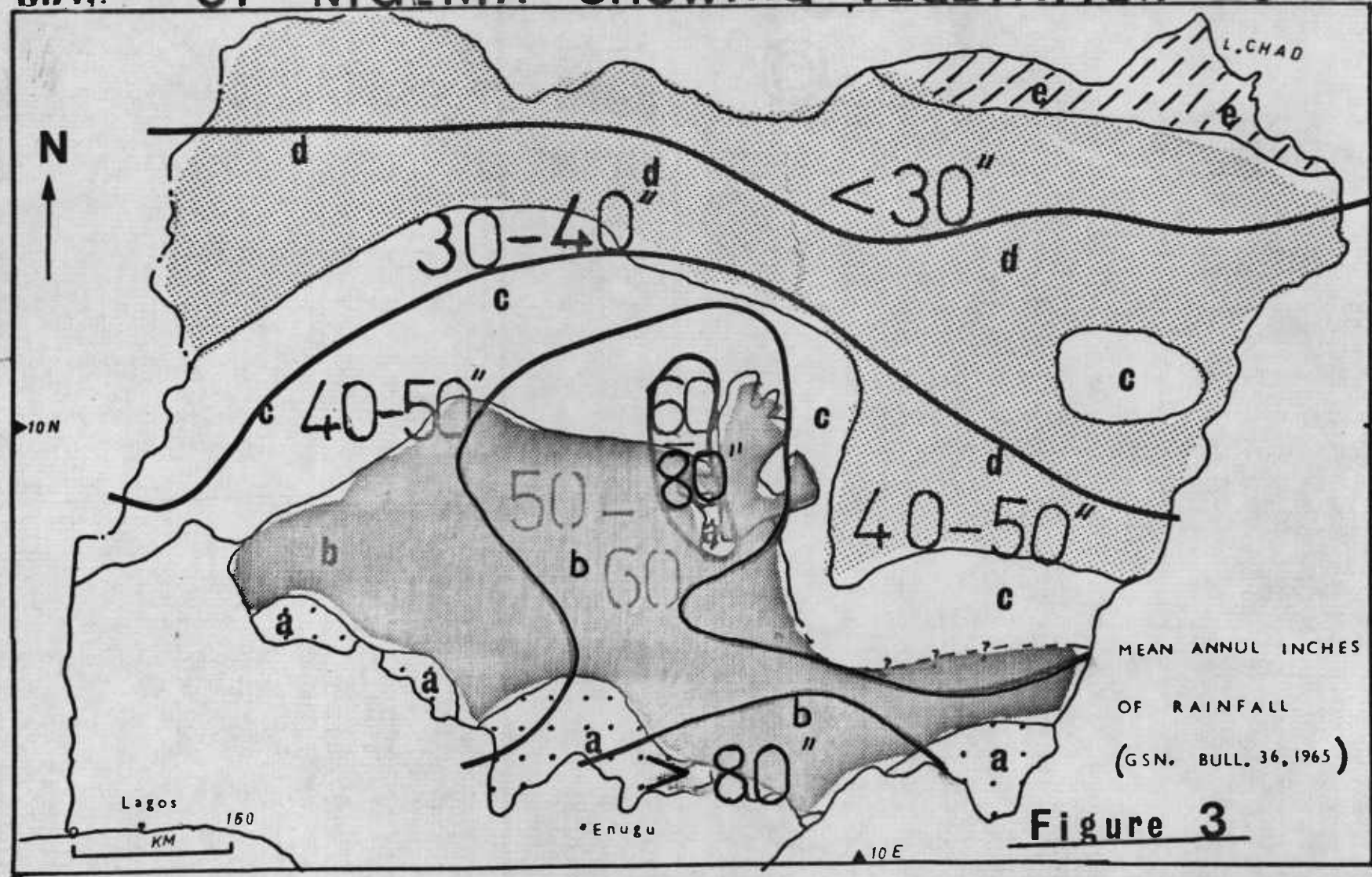
Weathering intensity permits a three-fold division of the relief of Central Nigeria into:

(a) Level surfaces and plateaux, (b) Scarps, and (c) Valleys.

(a) Level Surfaces

Large areas of Nigeria are represented by gentle rolling plains and level areas broken occasionally by domed inselbergs. There is characteristically very little movement of surface materials. The Zaria plains and the Jos plateau tops are good examples. Pugh and King (1952) recognised two level surfaces around Jos. The highest and oldest surface is considered to be older than the break up of Gondwanaland. This higher ground flattens out at about 1300 meters above sea level (4000'). Hills standing on this level surface reach 2,000 meters in height. The younger surfaces occur at about 700 and 500 meters elevation.

MAP. OF NIGERIA SHOWING VEGETATION ZONES



a, Derived Savanna; b, Southern Guinea Savanna; c, Northern Guinea Savanna; d, Sudan, and e, Sahel Savannas.

respectively. Some of these erosion surfaces are visible on LANDSAT photographs (Plate 1).

(b) Zones of transference

Zones of transference are areas where eroded materials appear to be in transit. Plateaux scarps and river valley slopes are good examples. Scarps appear as distinct tonal boundaries on LANDSAT images.

(c) Zones of Accumulation occur in low lying inland basins like the Benue trough. River valleys are also zones of accumulation.

Two major rivers, the Niger and the Benue drain the investigated area. The tributaries to these rivers often rise from the scarps which also act as major drainage divides. One such a scarp can be traced from Sokoto through Birnin-Gwari to Jos (figure 4), a distance of over 500 kilometers. The major rivers of Central Nigeria appear to be tectonically controlled by N-S basement failures. Minor dendritic patterns occur over the flat surfaces, where chemical activity also appear to be more pronounced.

1.4.4. Soil Developments

A highly weathered material rich in secondary oxides of iron, aluminium or both, devoid of primary silicates referred to variously by geomorphologists as

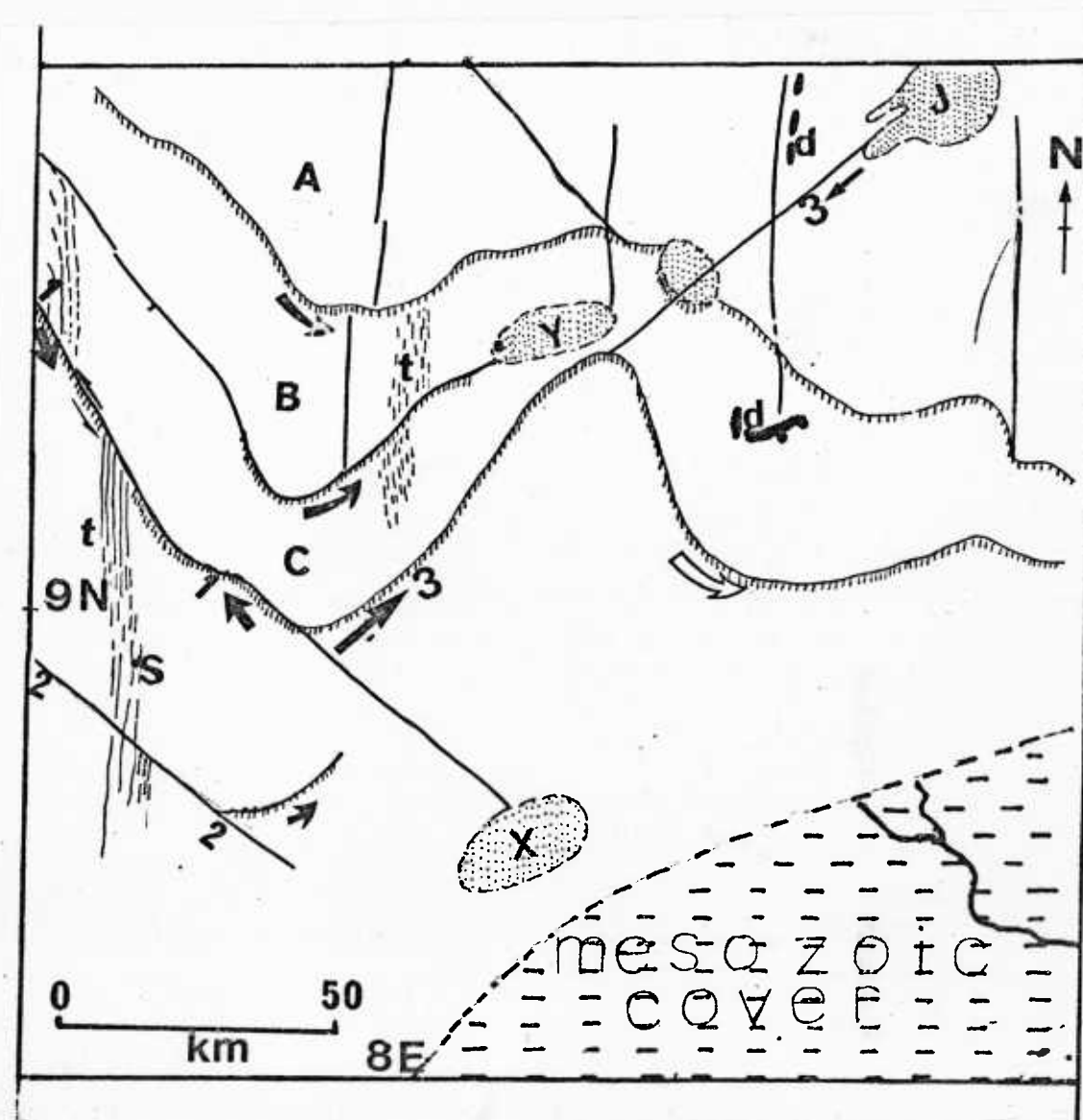


PLATE 1

A LANDSAT-1 image of parts of the Jos Plateau and the Benue trough showing erosion surfaces A, B, C.

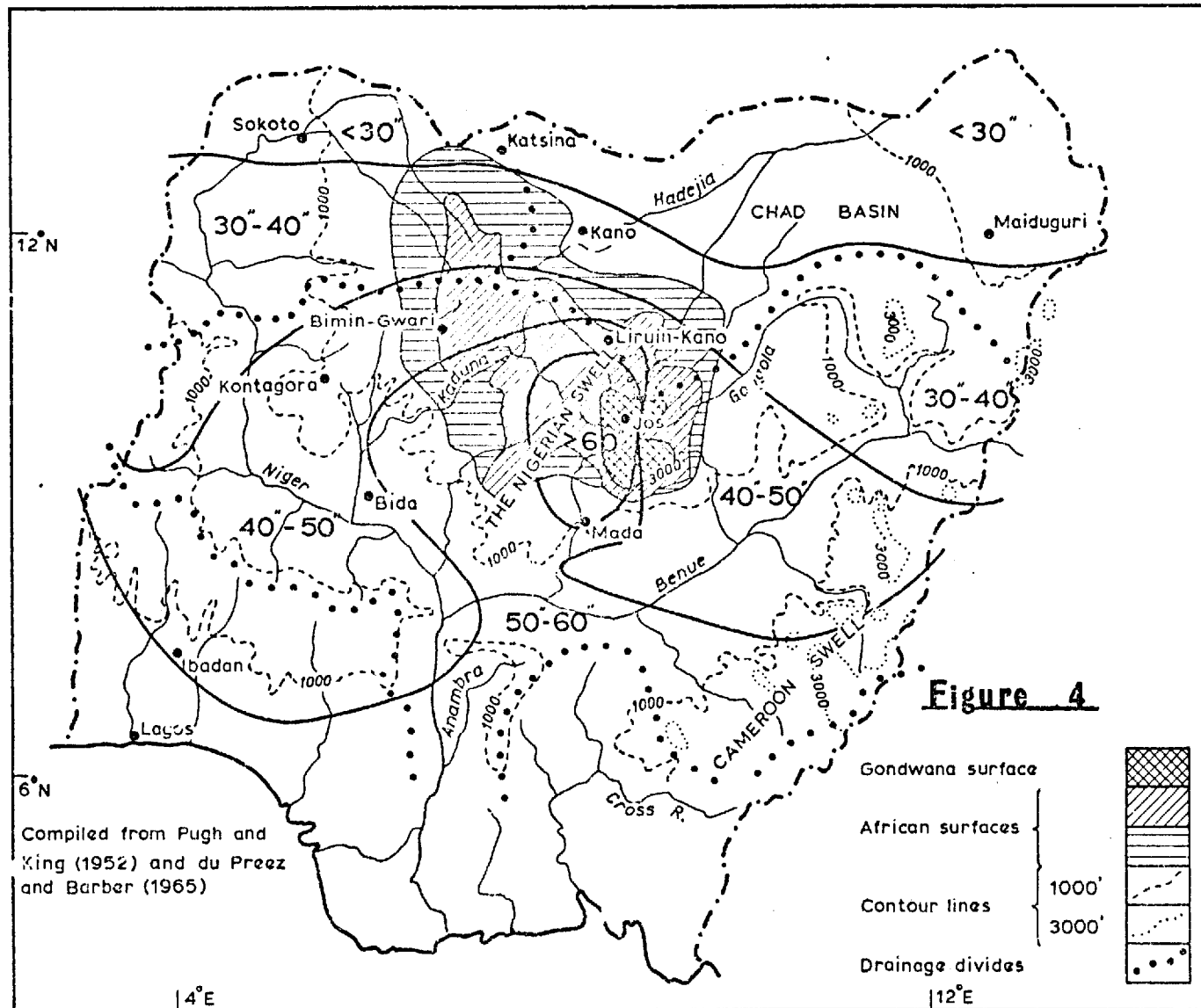
The edges of the surfaces appear to be major sinistral wrench faults (1, and 2).

Arrows indicate N-S lineaments.



A photogeological sketch showing the major features of Plate 1.

- J = Jarawa ring dyke complex
- Y = Kagoro ring intrusion
- X = Mada ring intrusion
- A, B, C = Erosion surfaces
- 1, 2 = Sinistral shear faults
- t = basement trends
- 3 = NE- trending lineament
- d = Tin mines - (open cast)
- S = metasediment



Compiled from Pugh and King (1952) and du Preez and Barber (1965)

MAJOR MORPHOTECTONIC FEATURES OF NIGERIA

laterites, duricrusts, plinthite, ferricrete or lateritic ironstone is the most widely developed soil type in Central Nigeria. Du Preez (1949) described the Nigerian laterites as "a mass that may be vesicular or concretionary or vermicular or pisolitic or more or less massive consisting essentially of iron oxide with or without clastic quartz and containing small amounts of aluminium and manganese."

Some geologists recognise two types of laterites in Nigeria based on their modes of occurrence. Dowling (1965) differentiated the plateaux type occurring on bevelled hills and peneplains from the foot slope or colluvial laterites. The formation of laterites is poorly understood. It is believed that reducing conditions are favourable for the mobilisation of ferrous iron (Thomas, 1974). Water table fluctuations resulting from the monsoonal rains may be a contributing factor. No matter how iron is mobilised, it is clear that fractures which act as conduits for underground water movement will also act as passages for mobilised iron. Ferrous materials are trapped within open fractures when the water table falls.

Depths to the unweathered basement in Central Nigeria vary with the locality. Very little work has been done in this direction. The depth to unweathered basement appear to bear some relationships with the variations in rock types, vegetation cover, land stability and tectonic effects. Scattered information on the depth

of weathering of the investigated area indicate that weathering depths average some thirty meters and may locally exceed fifty meters. Heavily jointed areas and interfluvies are reported to be heavily weathered (Thomas 1974). A mid-Tertiary age is usually assigned to most Nigerian peneplain laterites (Du Preez, 1949, McCurry, 1973).

1.5. A REVIEW OF THE GEOLOGICAL LITERATURE ON NIGERIA AND CURRENT NIGERIAN GEOLOGICAL PROBLEMS

The Nigerian land surface is almost equally represented by the Basement Complex and the younger sedimentary cover rocks. The blanket term 'Basement Complex' is used in Nigerian geological literature to refer to all rocks older than the Jurassic 'Younger Granites'. Organised geological studies in Nigeria began with the establishment of the Nigerian Geological Surveys in 1919. Up to 1960, geological work in Nigeria was guided mainly by economic considerations, with the result that geological information tended to be patchy with some areas like the Plateau tinfields receiving disproportionate attention.

Systematic mapping of the Nigerian Basement Complex by the staff of the Nigerian Geological Surveys is now in progress. Published and unpublished geological information of extremely variable qualities are available at the Geological Surveys Headquarters in Kaduna. There is a

general agreement among workers on Nigerian geology that the basement contains gneisses, migmatites and granites as well as distinct belts of metasediments (King and De Swardt 1949, Russ 1957, Orajaka 1964, Oyawoye 1964, Trusswell and Cope 1963, Grant 1970, McCurry 1973). There are differences of opinion regarding the number of meta-sedimentary groups and therefore of the number of orogenies affecting the Nigerian Basement Complex. Russ (1957) noted that there are enough metamorphic contrasts between low-grade metasediments and the surrounding migmatites and gneisses to justify a polycyclic origin of the Nigerian Basement Complex. Similarities in many respects were drawn (Russ 1957) between the Nigerian rocks and those of the fundamental complexes in Scotland, Canada and Scandinavia. This polycyclic view was shared by subsequent workers with the notable exception of Trusswell and Cope (1963) who hold a monocyclic view because they saw no evidence of any major structural breaks between the low-grade rocks and the adjoining migmatites.

Since the work of Trusswell and Cope (1963) many radiometric dates on Nigeria have emerged. These new ages range from 2750 m.y. Pb-isotopic age near Ibadan (Oversby 1975) through 1950 ± 250 m.y. and 1270 ± 75 m.y. Rb-Sr isochron ages near Ibadan and Kaduna respectively (Grant 1970, 1972). Hurley (1966) obtained a 2220 ± 30 m.y. for the Kaduna migmatites in addition to a widespread 700-450 m.y.,

Pan African event, also recorded by Grant (1970, 1972) and by Jacobson et al. (1963).

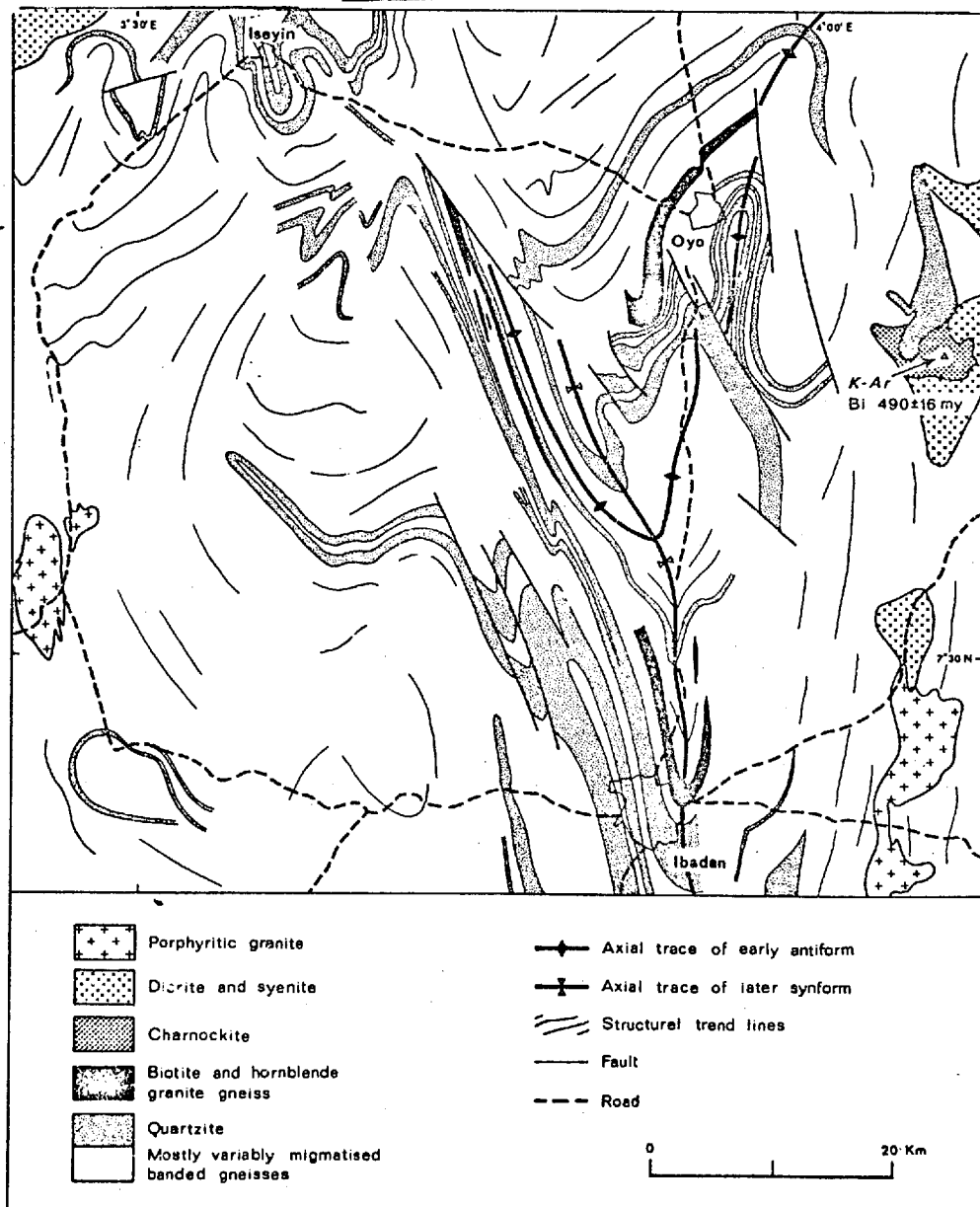
McCurry (1973) based on field mapping of Sheet 21 in Northern Nigeria and using available radiometric data supported the polycyclic view on the evolution of the Nigerian Basement Complex and also considerably improved the tectonic chronology and stratigraphy of the basement earlier proposed by Russ (1957). A sequence of events suggested for the South-western Nigerian rocks (Burke et al. 1976) follow essentially the same lines.

1.5.1. Major tectonic elements of the Nigerian Basement

Available geological evidence indicate that the Nigerian Basement Complex contains well defined North-South metasedimentary troughs separated by more crystalline gneisses and migmatites (McCurry 1973). It is now almost agreed by Nigerian geologists that the tectonic history of the Nigerian Basement Complex has been polyepisodic. Very little work however has been done to elucidate the structures characteristic of the different tectonic events. McCurry (1973) stated that migmatites display major over-turned isoclinal folds on aerial photographs and that these features are difficult to trace on the ground. Based on microstructural evidence, she deduced that her Eburnean (1950 ± 250 m.y.) structures tended to form flat-lying isoclinal, east-west trending folds. At Ibadan in South-west

Nigeria, Grant (1970) mapped a major flat-lying refolded structure over 50 kilometers long (figure 5). This structure defined by quartzites contains concordant granite-gneiss also refolded along a N-S axis. The axis of refolding is flanked by linearly arranged elongate intrusions of porphyritic granites as well as syenites and

Figure 5



The Ibadan refolded fold. After Grant 1970.

* charnockitic granulites. It was not previously realised that these linear arrangement of granitic rocks are fault controlled. The concordant granite gneiss associated with this large structure yielded an Eburnean (1950 ± 250 m.y.) age. The present study has identified many similar structures within the Nigerian Complex.

Two major dexteral NE-trending wrench faults having displacements of about 10 kilometers are known. One of them, the Kalangani fault, was mapped by Trusswell and Cope (1963) and the other, hereafter referred to as, the Yaribori fault, was mapped by McCurry (1973). A N-S mylonite zone was mapped in South-western Nigeria (Jones and Hockey, 1964). During the construction of the Niger Dam, two mylonite zones were encountered at the river bed during the drilling operations. No relationships between the mylonite zones and the two mapped faults and fractures are known.

The Benue trough, a compressionally folded intra-cratonic trough in Nigeria has also received a disproportionate attention in the Nigerian literature. Wright (1976) critically reviewed the theories about the origin of this trough and concluded that it is no longer adequate to associate all structures of this valley with the separation of South America from Africa. Plate tectonic models (Burke et al. 1970), Nagy et al. (1976), regard this trough as a suture and plate collision boundary,

a proposition unsupported by salient geological data on the trough (Olade 1975, Chukwu-Ike 1977, in press). This present study offers a completely new model about the possible origin of this trough based on satellite imagery data.

1.5.2. The relation of Nigerian rocks with those of the neighbouring West African Countries

The increasing geological and geochronological literature on Africa confirm that Africa represents a primitive crust more than 3,000 m.y. old and that a number of orogenies affected this ancient crust (Clifford, 1970, 1973) including two orogenies prior to 2500 m.y. It is now widely held that the oldest rocks in Africa are preserved in eight nuclei, around which a series of poly-episodic orogenies progressively wrapped. Precambrian orogenic events in Africa are known at 1850 ± 250 m.y. (Eburnean and Huabian), 1100 ± 200 m.y. (Kibaran orogeny) and a 600 ± 100 m.y. orogeny (Damaran - Katangan or Pan African orogeny). An older Liberian cycle (2700 ± 200 m.y.) previously associated with the so-called West African nucleus only, is now recognised in Nigeria (Oversby 1975).

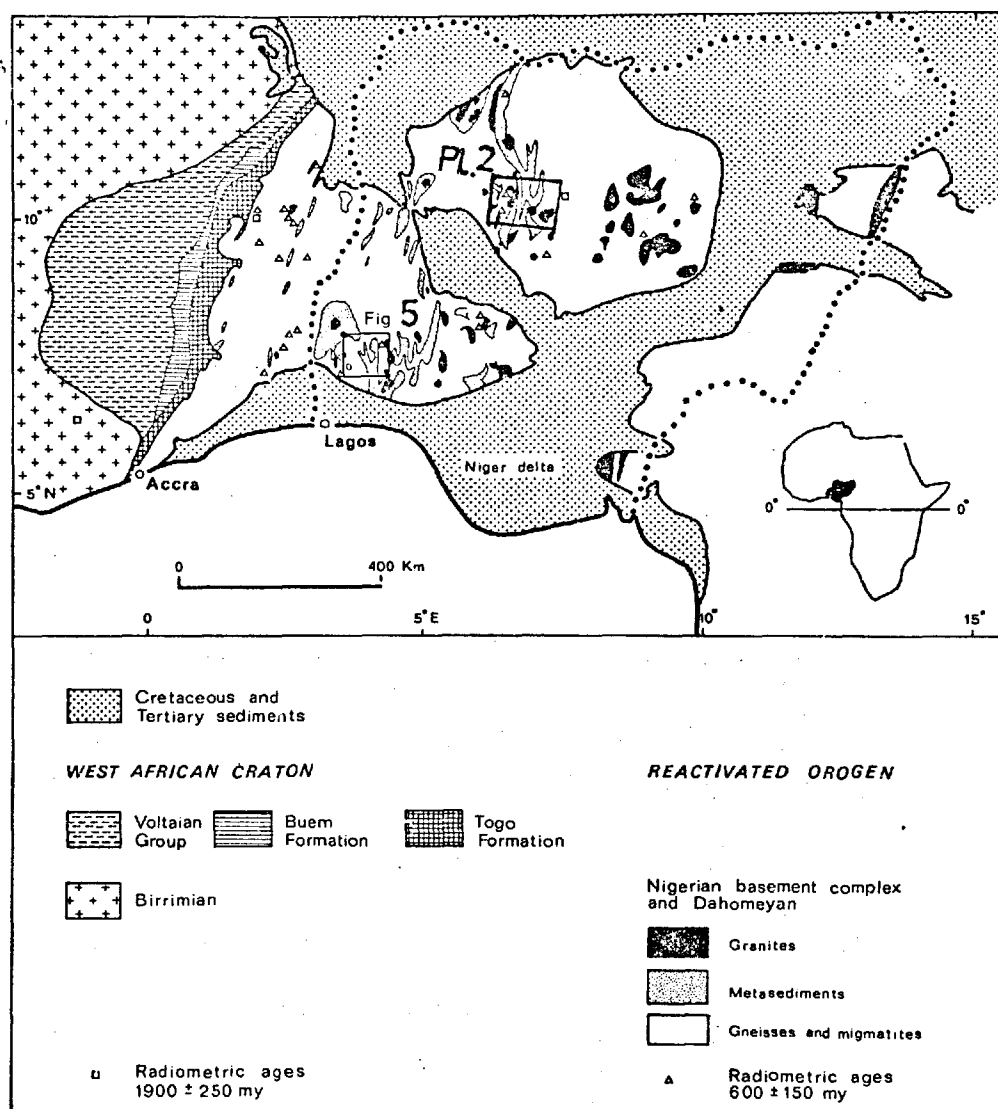
The great majority of radiometric age determinations in Nigeria, lie within the Pan African age range (600 ± 100 m.y.). Kennedy (1964) demonstrated that this episode dates the imprint of a widespread reactivation of the African shield. Radiometric ages in S.W. Algeria

(the Ahaggar) indicate that the Pan African event is also associated with rocks of Liberian age (Bertrand and Lesserre, 1976).

In West Africa, the boundary between the so-called Precambrian nucleus and the reactivated Pan African areas to the east of it is marked by changes in radiometric age magnitudes as well as the occurrence of late Proterozoic to early Palaeozoic rocks, known as the Voltian Group. The Voltian Group is succeeded to the east by the Buem and Togo formations (figure 6). Grant (1969) considered the Voltian Group, the Buem and the Togo formations as belonging to one sedimentary unit within one orogenic cycle. A positive gravity anomaly flanked by negative anomalies are also characteristic of this craton margin. It is notable that similar gravity anomaly patterns are known to occur within the Benue trough in Nigeria within the so-called Pan African belt (Cratchley and Jones, 1965). It is also pertinent to note that the same craton margins have continued to be tectonically active long after the Pan African event and have been sites of anorogenic and alkaline volcanism. The margins are also known to be belts of base metal (Cu, Pb, Zn, Co, Sn, W, Be, Nb-Ta) mineralisations (Clifford 1966) and have also remained sites of Mesozoic and Cenozoic marine sedimentation, an analogy which can also be extended to the Benue trough.

The origin of the craton margin sediments and meta-

Figure 6



The relationship between Nigerian rocks and those of neighbouring West African countries. The area covered by Plate 2 is indicated (box).

sediments has been explained in terms of plate tectonic model (Burke and Dewey, 1970). According to this model, the eastern margin of this craton represents a subduction zone where two plates collided in late Proterozoic - early Precambrian times.

1.5.3. Some Problems of Nigerian Basement Geology

Previous studies of the Nigerian Basement Complex geology has raised some problems. Since it is now realised that distinct narrow metasedimentary troughs occur within the Basement and that these troughs are bounded on both sides by elongate granites some of which are known to be post tectonic (McCurry and Wright, 1971), it is difficult to explain this unique arrangement of intrusions in terms of infolding and mantle gneissic doming or synclinoria formation, at all crustal levels.

Analogies have been drawn between the Nigerian low-grade metasediments and the granite-greenstone terrains of Southern Africa (Wright and McCurry 1970). In the latter, the greenstone belts are believed to represent the oldest rocks of the area, and possibly of the world, whereas in Nigeria there are both structural and lithological reasons to believe that the Nigerian low grade rocks are the younger series of the Nigerian Basement Complex rocks (McCurry 1973).

Though a polyepisodic origin of the Basement is

favoured, whether subsequent orogenies grew on older nucleus or not is unclear. The events responsible for the reactivations of the Basement if there was no crustal growths on older nuclei had not been recognised.

Two dexteral shear faults have been mapped in Nigeria. Their complementary sets have not been recognised.

The relationship of different groups of metasediments, their regional structural characteristics and spatial extents have been in doubt.

The origin of the Benue trough is uncertain. The reason why two episodes of folding should be recorded in the north of the trough and only one episode of folding in the south (Wright, 1976) poses a problem.

The controls of charnockitic granulites is not known as well as a general regional idea of variations in structural levels.

LANDSAT imagery studies have suggested some answers to some of the above problems, in addition to enabling a generalised tectonic chronology of the Nigerian Basement to be advanced.

1.6. RESEARCH METHODS

Two researches on various aspects of the use of LANDSAT imagery were already in progress in this department

when the present study commenced in 1974. There has therefore been established contacts with the Earth's Resources Observation Satellite (EROS) Data Centre in Sioux Falls, South Dakota. Techniques for handling various EROS products were already developed and logistic assistance derived from these older researchers saved a lot of time for the present investigation.

1.6.1. Selecting satellite images and air photographs of Central Nigeria

Enquiries about the satellite imagery coverage of Nigeria was placed with EROS Data Centre and a computer print-out showing scene identification numbers and cloud coverages of LANDSAT scenes of Nigeria was received inside three weeks. Suitable images initially based on percentage cloud coverages were selected. The print-outs also contained information on computer compatible tapes (CCT) for the same area. Black and White 2.2" negative transparencies were initially ordered for the whole country. From the negatives, paper prints at different scales were produced. False colour composites were generated from EROS for areas of interest and colour negatives were also produced from 7.3" positive colour transparencies via normal photographic techniques.

1.6.2. Satellite imagery interpretation techniques adopted for this study

For the present study, routine photo interpretation

techniques were adopted (Lattman 1958). Human photo interpretation uses the eye-brain system to search for simple patterns of features. These features are then interpreted in terms of geology. It is essential that a feeling for geology from photographs be developed. This takes some time and patience to acquire otherwise only the most obvious features can be interpreted from images.

Comparisons of features on bands of LANDSAT images with mapped information of prominent geological features were made in order to acquire some experience on the manifestations of different rock types on LANDSAT images of the study area. The variations in the appearances of the same features with the two seasons were also noted.

All interpretations were done on overlays of transparent mylar. It was a practice to assemble all the geological data interpreted from the component bands of a scene into one master interpretation whose information content could then be compared where possible with those existing on published geological maps. The differences were noted and it is these differences that were checked, where possible, in the field. The first round of interpretations on about 50 scenes covering the investigated areas, was completed in about six months. It generally took two weeks to produce one master interpretation of a scene from the component bands. Some areas of more complex geology took considerably longer. In all cases, bands

were interpreted individually before it was possible to decide whether a particular band represented the best single band of the area. A notable characteristic of multispectral satellite images is that apart from features like major rivers, correlation of features between different images of a scene may vary from about 5% to 100%.

Some six months after the first set of interpretations, the same prints were studied again without referring to the previous master interpretation. Though some vague mental picture of earlier interpretations still lingered, details were almost forgotten. A comparison of the interpretations showed that about 20% of the information on the second was not on the first. Altogether three rounds of studies were carried out on images of Central Nigeria, each new interpretation always adding something on the earlier ones. In a few cases, some previously studied features were considered incorrect. LANDSAT-2 images were obtained and carefully chosen to represent imagery acquired for a different season from those of LANDSAT-1. Seasonal factors were found to have a very minimal influence on images of Central Nigeria but climatic and microclimatic factors are considered to have a more profound effect.

Enlargements of LANDSAT images to 1 : 500,000 were found useful in resolving areas of ambiguity. An image may carry as many overlays as the interpreter considers necessary without overcrowding his interpretation.

The writer usually employed two overlays per image. One overlay carried the interpretation of lineaments, linear features and spatial distribution of intrusions while the second overlay carried information on folds, basement trends, broad lithological variations, as well as features of uncertain appurtenance. All interpretations of Central Nigeria includes scales larger than 1 : 1 million.

Placing single weight paper prints over light tables and 'eye-balling' them could indicate some features as well as orienting prints at various levels and angles with the eye. In areas where interpretation bias is suspected, the opinions of another interpreter were also sought.

It was also found useful to interpret two component bands of a scene, say bands 5 and 7 or a colour composite print with one other black and white band as stereo pairs using a stereoscope. This method is useful in rugged terrains because the interpreter can get the impression of features in three dimensions. It was also found useful to make use of the stereoscopic effects produced by the overlapping swaths no matter how small.

1.6.3. Air photo interpretation

Air photographs where available were found very useful in tracking down features of interest seen on LANDSAT images down to ground levels with a view to field

checking. Systematic interpretation of air photographs over the whole area was not attempted because of the enormous number of photographs that would have been involved (about 200,000 prints). Extensive use of air photographs would have made research costs prohibitive and would have defeated the purpose of the investigation. Stereoscopic interpretation of air photographs was the main method of air photo study. Mosaics and print-lay-downs were studied in much the same way as LANDSAT images.

1.6.4. Geophysical data and LANDSAT information

Available geophysical data on Nigeria are scanty. Recently completed aeromagnetic survey of the whole country were not available at the time of this work. There existed however some regional aeromagnetic contour maps of North-western and western Nigeria carried out by the United Nations in collaboration with the Geological Survey of Nigeria on a 1 : 250,000 scale. Gravimetric surveys of the Benue trough was carried out in 1963 and also exists on a similar scale. Wherever such geophysical information exists, correlations between them and LANDSAT imagery features are presented.

1.6.5. Ground checking of LANDSAT data

The Nigerian Basement Complex rocks are poorly exposed as a result of thick soil profiles and lateralisation. This situation makes air photographs and satellite

images indispensable for geological work. Images of the land surface were found useful in providing a good mental picture of what to expect in the field. This enabled the writer to plan field work in such a way as to save time and unnecessary difficulties.

Before embarking on field work reference was made to all available geological records at the Geological Surveys Headquarters in Kaduna. Though four weeks were spent looking at these unpublished works, considerable time was saved at the end. Information available in the unpublished records were found useful in differentiating such features as dykes from fragmentary metasedimentary quartzite ridges and in confirming the tectonic significance of some lineaments. If a LANDSAT lineament is found to be partly-mapped as a fault, its existence is regarded as having been confirmed. The writer observed that referring to previous work was very useful because it afforded the interpretation controls needed for the present study and considerably reduced the amount of field work required per frame of satellite imagery. Not all features seen on LANDSAT images could be found on maps, but reference to geological records helped feature recognition.

Even when LANDSAT imagery and the topographic maps are the same, some discrepancies in the transfer of features from one to the other may be observed. The mismatches are

due to projection differences. LANDSAT images were presented in Universal Transverse Mercator Projection while most maps of Nigeria are on conoscopic projection. These projection mismatches have been known to produce inaccuracies in the ground location of features observed on LANDSAT images. These inaccuracies range from $\frac{1}{2}$ km to $1\frac{1}{2}$ km. This is considered acceptable for the type of regional work under consideration.

1.6.6. Analyses of interpreted LANDSAT data

Lineaments interpreted from LANDSAT photographs were compiled manually. Rose diagrams of directional statistics were then drawn. Intersection points of lineaments are considered favourable sites of mineralisations (Wertz 1970, Norman, 1976). Such intersection points were carefully studied for Central Nigeria.

There was also a visual search for lineament patterns and associations with intrusions, metasedimentary belts and mining districts. Regional differences in fold geometries were also noted.

Curved lineaments were also particularly studied especially the curved concentrically arranged lineaments and fractures. The centre points of the concentrically arranged lineaments were noted as well as the common association of centres of concentric fractures with sedimentary and metasedimentary troughs.

Density slicing of LANDSAT grey levels was carried out in order to assess the usefulness of this method in studying lithologic variations. This technique involves scanning the LANDSAT negatives with a television camera connected to a densitometer. Variations in the grey levels of the negatives are colour coded and displayed on a television screen. Density slicing was found useful in enhancing certain directional features as well as some bulk lithologic variations.

CHAPTER TWO

FACTORS AFFECTING THE AMOUNT AND TYPE OF INFORMATION OBTAINABLE FROM SATELLITE IMAGERY

2.1. OBJECTIVE FACTORS

Several objective factors affecting the type and amount of information obtainable from satellite imagery are quite similar to those that impose limits to the perception and interpretation of features from air photographs. Some of the objective factors are the scale of imagery, climatological conditions and sensor factors.

2.1.1. Sensor factors

The usable information recorded by a sensor is usually called a signal, while other tendencies to mask the signal are regarded as noise. In orbital imaging, the term amplitude resolution is a measure of the signal-to-noise ratio of a sensor, and therefore is an inherent characteristic within the system. Factors such as the optical efficiency and obscuration of the scanning mirrors and pre-amplification noise belong to this category. The alignment of the imaging sensors relative to the space craft could change and this may affect positioning accuracy of recorded information. Pre-planned orbital paths of the space craft may be different from those actually taken by the space craft. This is usually referred to as ephemeris

and may often constitute errors in the positioning accuracy of imaged features.

Closely associated with sensor factors are some amount of degradation introduced by hardware used in processing the satellite data on the ground. Such errors are introduced by photographic printing inaccuracies, enlargement distortions, computational errors and projection distortions.

2.1.2. Climatological factors

LANDSAT's orbits round the Earth is sun-synchronous, so it passes the same areas at about the same local time every 18 days. Though the local time remains the same, the apparent north-south migration of the sun causes differences in the sun elevation angle. In winter over the northern hemisphere, for example, the sun elevation is low and the low sun angle elevation introduces changes in the scene brightnesses and therefore introduces variations in the reflected solar energy affecting the sensors. The sun's elevation affects the quality of imagery at both high and low latitudes.

2.1.3. Rainfall, soils and weathering

Since the photogeologist primary studies the surface of the ground in an attempt to understand the geology of a place, the dynamic natural forces of the locality of interest is of considerable importance. The

topographic manifestation of a place depends not only on tectonic causes but also on geomorphological factors like erosion, rainfall, acidity and temperature conditions. These geomorphological factors are influenced by the type of rock in a particular place.

The rainfall of a place affects the amount of run-off, and therefore of erosion. In Nigeria, for example, no totally cloud-free imagery has been obtained over areas with over 200cm. of rainfall annually. Also associated with this heavy rainfall are deep soil profiles and dense vegetation overgrowths, features which tend to mask the underlying geology. Moderate rainfall to arid conditions tend to be ideal for cloud-free satellite images.

Vegetation can also enable important geological deductions to be made. For example, it has been noticed that areas underlain by low-grade pelitic rocks within the Nigerian Basement Complex tend to support more luxuriant vegetation than the surrounding gneissic terrains. This characteristic enables the contacts between the two rock types to show up prominently on orbital images. False colour composites enhance the differences in vegetation vigour on photographs. Differences in vegetation vigour could reflect differences in the underlying geology.

2.2. Systems factors

Some imaging factors also affect the amount of information obtainable from photographs. With the satellite at an altitude of over 900 kilometers, scalar problems are about the most important. As a result of high altitude, large areas are recorded at the same time by the satellite. It is not possible to have a large areal coverage and a large scale as well, per print.

2.2.1. Scale of satellite imagery

The ratio of distances between corresponding pairs of points on both the photograph and on the ground (or map) is a measure of scale. For aerial photography which is a perspective representation of ground features, distortions occur outside the centre of the photograph, so the relative positions of features are not identical to those on the ground. Multispectral scanners are different from air photography in having minimal image distortions. Multispectral Scanner images approximate to orthophotos. LANDSATS belong to low orbit satellites (250-1200 Km above the ground) as distinct from geostationary satellites hovering some 36,000 Km above the ground. The scale of imagery, as in the case of air photography, depends on the height of the space craft. Satellite imagery studies tend to be convenient at 1 : 1 million scales as well as 1 : 500,000 and 1 : 250,000. Enlargements larger than the latter tend to be blurred.

It is therefore obvious that only major features can be seen from orbital images.

2.2.2. Resolution and registration factors

There are some relationships between scale and resolution of photographs. The resolution of an image is the smallest image dimensions that can be recognised on photographs. It is usually measured in lines per millimeter. Enlargements do not always improve resolution since experience shows that beyond a certain degree of enlargement the sharpness of the image is lost. It is considered meaningless to look for details in satellite images because the nature of these images certainly precludes most details.

The resolution capability of LANDSATS 1 and 2 is limited to about 80 meters. This coarse resolution drastically limits the size of objects visible on LANDSAT imagery to about one kilometer.

Registration refers to a comparison between two images of a ground scene. The term temporal registration refers to a comparison between two images of a ground scene taken at different times while spatial registration refers to two different spectral images of the same ground scene taken at the same time. There are differences in the registration - spatial and temporal - of MSS images. The registration accuracies for bulk processed products

and the positional mapping accuracy of EROS films and paper products are as follows:-

<u>Registration Accuracy</u>	
All Products	159 meters.
<u>Positioning Mapping Accuracy</u>	
Film Products	743 meters.
Paper Products	757 meters.

After, NASA, 1971.

TABLE 2

MSS bulk output product-Residual Errors. These errors are considered reasonable for the scale of investigations involving these products.

2.2.3. Dynamic range of tones

Image contrasts or tone contrasts are a measure of the ratio of the light to the dark areas of a target feature. The term contrast is also used to refer to the difference between an object and its background. The gradations of grey tones in a black and white image is referred to as the dynamic range of tones. Below a LANDSAT image is a grey wedge, indicating its dynamic range of tones, which is an indication of the brightness range of the scene. Image contrast stretching is the adjustment of the grey levels or dynamic range of tones to bring out suppressed levels. Using a computer, 256

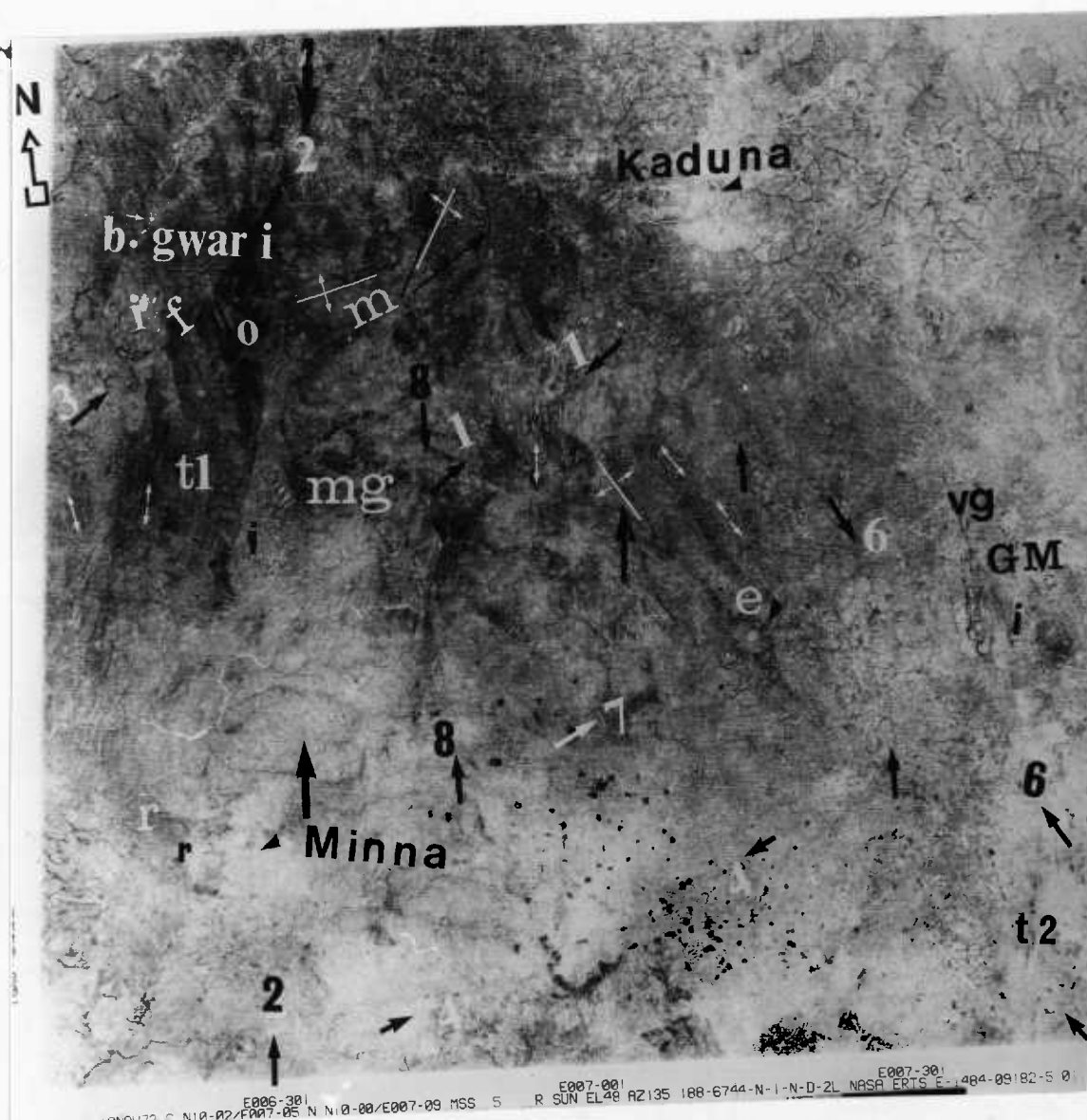
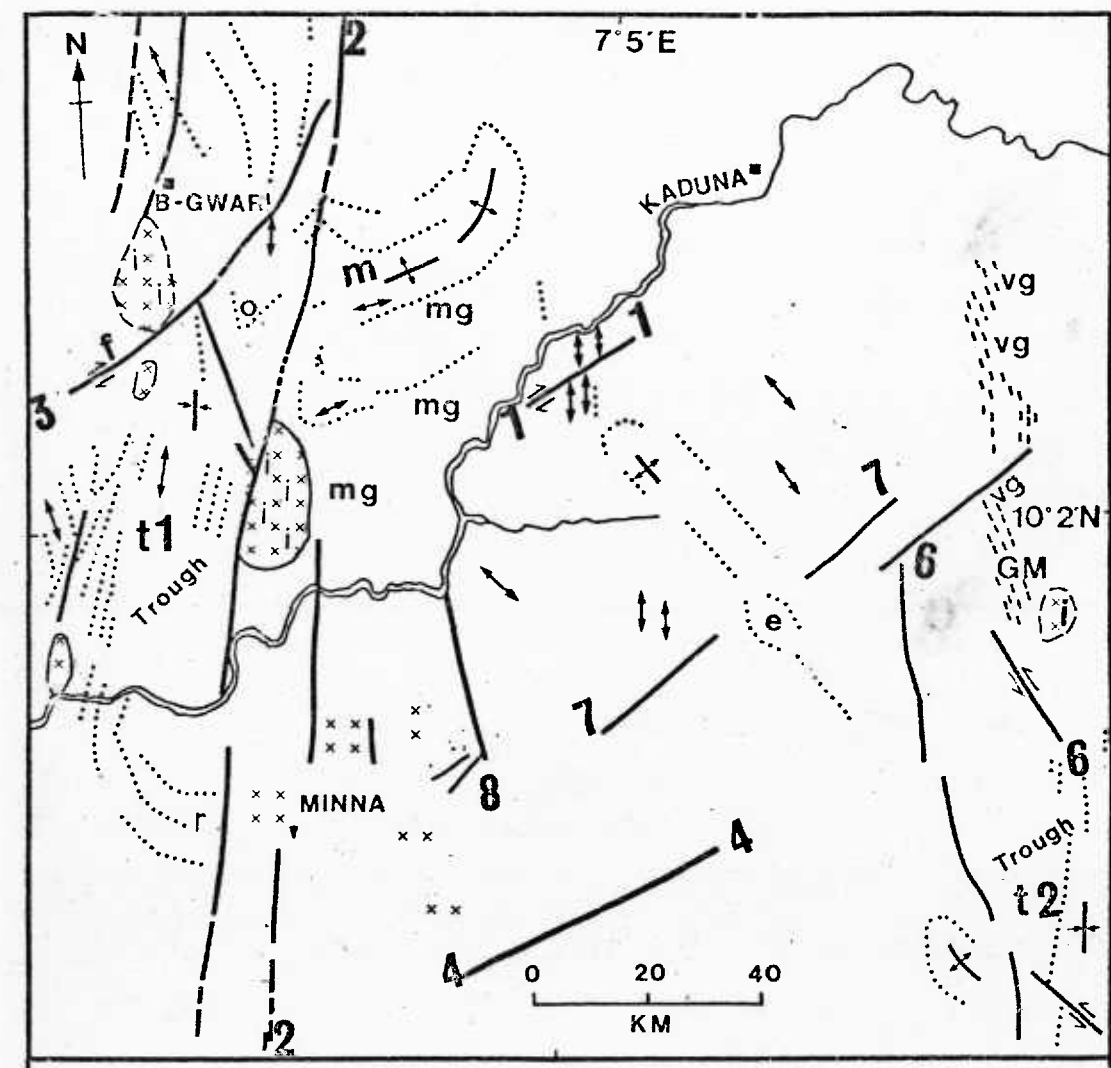


PLATE 2

A LANDSAT - 1 image of NW - Nigerian showing tonal contrasts between the low grade rocks, tl, and the adjacent migmatites, mg.



A photogeological outline of the main features of Plate 2.

Small arrows indicate basement trends

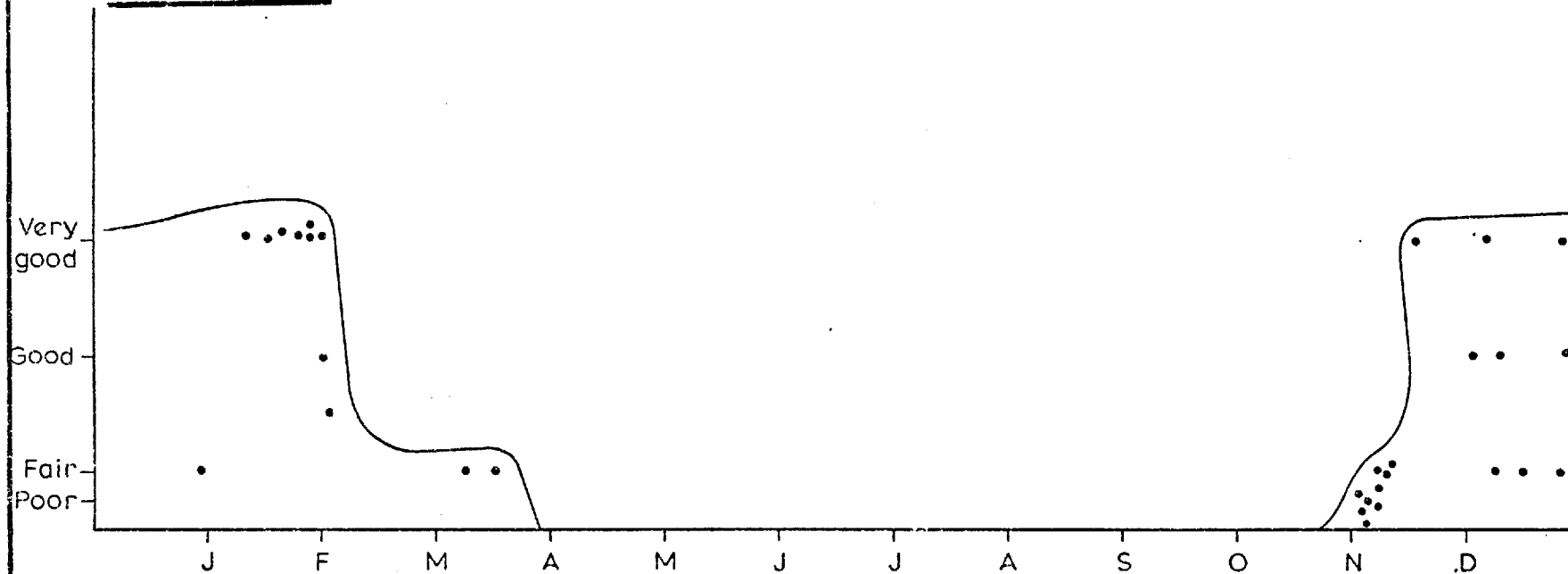
- 1 - 8 = lineaments
- i = trough marginal elongate intrusion
- r = metasediments wrapped round a stock
- e = "eye-shaped" feature
- t1, t2 = metasedimentary troughs
- m = F1 structure (refolded E-W trending folds)
- O = F3 fold
- Gm = Granitised metasediments; vg = vestiges of trough.

grey levels can be differentiated on a LANDSAT scene. Limited tone contrast allows for the differentiation and recognition of limited geological features from their background, but some areas have inherent poor image contrast. In Nigeria, for example, monotonous rolling savannah plains north of Zaria exhibit low contrast ranges.

Good tonal contrasts can improve resolution. It has been observed that in many LANDSAT scenes of Central Nigeria (Plate 2) highways 15 meters wide are resolved. Over some areas south of River Benue some seasonal roads about 5-10 meters wide appear clearly on LANDSAT images. Tonal contrast is very vital in the recognition of image objects. It is also one of the reasons why lineaments whose trends are marked by high linear moisture contents show up clearly despite their narrow widths.

2.2.4. Limited stereo effects

Over the equatorial regions the overlap between adjacent paths of the Satellite, LANDSAT is about 12-14%. This means that only 12-14% of two LANDSAT images can be seen in three dimension. For an investigation involving many successive paths about 24-28% may be the greatest percentage overlap of images that could be viewed stereoscopically. Though two bands of a scene can be examined under the stereoscope, it is not clear why a three dimensional effect should be perceived, using such bands.

Figure 7

An assessment of the best months for Landsat imagery in Nigeria

Number of cloudfree scenes used = 31

Stereoscopic examination of air photographs is regarded as very vital in photogeology (Allum 1960) because the vertical exaggeration produced under a stereoscope and the three dimensional effects make the objects studied much more natural. Although shadows give some three dimensional effects on LANDSAT photographs, these do not improve the efficiency of an interpretation quite as much as stereoscopic examinations. The small percentage overlap of satellite images in lower latitudes makes it necessary that the interpreter must be well grounded in geology to be able to extract a lot of information from these images.

2.2.5. Atmospheric conditions and best times of imagery acquisition

Closely related to weather conditions are temporary effects produced by atmospheric conditions. Haze, cloud cover and poor atmospheric conditions are factors that tend to obscure details on satellite images. These factors tend to be temporary in most places and therefore make it necessary to know the best seasons for imagery acquisition over any area to be studied. Figure 7 shows the statistics of times of best imagery acquisition for Central Nigeria.

2.3. SUBJECTIVE FACTORS

Most users of photographs realise that important factors other than the objective factors affect interpretation. These are known as subjective or human factors,

both physical and psychological. Photogeology is a science-based skill (Norman, 1969). Like most scientific procedures it involves methodical procedures like perception, recognition, analyses and deduction. Perception is an eye-brain process and therefore is bound to be affected by the environment and mental state of the interpreter. Fatigue tends to give rise to wrong or inadequate perceptions. It is therefore necessary that an interpreter should be both physically and mentally fit.

Of utmost importance in the interpretation of orbital imagery is the effort required in assuring oneself that previous knowledge does not bias or prejudice one's interpretations. If an interpreter wants to use LANDSAT images to promote certain objectives it is possible to see and select unconsciously those features that corroborate the objectives, thus shutting his mind to the wealth of evidence to the contrary. It is not advisable to start interpretations with set hypotheses.

2.3.1. The experience and geological background of the interpreter

Practically everybody can derive some form of information from images. The interpretation of geological features from photographs demands a specialised skill. It requires that the interpreter recognises that the landform he observes is a product of different inter-related dynamic processes. The interpreter therefore

requires a broad background, not only in geology but also in geomorphology, climatology, soil science and geobotany, in order to derive the maximum geological detail from a photograph. With wide and varied background, and constant use of images, the interpreter improves his mental and visual acuity and develops a strong feeling for geology from photographs. Special interpretations of particular areas require, in addition, a good understanding of the geological history of that area as well as other local factors that are likely to affect the interpretability of the images of that area.

The range of subjective and objective factors affecting photo interpretation of satellite images make field checks on interpreted features a necessity. Even after that, interpretations of an area should be related to its interpreter and should not be accepted as a generally agreed information until substantiated as such. The range of factors affecting the interpretation of features from photographs is shown in Table 3.

2.3.2. Methods of interpretation

A factor not always seriously considered is the methodology of extracting information from photographs. Experience shows that interpreting directly on satellite images invariably leads to some confusion and a tendency to over-look a lot of information.

TABLE 3 : FACTORS AFFECTING THE INTERPRETATION OF IMAGES

Object Space Factors	Factors that Affect Interpretability	
SHAPE LENGTH SIZE (AREA) EXPOSURE LEVEL ACTINIC BRIGHT- NESS CONTRAST	PHYSICAL (Inherent limits set by physical characteristics of imaging systems)	IMAGE FACTORS Sharpness, focus, aberrations, image motion, scale, grain detail and shape transfer function. Gamma, Exposure Transfer function, Latitude, Printing and projection losses. PHOTOGRAPHIC FACTORS
	PSYCHOPHYSICAL Inherent limits set by viewing process.	Sharpness of image Contrast of image Scale of image Scale of viewing Shape of object Illumination in viewing Conditions of viewing - Projection vs. direct - binocular vs. monocular - stereo vs. non-stereo Single image or mosaic Visual activity Experience Motivation Skill Intelligence Prior knowledge Environment.
	PSYCHOLOGICAL Inherent limits set by the human being.	

(Modified after MacDonald 1957)

The use of one overlay on a LANDSAT image also tends to result in the overcrowding of details on such an overlay. Over-crowded details also blurs the interpreter's mental picture of his interpretation. Clearly laid out interpretations enables the interpreter to see the relationship between imagery features, more clearly. At least two separate overlays for recording different types of information is considered minimal for satellite imagery interpretation of a scene.

The type of overlay employed is very often of some importance. Translucent and semi-transparent overlays are not very useful. It is necessary that very clear transparent material be used over the images. This ensures that the interpreter does not have to lift over his overlay for each and every pencil mark on the overlay, thereby saving some time. When two such transparent overlays are used, the master interpretation can readily be seen by putting one interpretation over the other.

2.3.3. The length of time available for the interpretation

Most LANDSAT scenes cannot be properly interpreted in one week. Very many scenes may require two weeks or more for a very experienced interpreter to accomplish. For a beginner very many months of relating photographic features to geology may be required to appreciate features on satellite photographs. The writer's experience has

been that despite considerable field experience on Nigerian metasedimentary belts, the interpretation of new features from the image coverage of this area had continued for months. Most of the features were extracted within the first few weeks, but new information continued to emerge as a result of associating interpreted features and patterns for six months after the commencement of the interpretation. Detailed reconnaissance data can scarcely be obtained from a few days' work with some of these images.

2.3.4. Some subjectivity in lineament selection from orbital imagery, based on intrusions

Lineaments are one of the most widely recognised features that can be extracted from orbital images. Most interpreters infer lineaments based on the arrangements of igneous bodies. Lineaments, so selected, are considered to be subjective, because it is possible that radically different trends could be interpreted from a set of igneous intrusions. Figure 8 shows the possible number of lineament trends that can be interpreted from seven intrusive bodies. Though Figure 8 is only a hypothetical diagram, it shows what tends to happen and why some interpreted lineaments may very often have no corroborative field evidence whatever, simply because they do not exist.

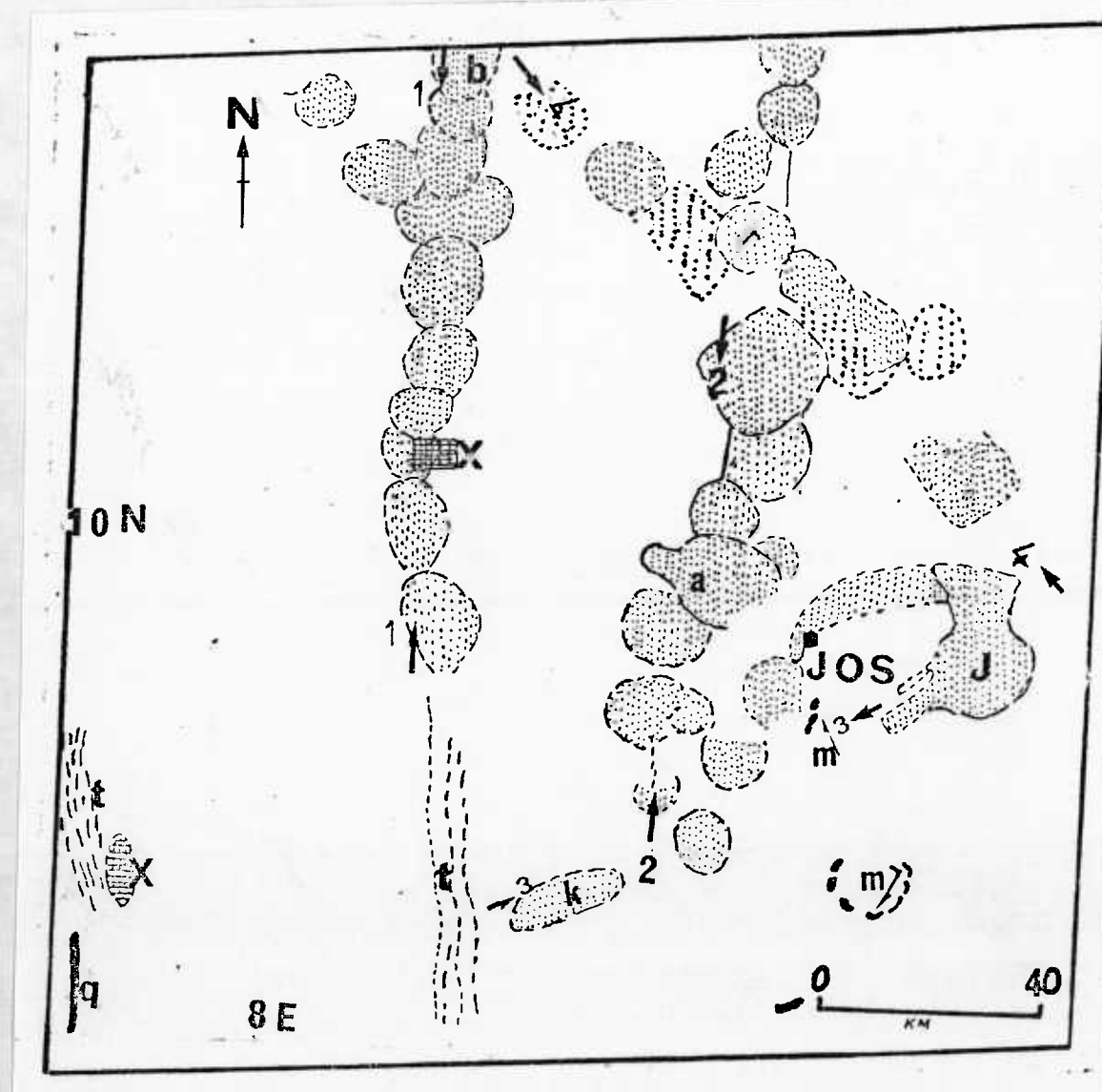


PLATE 3

A LANDSAT-1 image of the ring complexes of the Jos Plateau, showing N-S overlapping intrusions

1, 2 and mines, m.

t = part of metasedimentary trough, t2, covered by Plate 2



A photogeological outline of the main features of Plate 3

1, 2, N-S lineamenta

3 = NE trending lineament

4 = NW alignment of ring intrusions

a = Amo-Buji complex

J = Jarawa complex

b = Banke ring intrusion

x = 600 $\pm$ 100 m.y. "Older Granite".

q = quartzites.

t = basement trends;

k = Kagoro complex

r = Rishi complex

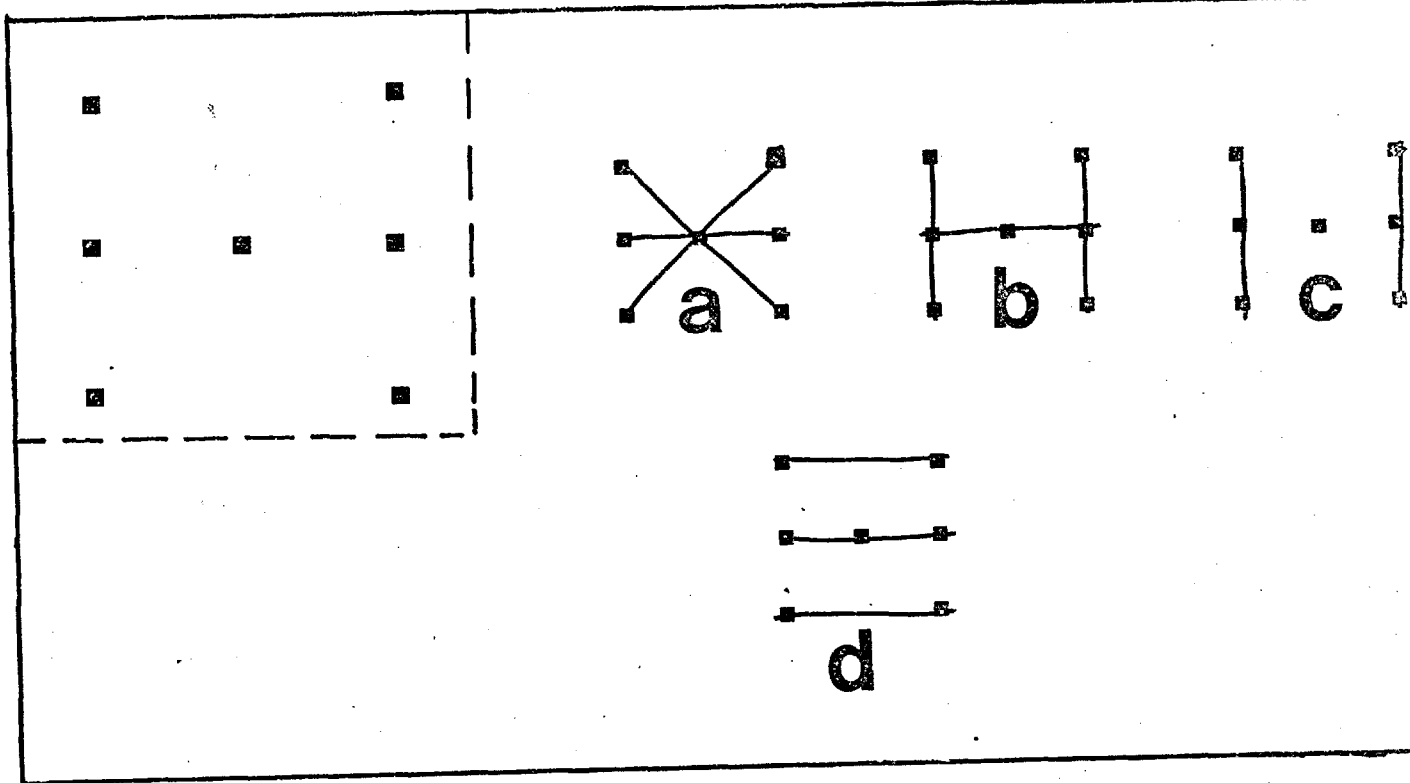


Figure 8. Diagram illustrating the subjectivity of lineament trend interpretation from igneous bodies alone.

It is suggested that though contiguous arrangement of intrusions for several miles (PLATE 3) can indicate important lineaments, it is insufficient to propose a lineament by joining two distant intrusions. When two distinct intrusions are suspected as being controlled by the same tectonic element, traces of the connecting link ought to be established on either the image or on the ground, based either on linear alignments of vegetation and topography or on fracture zones.

CHAPTER THREE

SOME USEFUL CRITERIA FOR TECTONIC INTERPRETATIONS FROM SATELLITE IMAGES

3.1. DIRECTLY OBSERVED FEATURES ON IMAGES

The several factors affecting the type of geological data obtainable from satellite images of Nigeria were considered in the last chapter. Climatic factors play a major role in determining the manifestation of geological features such as intrusions, faults and volcanic rocks on orbital images. There are also other geological data that can be inferred from certain patterns and feature associations established for an area. The more important criteria for the tectonic interpretations of satellite images of Central Nigeria include lineaments, intrusions, basement trends, metasedimentary structures and drainage patterns.

3.1.1. Lineaments

Most users of LANDSAT imagery would agree that by far the most prominent features interpretable from satellite images are lineaments. Lineaments are defined here as significant lines on the earth's surface of "a precision which rules out fortuity" (Brock, 1957). Though lineaments manifest themselves as linear alignments of vegetation, topographic changes, streams and fractures, their causes are not precisely known. Except where a

deep tectonic origin for a lineament is supported by geophysical evidence, it is often difficult to differentiate those lineaments resulting from deep-rooted tectonic causes from those of a more extrinsic nature.

On satellite images, lineaments can show up either as visible lines or as changes in photographic tones. If tonal changes occur persistently along a line for several tens of kilometers, a lineament is indicated. Where a basement lineament fracture zone or lineament is covered by younger sedimentary rocks, the clarity of the feature on LANDSAT images is considerably diminished. The trace of such concealed features can however often be indicated by a linear arrangement of volcanism, intrusions, brine springs and mineralisations. Repeated movements of concealed lineaments can manifest as faults in the younger rocks. The ground locations of some lineaments are generally wide topographic depressions. In areas of heavy rainfall such depressions may contain rivers, streams or marshes. Jointing is usually better developed than in the adjacent area. The fracture traces within the lineament zone as exemplified in Nigeria, tend to have a preferred orientation corresponding with the general trend of the lineament on the ground. Some lineaments of Central Nigeria are positive topographic features. The positive lineaments tend to be fracture zones infilled with hard and resistant substances like quartz or dykes.

The geometry of lineaments vary. Some are straight, while others are curved. Some lineaments are partly straight and partly curved, while others are arranged en-echelon. Experiences from lineament studies within Central Nigeria show that traces of some lineaments mapped by other workers as faults, when traced across two or more satellite image frames show marked curvatures. Also in Nigeria, there are lineaments arranged in a concentric pattern.

It is not always clear whether all the lineaments observed on images are due to geological causes. In built-up areas it is difficult to differentiate some cultural features from tectonic lineaments. Formation contacts that may not be tectonically controlled may show up as lineaments. Studies of Central Nigerian lineaments are not complicated by excessive cultural effects since there is hardly any mechanised agriculture and features that may introduce spurious effects. It was also observed that band 5 defines cultural lineaments very well in Nigeria. Cultural lineaments are also readily recognised from the way they anastomose from urban centres.

Lineaments, like air-photo derived fractures often occur as an array of parallel or sub-parallel traces on images. Such lineaments are considered to belong to a system and to be genetically related. When one lineament system persistently truncates another over an extensive

area, the truncated system is considered to be the older. Studies of Central Nigerian lineaments also have shown that lineaments belonging to a system may occur at regular spacing, (Chukwu-Ike and Norman, 1977). The reason for this regular occurrence is largely speculative but may not be unrelated to stresses caused by changes in the rotational speed of the earth.

Neither the classification of lineaments nor the usage of words like "linear" and "lineation" as synonyms for lineament defined above, is widely accepted by geologists. O'Leary et al. (1976) suggested that the term "linear" should be used as an adjective to describe the line-like nature of a feature, while the term "lineation" should be left for the description of rock fabrics. These definitions are adopted in this thesis. The writer strongly feels that a non-genetic connotation should be associated with the word "lineament" to avoid a too-restrictive meaning. The term as originally defined by Hobbs (1904) did not have any genetic connotation. Words like 'tectonic', 'topographic', 'cultural' etc. could be used to qualify lineaments when such origins are definite. For the purposes of this thesis, the word lineament is intended to stand for a "tectonic lineament" unless otherwise stated.

Arbitrary classifications of lineaments into short, long and intermediate, occur in the geological literature

(Kowalik and Gold 1976). Some lineament tectonicians prefer to classify lineaments into global, regional and local (Katterfeld, 1976). The difference between local lineaments on the one hand and regional and global lineaments on the other, as suggested by Katterfeld (1976), is that while regional and global lineaments occur in parallel sets, local fractures and lineaments are not as systematic. Studies of Central Nigerian lineament show that non-systematic patterns are related, quite frequently with local tectonic disturbances.

3.1.2. Criteria for inferring types of faulting from LANDSAT lineaments

Geologists recognise normal faults, reverse faults and strike-slip faults as the three main types of faulting. The distinction between the three types is based on relative displacements of the same features on opposite sides of the fault. The type of faulting in an area gives some information about the initial stress distribution causing the faulting (Price 1966, Hills, 1970). The same characteristics used in classifying faults may sometimes be obvious from orbital images. Some of the characteristics used for inferring the types of movement on LANDSAT lineaments include the relationship between lineaments and other features, the regional configurations of metasedimentary troughs, and the cross-cutting relationships between lineaments.

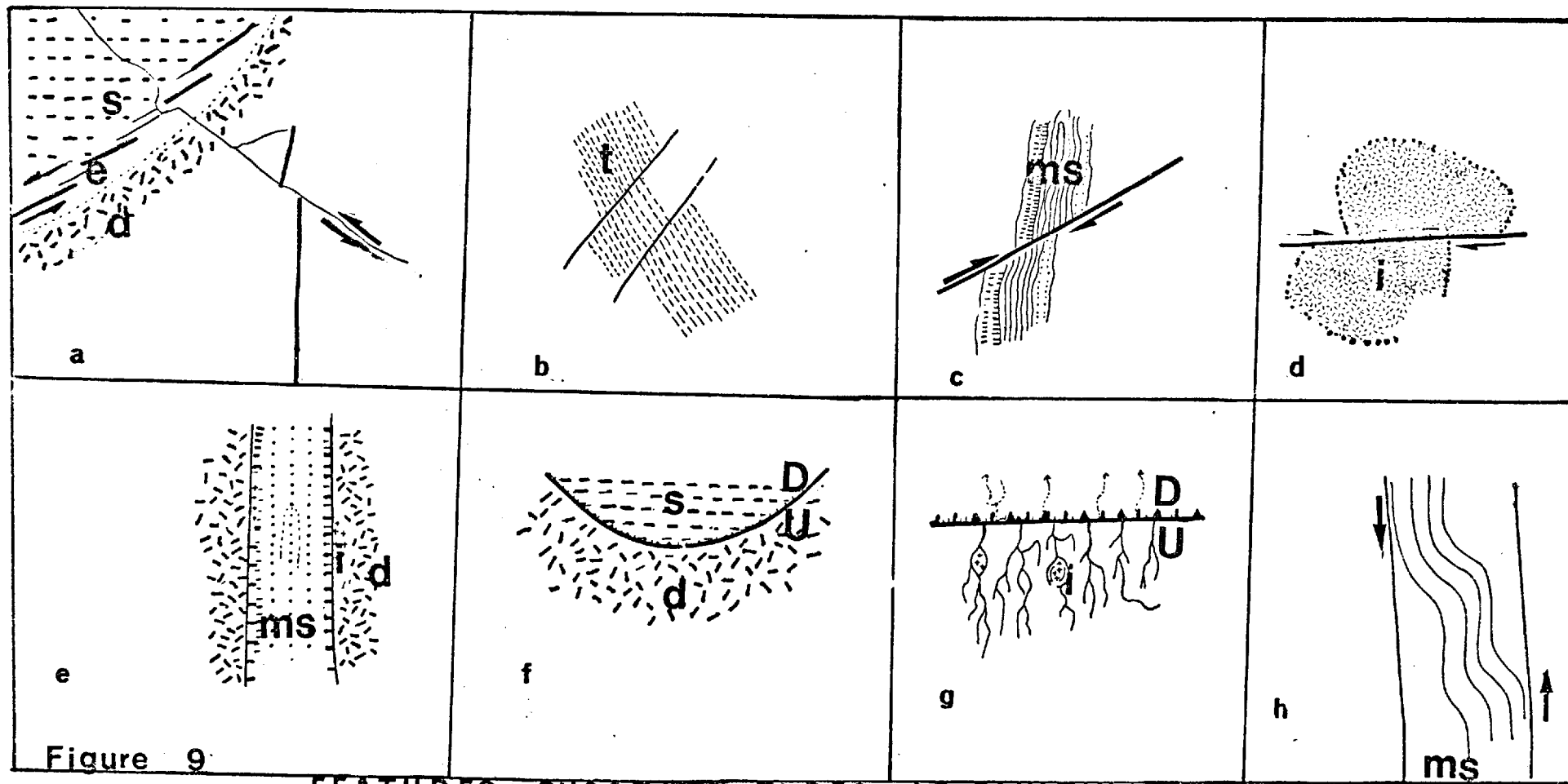


Figure 9

FEATURES SUGGTING TYPES OF FAULTING ON IMAGES

S, ms metasediments; i intrusion; d older basement t trends;

e en echelon fractures; $\frac{U}{D}$ lineaments.

(a) Cross-cutting relationships

Cross-cutting relationships between two lineament trends can very often indicate the dominant type of faulting. In practice, however, movements along a lineament may show both strike-slip and vertical movements. In two dimensional photographic studies, strike slip faults tend to be the more easily recognisable. When one lineament displaces another, in a horizontal sense, strike-slip faulting can be inferred (figure 9a). In strongly foliated rocks, lineaments associated with strike-slip movements cause the foliated rocks to have a zig-zag edge depending on the relative motions. Such excursions of foliations along lineaments are indicative of strike-slip faulting. (figure 9b). Transcurrent faults are also indicated by horizontal shifts of narrow meta-sedimentary troughs as well as similar displacements of an intrusive body (figures 9c and d).

(b) Structures suggestive of normal faults

Normal faults are suggested on LANDSAT images by the association of lineaments with margins of sedimentary and metasedimentary basins, (figure 9e). Within the NW Nigerian metasedimentary belt, discrete N-S metasedimentary troughs are known. The present study has shown that there are marginal lineaments to these troughs. Elongate intrusions are associated with the marginal lineaments (Plate 2). Isoclinally folded quartzites and pelitic

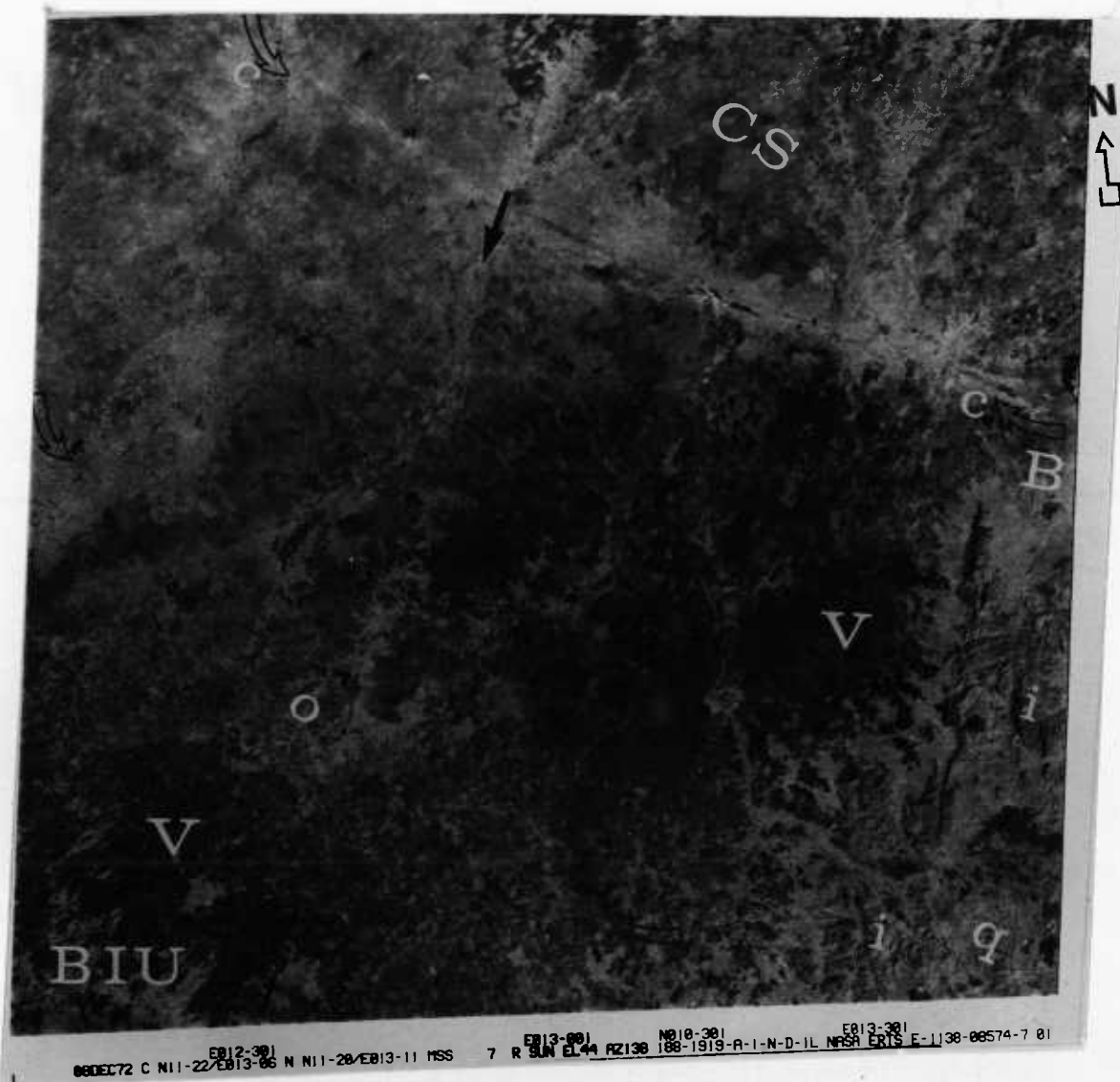
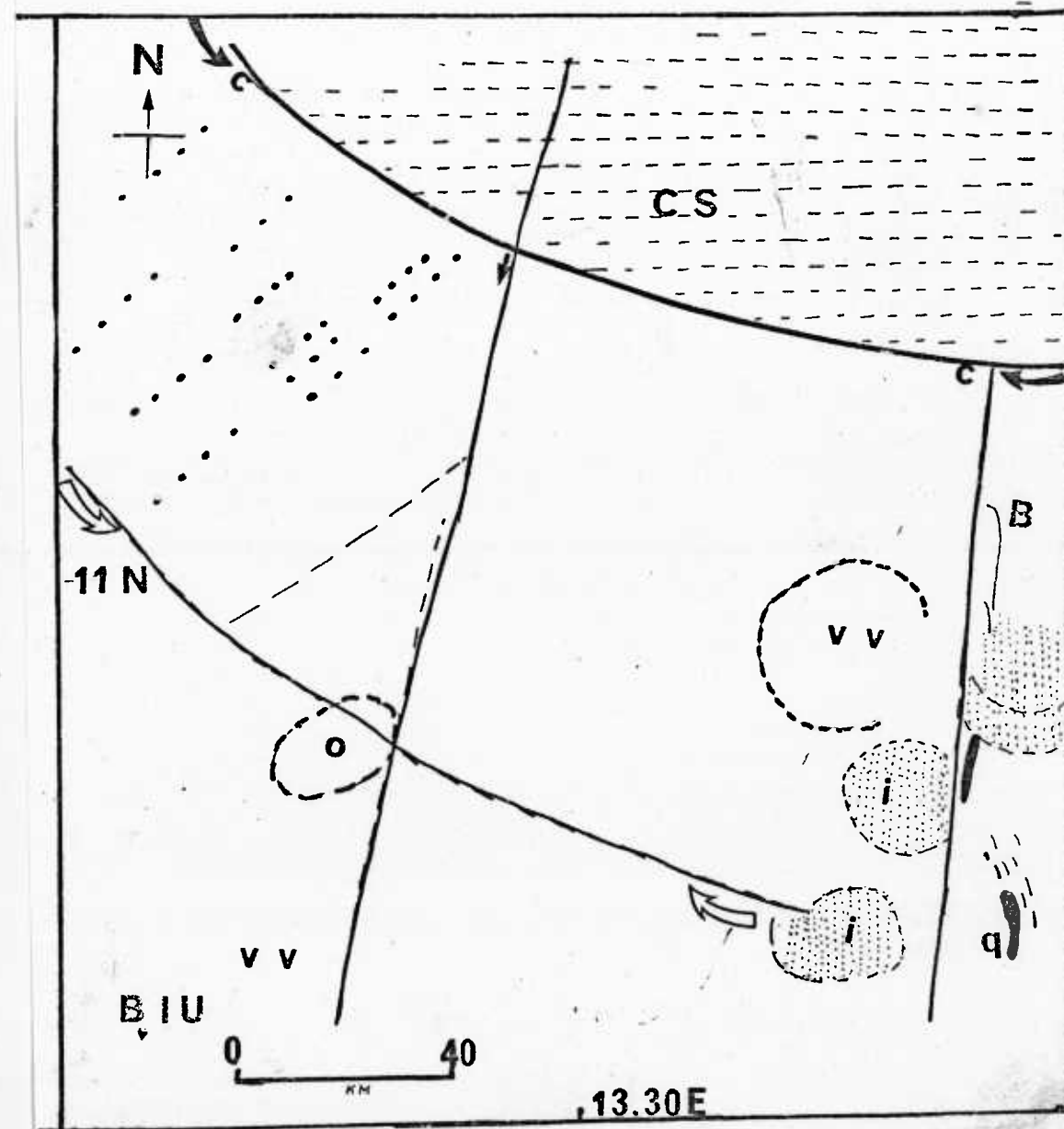


PLATE 4

A LANDSAT-1, image of Biu-Maiduguri areas showing the Chad basin CS and a curved lineament, c.

Note another faint curved lineament (arrow) passing through the circular feature o. The trace of a N-S lineament is shown by a black arrow.



A photogeological sketch of the main features of Plate 4.

- V = volcanics
- B = Basement complex
- q = quartzites
- i = granitic intrusions
- c = circular lineament
- o = circular feature (concealed)
- CS = Chad basin sedimentary rocks.

schists occur within the troughs. It is thought that the marginal lineaments are fracture zones that are associated with the basin subsidences and related magmatism. The marginal lineaments therefore appear to have had strong vertical stress components.

Circular and concentric lineaments, hundreds and even thousands of kilometers in diameter often have their centres located inside Phanerozoic sedimentary basins. The contact between the basin and the older basement is often the location of a curved lineament in Central Nigeria (Plate 4). Such curved basin-margin lineaments on LANDSAT images are interpreted to be normal faults (figure 9f).

In some areas like the Zaria-Malumfusi axis in Central Nigeria (Plate 5), it is seen that drainage is well defined along one side of a drainage divide. Laterites, and duricrusts also tend to be better developed on the side with well defined drainage. The area with well-defined drainage on LANDSAT images tend to be relatively more youthful topographies and therefore areas undergoing uplifts. The line along which the drainage is divided, is interpreted as forming the block boundary and axis of uplift. It is therefore most probably a normal fault or a shear fault with a strong vertical stress component.

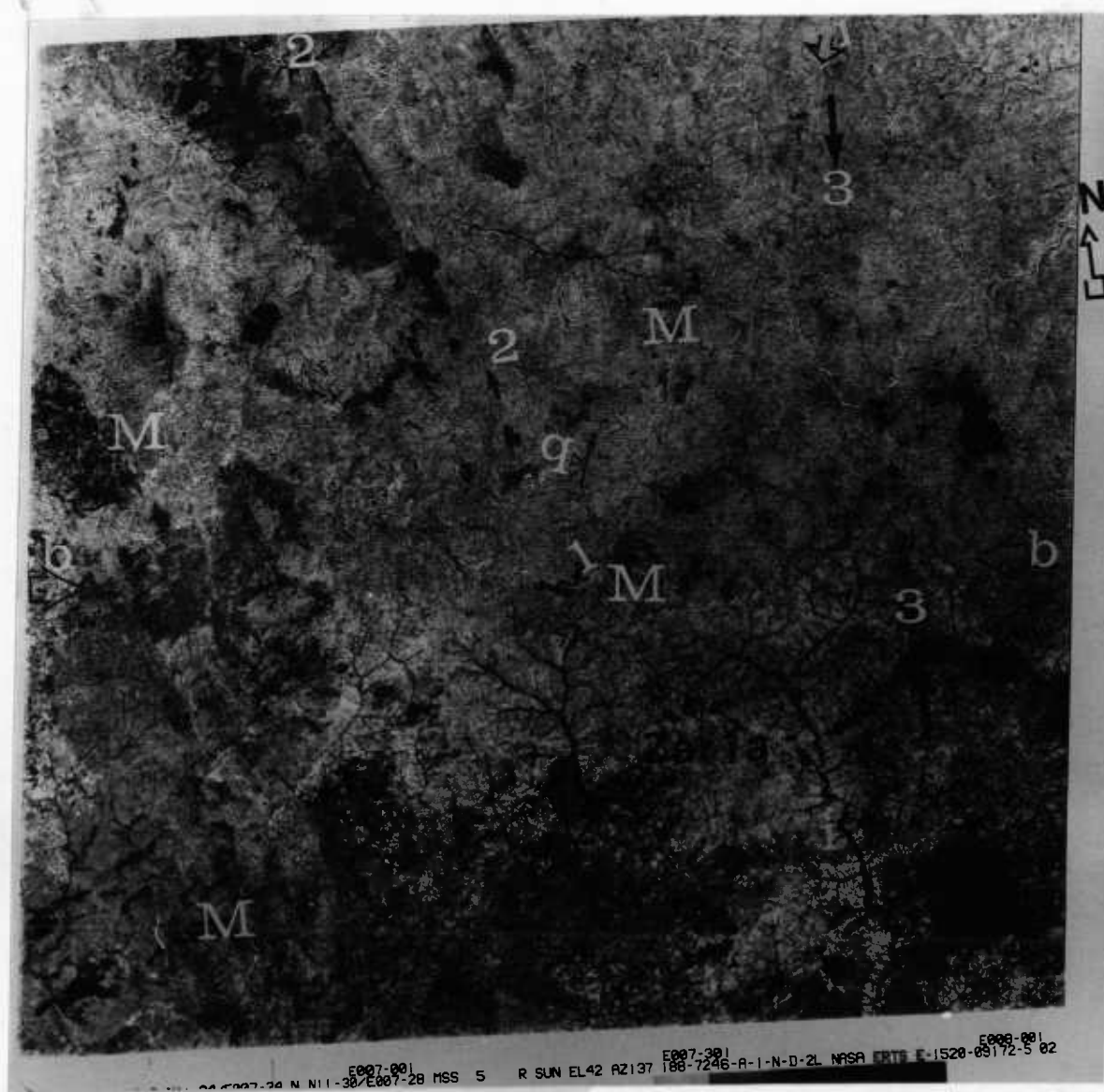
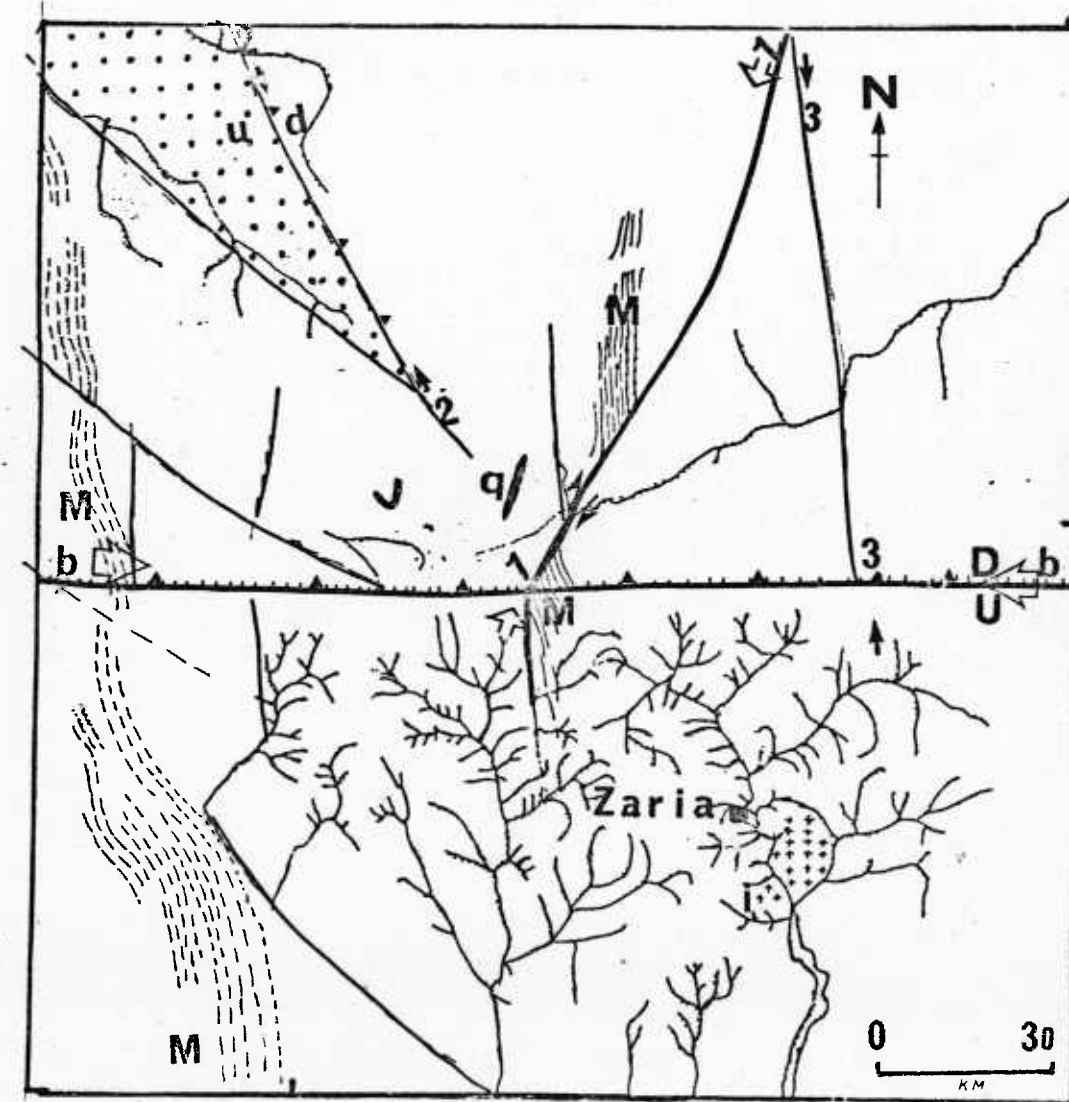


PLATE 5

A LANDSAT-1 image of Funtua-Zaria areas showing a suspected crustal block boundary and line of uplift, b.

M indicates metasedimentary troughs.

Note the sigmoidal shape of metasediments near the left margin of the image.



A photogeological outline of the main features of Plate 5.

b = suspected crustal block boundary

1 = Yaribori fault (mapped by McCurry 1973)

2 = A NW trending shear zone

3 = A N-S shear zone

i = a circular feature

q = a quartzite ridge

D/U = inferred directions of block movement.

(c) The geometry of linear troughs

The Western part of Plate 5 shows a belt of meta-sedimentary rocks. The present study has shown that this and other metasediments occurring within the Central Nigeria are fault bounded. The metasediments within the trough in figure 5 appear sigmoidal in shape. This basin configuration may be suggestive of shearing movements of the flanking faults (Prof. J. Watson, personal communication). In the present case, a right lateral shear movement for the marginal fractures is suggested by the trough configuration

3.1.3. Basement tectonic trends

The term 'tectonic trend' is used here to describe any linear fabric in rocks and formations. It included such things as foliation in gneisses and other rocks, strikes of lithological units, fold axes, trends of pegmatitic veins and sheets, closely spaced fractures and other fabric elements. Tectonic trends have been used in Precambrian geology to elucidate the history of a complex basement terrain (Hepworth 1967). The use of trends alone for inferring the tectonic chronology of a basement is suspicious because of the tendency for trends to be obliterated by subsequent orogenies and also the tendency for trends referable to one episode to change directions. The concept that Precambrian terrains like those of Africa are made up of ancient undeformed nuclei

around which successive orogenic belts have progressively wrapped, further strengthened the association of trends and orogenies. Although so many causes can give rise to structural trend, their use as diagnostic features are still recommended (Hepworth 1967). However their use for Precambrian correlation needs to be more specific to features such as relic bedding trends or distinct fracture trends.

Many types of basement trends can be discriminated on LANDSAT photographs. Basement trends representing relic metasedimentary bedding appear as long continuous lines (Plates 2, 5 and 6). Trend lines arising from strong schistosity as in banded gneisses appear short and less distinctly (f, plate 7). Trend lines due to fracturing appear dark and continuous and may connect two or more intrusions.

The advantage in using orbital images for basement trend studies is that, deflections in trends belonging to one orogenic event can be readily identified. This is so, because each image covers a very large area and therefore becomes useful in tracing trend lines along their strikes. Good examples are refolded lunate folds within the Nigerian basement which are each over 50 kilometers long. Their strikes change from NW through E-W to NE (m, Plate 2). These variations in strike associated with one structure may be more difficult to comprehend in the absence of LANDSAT synoptic images.

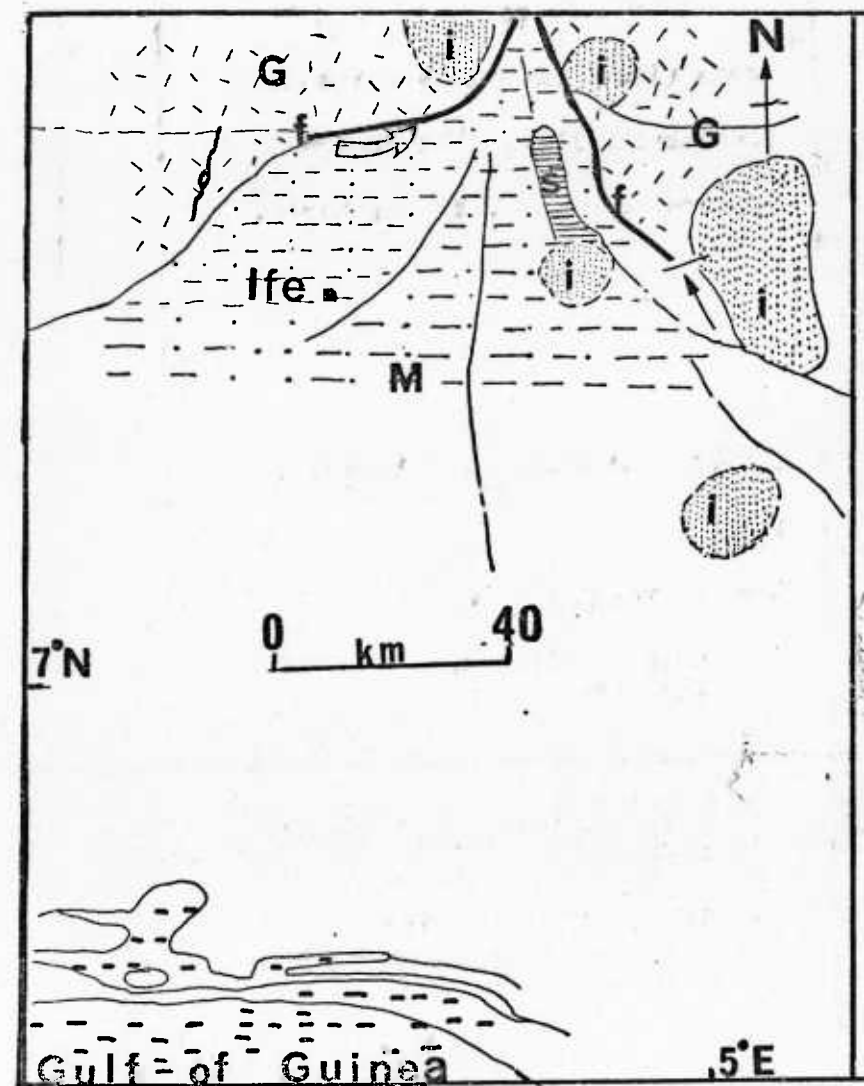
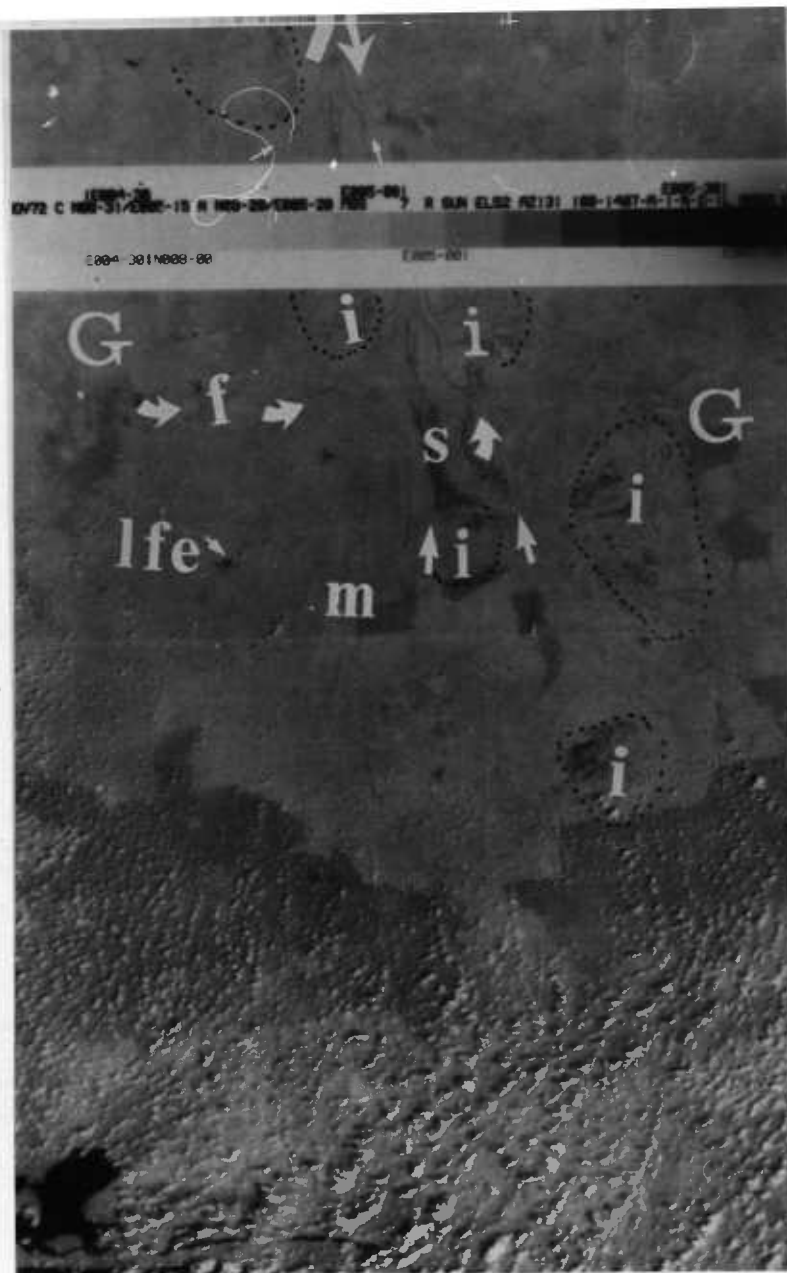


PLATE 6

A LANDSAT-1 image of Ife and Iwo areas (left) showing a suspected Precambrian rift. The trough appears to die out to the North.

A photogeological sketch of Plate 6 (right).

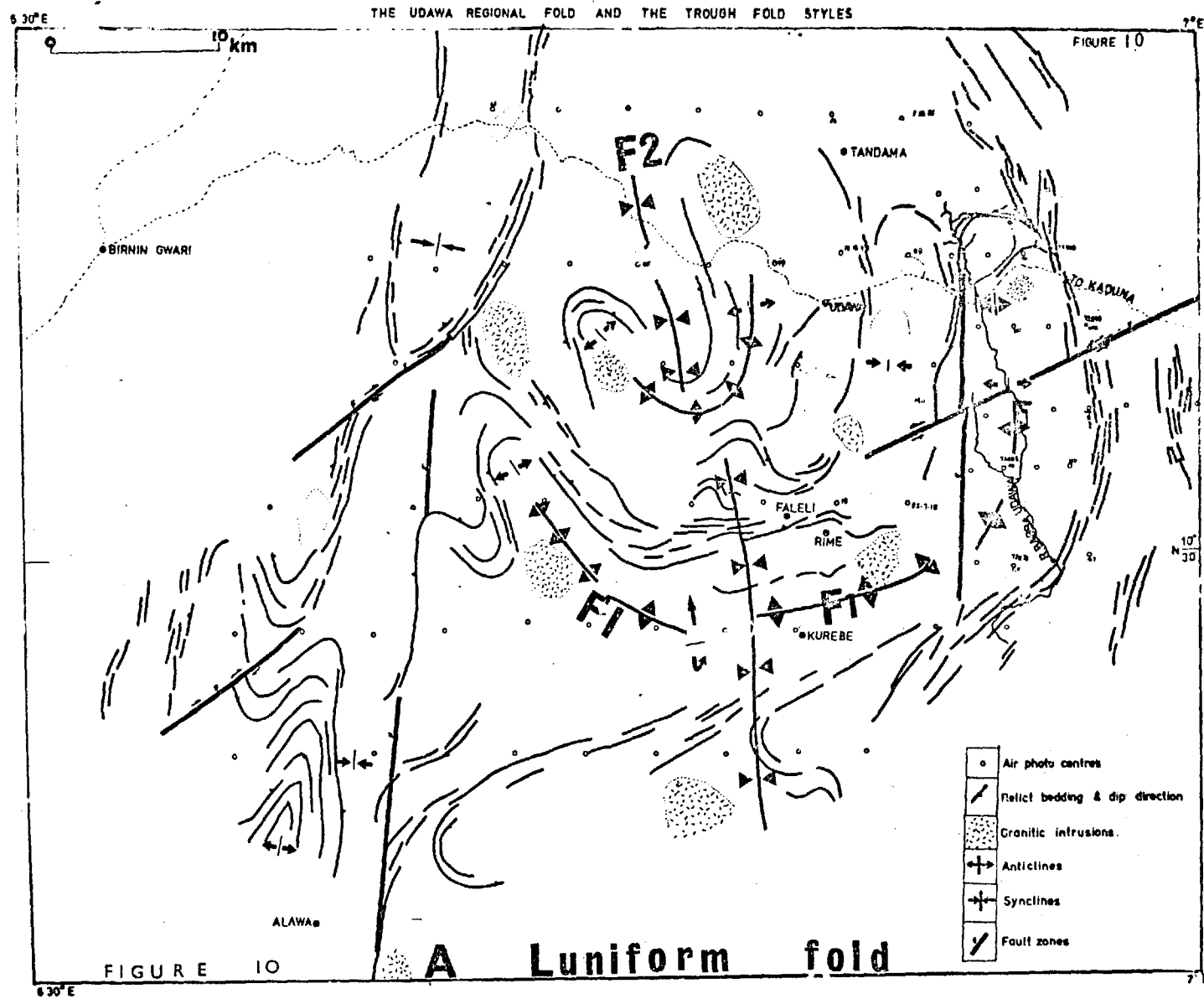
G = a granulitic basement

f = marginal fracture zones of the rift.

s = schists

i = marginal intrusions of the rift.

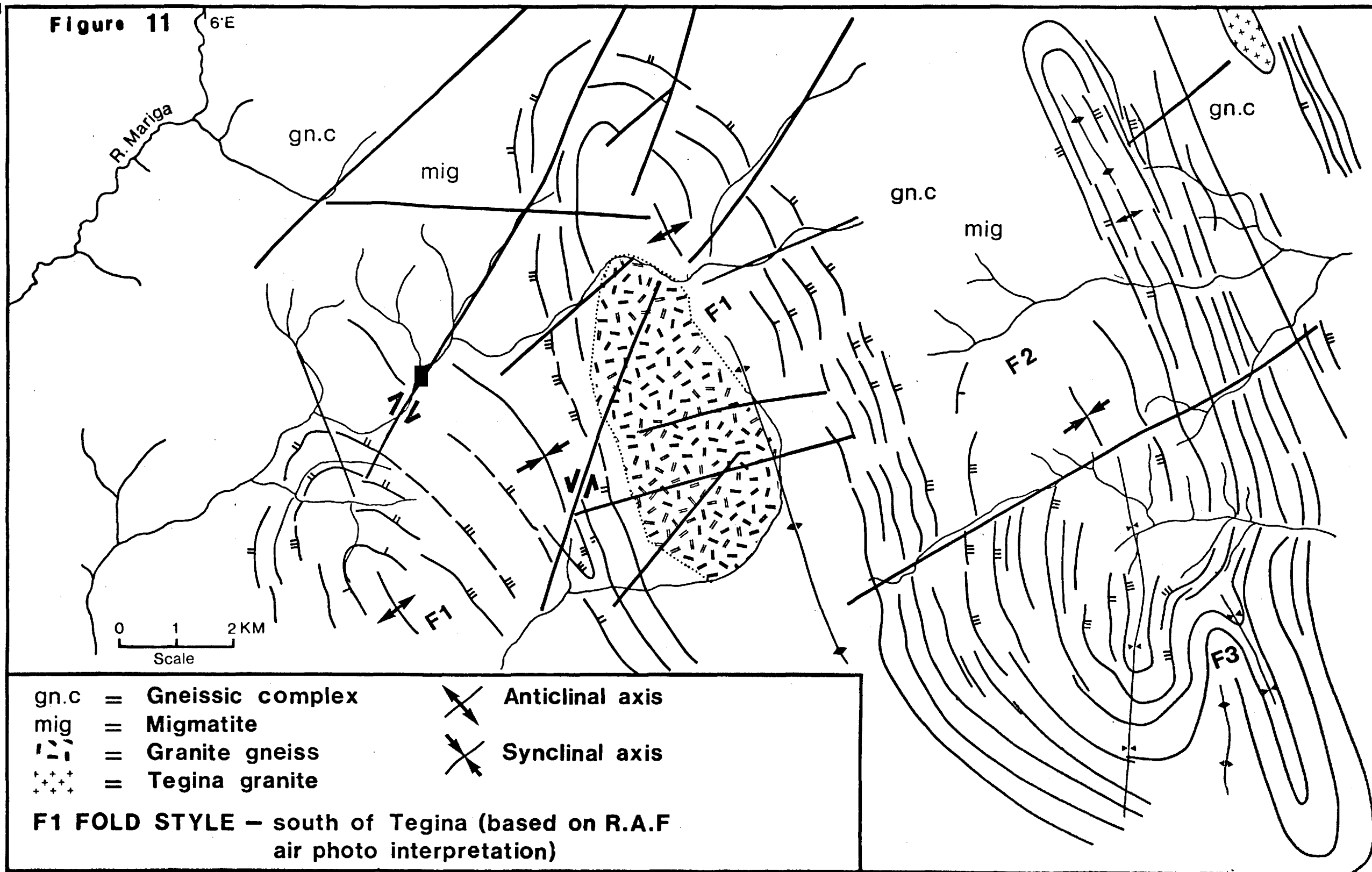
m = low grade metasediments



10° N

Figure 11

6° E



3.1.4. Fold geometries

The present LANDSAT imagery studies of the Nigerian metasedimentary belts, indicate that several regional variations in fold styles can be recognised. The variations in fold styles are regional and are considered to be independent of lithology. They therefore have been associated with regional stress changes. After establishing the different fold styles, criteria for dating their chronological sequence were sought from the images.

In Central Nigeria, three major fold patterns of regional significance are recognised in this study. Very frequently LANDSAT images indicate the nature of refolded structures. The axis of refolding corresponds to the axial trend of a later fold (figures 10 and 11). Variations in the tightness of folds having the same axial trend suggest coaxial refolding.

3.1.5. Drainage patterns

Second order and lesser order tributaries of rivers are generally poorly resolved on LANDSAT images of Nigeria. Vegetation associated with such lesser order drainages in Central Nigeria show up on false colour composite images as red lines (Appendix 1). Generally, drainage networks appear better defined over rugged terrains and uplifted areas.

False stereoscopic studies of two component bands

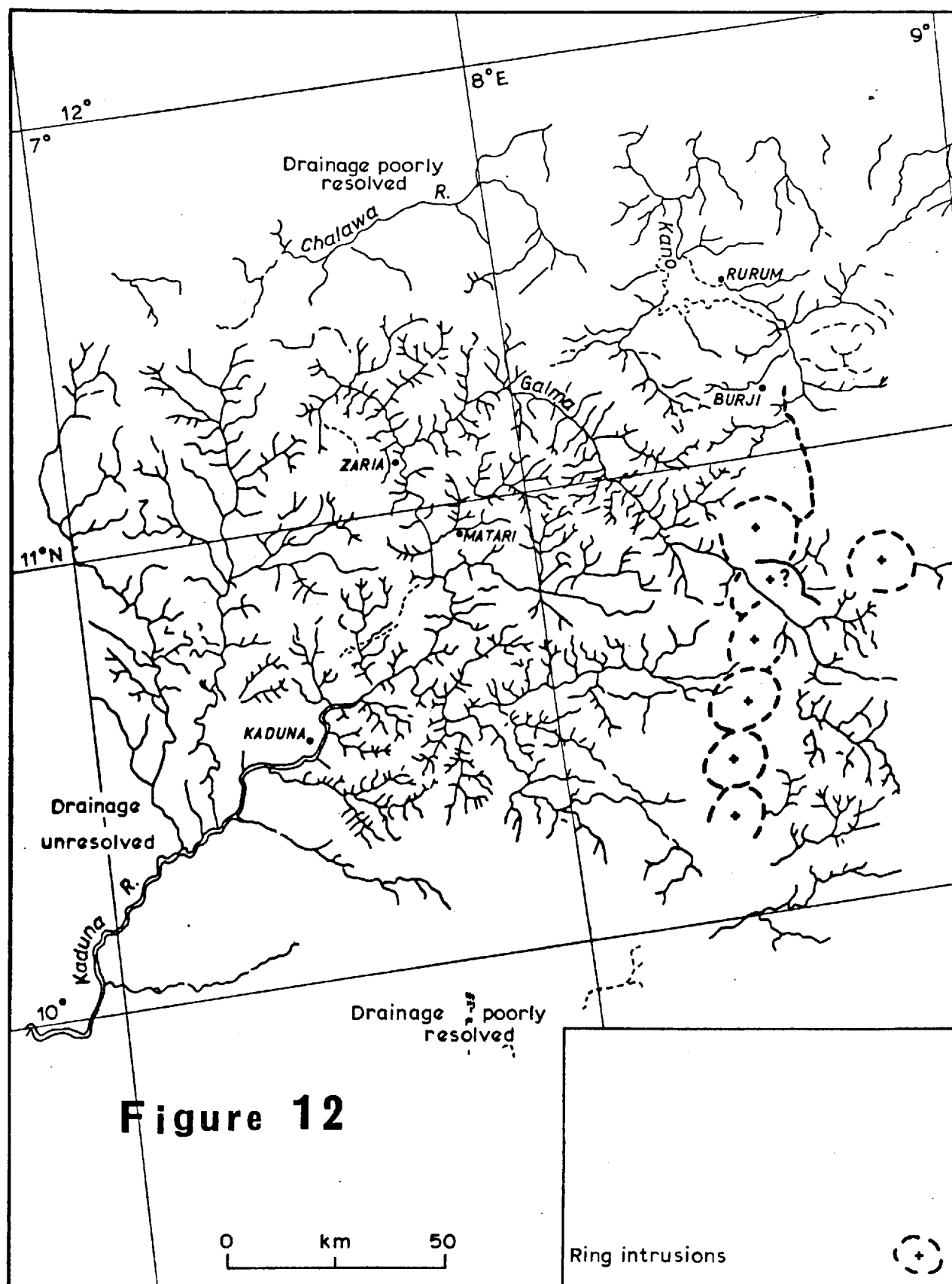
of a LANDSAT scene was found useful in drainage studies using satellite images, because the river courses appear clearer. LANDSAT images have also been found superior to air photographs in relating collinear river courses that may be structurally controlled. Plates 2 and 5 illustrate some drainage characteristics of images and figure 12 illustrates possible structural interpretations from Plate 2.

3.1.6. Major tonal contrasts indicative of major changes in lithology

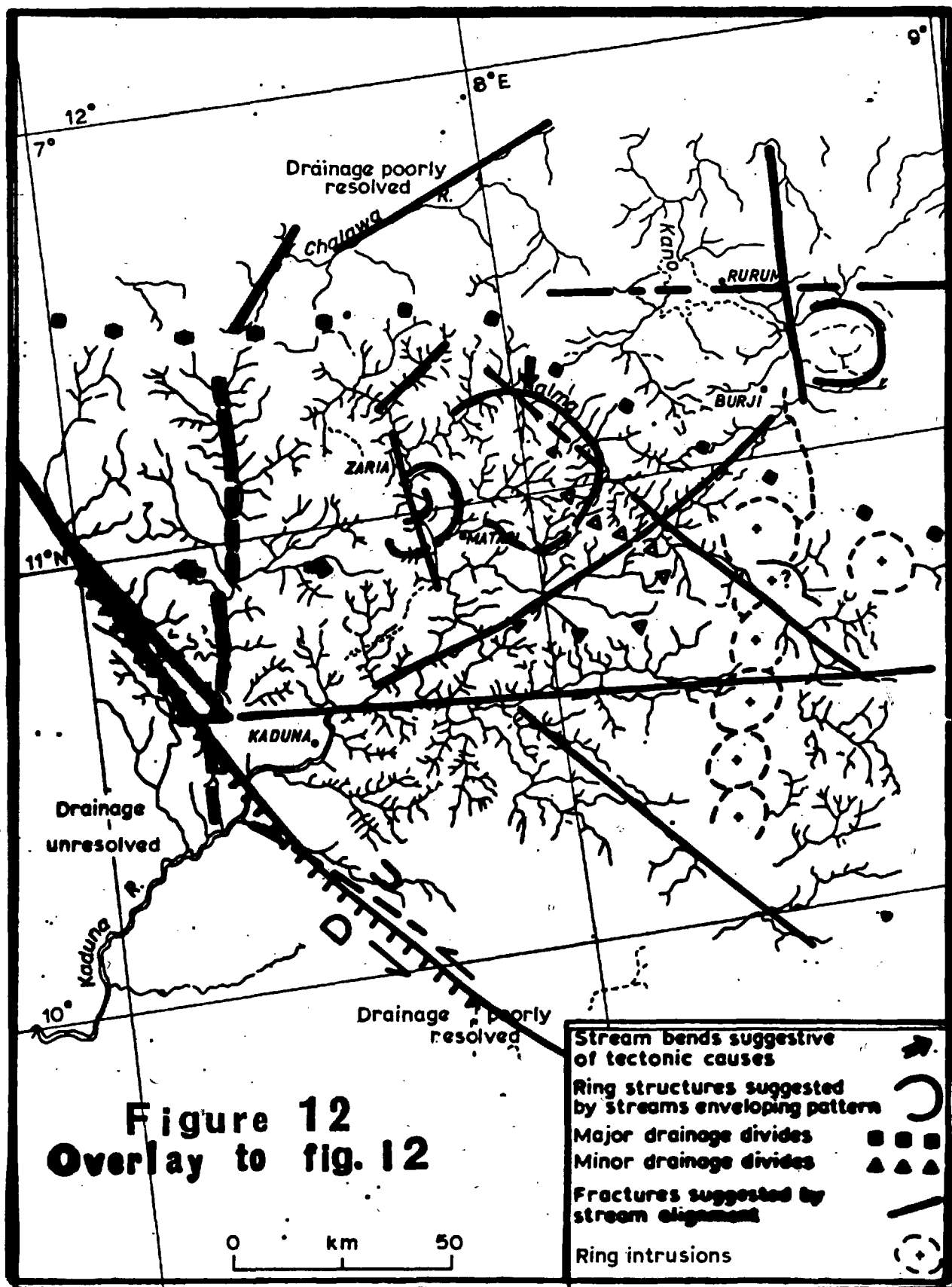
It is difficult to name any rock type from LANDSAT images. Major rock groups, however, appear differently on images, as a result of differences in spectral reflectivities and absorption. Vegetated areas contrast with bare areas on images. Plate 2 shows that the metasediments of NW Nigeria appear darker in tone than the surrounding migmatites and gneisses. It was found very helpful to trace off areas of distinct tonal contrasts and to check such areas for the possible causes of the tonal characteristics. Generally major changes in rock type give rise to differences in vegetation overgrowths which in turn may affect image tonal contrasts.

3.2. FEATURES INTERPRETED FROM PATTERNS AND ASSOCIATIONS OF ONE FEATURE WITH ANOTHER

Pattern is defined as "the spatial arrangements of objects" (Colewell, 1954). The repetition of certain



Landsat drainage analysis of parts of
Central Nigeria



Landsat drainage analysis of parts of
Central Nigeria

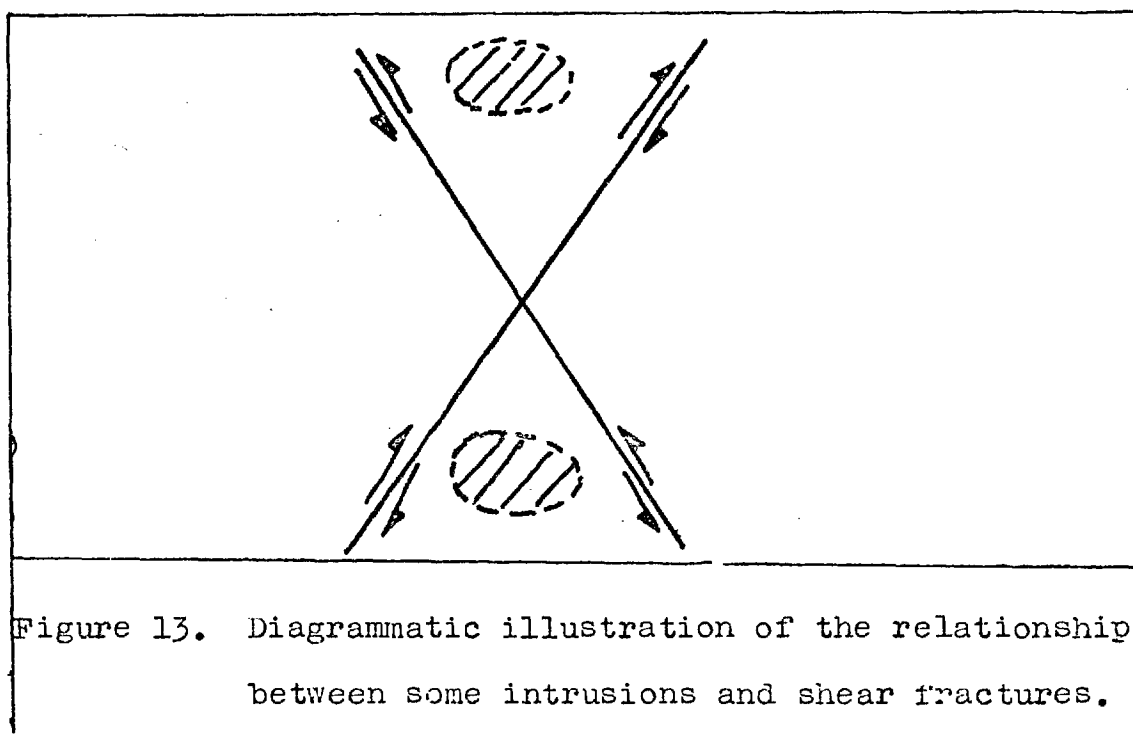
general forms or relationships of many objects can be noticed on photographs and this aids the photo-interpreter in recognising them. Orbital imagery studies of Nigeria show that certain imagery features are closely associated, and provide good interpretation guides even under conditions of thick soil developments and laterites.

3.2.1. Domes, intrusions and metamorphism

Circular features are common in many LANDSAT photographs. The causes of these features or what they represent are very often uncertain. Field checks on some of the circular features in Nigeria show no ground evidence while some others indicate the presence of domes by very gentle dip changes. Many lineaments of Central Nigeria are associated with intrusions of different shapes, having different radiometric ages. Some granitic intrusions associated with the Nigerian lineaments are elongate in shape with their longer axes oriented towards the north (Plate 2). The elongate intrusions yield a Pan African age, 600 ± 100 m.y. (Jacobson, Snelling and Trusswell, 1964).

The recognition of this pattern enables some important deductions to be made. In eroded soil covered areas, of Nigeria granites may remain relatively higher in elevation and more resistant. Such granites when elongate may suggest not only the presence of crustal lineaments but also that the area in which they are found

may have been affected by the Pan African event. Thus the pattern established for some exposed areas becomes useful in other soil covered terrains. It was also noted that apart from the relationship established for elongate intrusions and lineaments, other relationships are evident. Some circular structures occur at the intersection of shear fractures. The movement along such shear fractures suggest that they may possibly be conjugate. Circular features like those near Minna (Plate 2), occur at the tensional wedge of two shear fractures.



It was stated in the previous section of this chapter that low grade metasedimentary rocks have a contrasting tone on images. Lineaments and intrusions occur marginal to metasedimentary rocks now known to occur in discrete troughs over Central Nigeria. Prior to the recognition of the marginal fractures to these troughs,

previous workers (Wright 1976) considered that the marginal intrusions rose in the manner of mantled gneiss domes. The recognition of linear axes of intrusions separated by low grade metasediments suggests that axes of intense heat flow and therefore of metamorphism have some bearing with the location of the lineaments. Barrovian type metamorphic zoning is lacking under this circumstance. Regional metamorphic grade tend to follow geological structures. Photogeological examination of uplifted areas in Nigeria (Plate 3, The Jos ring complexes), shows that the alignment of intrusions in a chain-like manner may be a low level equivalent of the low grade marginal intrusions occurring elsewhere. The ring complexes may have enclosed metasedimentary rocks now completely eroded away.

3.2.2. Structures suggestive of ancient graben

Structures considered by some geologists to represent Mesozoic-Recent rifts, such as the East African rifts, are characteristically long, narrow down-dropped parts of the earth usually less than 90 kilometers wide. They may be branched and may contain sedimentary rocks. Gravity anomalies along the rift are also known to be elongate and often arranged symmetrically about the rift axis (Cratchley and Jones, 1963, Milanovsky, 1976). Rifts are also known to be axes of high heat flow (McConnell, 1974, Milanovsky, 1976).

Very little work has been done on the criteria for recognising ancient rifts on cratons, because rifts have, for a long time, been considered by most geologists as entirely Mesozoic-Cenozoic features. McConnell (1974) suggested that this notion is very wrong and that very ancient geological structures may have predetermined the location of Phanerozoic rifts. Milanovsky (1976) suggested that based on statistics available to him, continental rifts tend to parallel or lie along direct continuation of oceanic rifts and that some rifts may appear to die out at both ends. It is pertinent to note that the relationship between oceanic and continental rifts as indicated by Milanovsky (1976), is explained by the concept of astrons (Norman, Price and Chukwu-Ike 1977) which will be discussed later in this thesis.

Satellite images appear to be very useful in suggesting locations of ancient rifts. The images cover areas far larger than the width of an average rift. Marginal fractures and lineaments to the rifts as well as intrusions associated with such marginal fracture zones are frequently well defined on orbital images. Metasediments within the ancient rifts usually display a marked strike discordance with those belonging to the rocks of the older rifted basement. The concentration of igneous activity on the marginal lineaments of a suspected ancient rift is probably indicative of high heat flow similar to those of Phanerozoic rifts. Plate 6 shows a

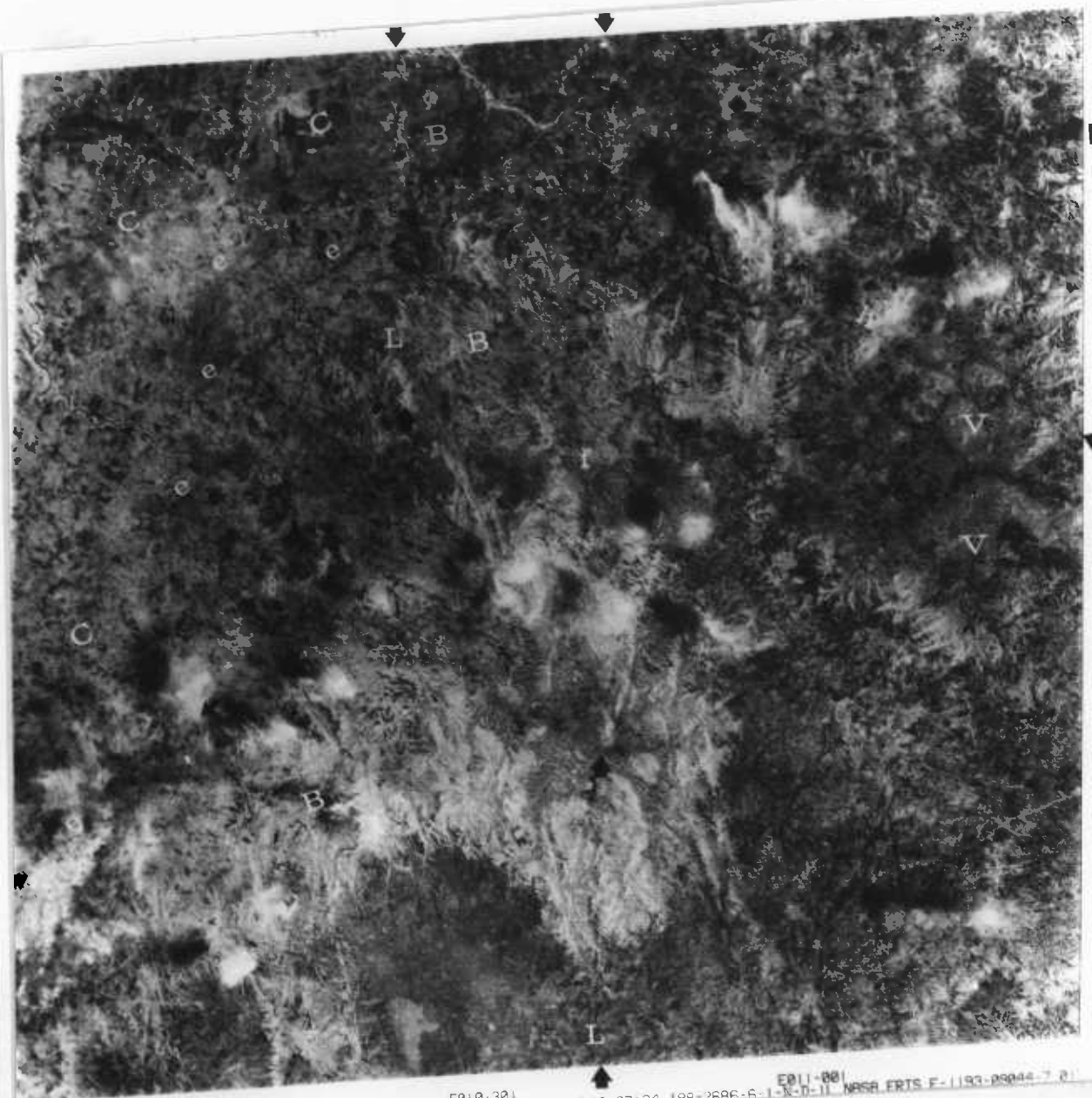
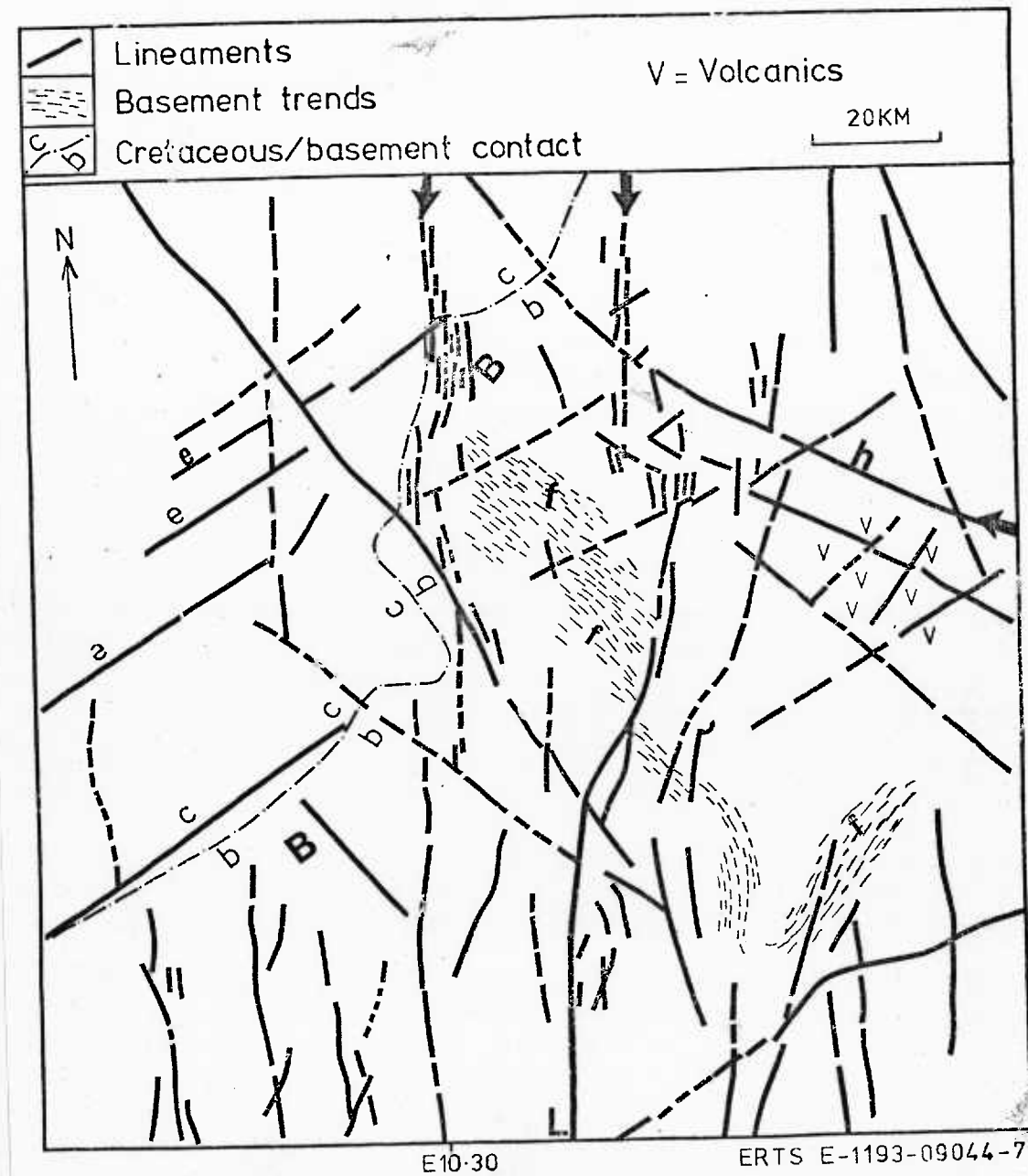


PLATE 7

A LANDSAT- 1 image of Southern parts of the Benue trough showing trough marginal en-echelon lineaments and the tonal contrasts between the Basement, B, and the Phanerozoic cover, C.



A photogeological outline of the main features of Plate 7.

- e = en echelon fractures and lineaments.
- L = N-S lineament
- f = foliation trends
- v = volcanics
- h = NW trending lineament
- C = Cenozoic sediments
- B = Basement complex

feature suspected from LANDSAT imagery to represent a Precambrian rift. The intrusions are arranged along the marginal fractures. The metasediments within the fractures are low-grade and contrast with the amphibolite-granulite facies of the older rifted basement.

3.2.3. Fracture patterns

Fracture patterns known to be associated with certain rock-types such as basalts and granites are often interpretable from LANDSAT images. In the absence of good geological maps, such areas of peculiar fractures were field-checked. Plate 7 shows a N-S lineament controlling some volcanic rocks marked V. The volcanic rocks are alkaline basalts. Field checks on the basalt indicate that it is lateratized and characterised by hexagonal jointing. An examination of Plate 7 indicates that large hexagonal lineament patterns are visible on LANDSAT images.

Plates 8a and 8b also show some regular arrangement of orthogonal linear features. Geological maps of Nigeria clearly show that both Plates 8a and 8b cover dominantly granitic terrains. Although the distance between the locations of Plates 8a and 8b is over 800 kilometers, the similarities in the type and arrangement of linear features and tones of the images, suggest that the underlying rocks are similar.

N
1



PLATE 8

LANDSAT images of Central Nigeria,
showing faint orthogonal lineaments,
at Abuja area (far left) and east
of River Gongola (centre) and around
the Nigerian- Cameroon border (right).
Arrows show the traces of the
orthogonal fractures.

g = granite

v = volcanics

Note that the trends of fractures
in (a) and (b) are different from
those of (c). This may suggest
that the granite body (c) was
affected by a different stress
system from those of (a) and (b).

1.6 = N-S lineaments

3.2.4. Inferring different relative erosional levels

LANDSAT images often suggest variations in different erosional levels. Plate 1 shows how tonal changes can suggest step-like arrangement of scarps or step faults. The higher surfaces represent the older and vertical movements therefore are predominant.

It is also possible on LANDSAT images (Plate 2) to trace metasedimentary troughs along their strikes, from areas where the metasediments are well displayed through areas where they are partly preserved to areas where only their vestiges are discernible. Such vestigial areas are interpreted as representing former lower crustal levels, now exposed by erosion.

CHAPTER FOUR

THE RELATIONSHIPS BETWEEN AIR PHOTO DERIVED FRACTURE TRACES, FRACTURE ZONES AND SATELLITE IMAGERY LINEAMENTS AND CURRENT THEORIES ABOUT FRACTURES AND LINEAMENTS

4.1. FRACTURE TRACES SHOWING ON AIR PHOTOGRAPHS

A photogeological fracture trace often referred to simply as "fracture trace" is the photographic image of linear features such as topographic, drainage, vegetation soil and rock tonal alignments, visible on images and suggestive of physical breaks or fractures of any length on the surface of bare or soil covered rocks (Zwain 1976, Huntington 1975). Earlier workers on fracture traces (Norman, 1968, Lattman 1958) were concerned with ascertaining the geological significances of these air photo linear features.

Permyakov (1949), Blanchet (1957), Lattman and Nickelsen (1958) have suggested that linear features observed on air photographs under a mile in length are reflections of local jointing and small faults. Norman (1968) argued that depending on the area investigated, that as low as 30% of linear features observed on photographs may represent fractures while as high as about 70% may be reflections of soil tonal changes, lithological boundaries and glaciation features.

4.1.1. Qualitative aspects of fractures

Air photo fracture traces commonly appear rectilinear or curvilinear in shape. Frequently sinuous features are observed, as well as annular fractures. Some geologists believe that during the formation and propagation of fractures sinuous shapes may be developed as a result of stress build-ups at the ends of the faults and fractures. Ring-shaped fractures however demand a different explanation for their formation. Most fractures showing on air photos are steeply dipping.

Some fracture patterns are associated with certain geological structures. For example, radial and annular fracture patterns have been associated with domes and igneous intrusions (Norman 1976); some parallel fractures may be associated with fold axes. Fractures associated with a particular tectonic compressive force can occur as conjugate sets whose intersections may often subtend angles of about 60° . Zwain (1976) suggested that the attitude of a folded bed can affect the characteristics of fractures developed and that the steeper limb of an asymmetrical anticline often contains shorter, more closely spaced fractures having more acute angles of intersection than the gentler limbs.

Orthogonal and sub-orthogonal fracture intersections are often associated with less deformed parts of the earth, although some rock types, including granites,

characteristically exhibit orthogonal fracturing.

4.1.2. Quantitative aspects of fracture traces

The number of fracture traces obtainable from air photographs are often very numerous and require some statistical treatments to arrange them into sets. The statistics commonly employed include the study of directional variations, differences in length and in frequency and density per unit area. Classifications of fracture traces based on lengths are arbitrary and vary from one investigator to another. Lattman (1958) considered joints and other linear features that are less than a mile in length as "fracture traces" and those more than a mile in length as "lineaments". Haman (1964) considered that the term "fracture trace" has a genetic connotation and should not be associated with the term "lineament". He therefore suggested the term "macro-fracture" for joints and air photo linear features more than one mile in length. It appears that a tectonic lineament and a fracture as seen on air photographs and images mean the same to most geologists except for the differences in lengths.

4.1.3. The techniques of fracture trace analyses

Fracture trace analysis from air photographs is a rapid way of studying linear breaks in rocks over a large region. Fracture trace interpretation draws a lot

from laboratory experimental work on the behaviours of rocks under stresses. Qualitative and quantitative study of fracture patterns are considered important for mineral and oil exploration.

Blanchet (1957), pioneered the development of fracture trace analyses as an exploration technique. He indicated that the crust of the earth is systematically and extensively fractured in four principal directions, N-S, E-W, NW-SE and NE-SW. Blanchet (1957) attributed the development of the four directions mainly to stresses such as the gravitational effects of the moon and the sun and to changes in the rotational speed of the earth. Blanchet (1957) argued that if the earth were homogenous, fractures would occur in the four directions mentioned above but that structural and stratigraphical anomalies introduce departures from this systematic fracture arrangement. Blanchet correlated more than average fracturing per unit area to such features as salt domes, buried intrusions and anticlines. Huntington (1975) and Zwain (1976) contain comprehensive reviews on the techniques of fracture trace analyses as an exploration tool.

4.2. THE FORMATION AND PROPAGATION OF FRACTURES

Fracture traces have been reported in recently deposited sediments as well as in older rocks (Rumsey 1973). It is difficult to envisage such soft rocks as having undergone brittle deformation. Fracture trace

analysts believe linear features appearing on unconsolidated sediments as resulting from a process of fracture propagation from the underlying rocks. The mechanism whereby fractures traces are transmitted through sedimentary piles from the underlying basement is poorly understood and the following processes have been suggested:-

4.2.1. The fatigue theories

The fatigue theories propose that small stresses of a certain critical value when applied periodically lead to rupturing of rocks. The fractures produced by fatigue start off as minor cracks which gradually increase with subsequent application of stresses. Thus the fatigue theory allows for rock failures under stress well below the ultimate strength of the rocks. Fatigue stresses and strains are accumulated by both internal and external forces. The following suggestions are put forward as producing the fatigue stresses:-

(a) The moon's gravitational attraction of the earth

The attraction of the Moon and Sun on the Earth produces periodic rise and fall of the sea level. High tides in some places may reach about 10 - 15 meters. Some earth scientists believe that the tidal forces produce fatigue on the crust as a result of the repetitions of the applied stresses. Blanchet (1957) and Hodgson (1961) supported the idea of systematic fracture generation and

upward propagation by the periodic action of tides on the crust.

(b) Seismic activity

Some geologists maintain that fractures in cover rocks are produced by earthquake shock-waves, resulting from the release of accumulated stresses and strains within the crust. Seismic energy is believed by many to be responsible for the development and reactivation of fractures (Mollard, 1959).

(c) Rotational stresses of the earth

It is known that the Earth spins around its axis. It also rotates round the sun. Some geologists believe that the rotation of the Earth about its axis and its revolution round the sun produce major N-S and E-W stresses. These stresses then give rise to crustal fractures and lineaments (Moody and Hill, 1956). The departure of the earth's course round the sun from a circle and the oblateness of the earth indicate that a North-South stress system may exist. It is believed that the combination of N-S and E-W stresses deformed the earth's shape into an ellipse and that the N-S stresses are constant for all areas of the earth while the E-W stresses decrease polewards.

4.2.2. The gravitational theories

The gravitational pull at the earth's crust is

regarded by some geologists as an important factor in the formation and propagation of crustal fractures. The gravitational theories are based on stresses set up by sedimentary piles and by isostatic imbalances resulting from erosion and deposition.

(a) Stresses set up by compaction

The accumulation of thousands of meters of sediments can give rise to strong lithostatic pressures. These lithostatic pressures can create additional pore-fluid pressures within the sediments thus weakening the shear strength of the rock masses. Failures and flexuring take place within the rocks being buried in an attempt to adapt to these pressure conditions. It is known that in sedimentary basins containing rock salt, upward salt movements can be initiated by lithostatic pressures alone and halokinesis (salt movement) can give rise to fracturing of competent rocks in a sedimentary succession. Lithostatic pressures can also give rise to differential compaction and dewatering of certain rock types like clays. These volume changes can give rise to tension fractures.

(b) Isostatic adjustment

Isostasy is the tendency for the earth's crust to attain equilibrium, mostly as a result of mass transfer from one place to another. The erosion of the rocks from mountainous and high areas causes a relief of loads from

the crust. Deposition of sediments conversely adds more load to the crust. Relief of loads causes uplifting while deposition leads to crustal subsidence. The whole concept is based on the assumption that the earth's sialic crust (30Km thick) rests on a liquid sima. Some geologists believe that isostatic movements can give rise to earthquake shocks which in turn can produce fractures and lineaments through soils, sediments and glacial drifts (Mollard, 1957).

4.2.3. Meteoritic impacts

Studies of the Moon and Mars and other planets of the solar system indicate the existence of large craters and circular fractures as well as areas of mass concentrations. These structures have been interpreted as resulting from large meteoritic impacts (Baldwin, 1968). Wise and Yates (1970) suggested that lunar impact structures were later modified by endogenic processes such as volcanisms.

Small impact structures have been reported on the earth by geologists but not at the scale it occurs in other planets of the solar system. The present study has drawn attention to a unique arrangement of concentric lineaments often thousands of kilometers in diameter. These concentric lineaments are associated with peripheral graben and intrusions (Norman, Price and Chukwu-Ike, 1977) and closely resemble structures obtained by Gareth Jones (1965) from detonating 500 tons T.N.T.

It is most likely that since the earth must have had a similar origin to other bodies of the solar system, it must have been hit by large meteoritic impacts. This situation appears more likely when it is realised that the gravitational attraction of the earth is many times greater than that of the moon. The large concentric African lineaments, which will be described in later chapters may have originated from impacts. The term 'Astron' has been suggested for the strain-hardened cratons associated with such impacts (Norman, Price and Chukwu-Ike, 1977).

4.3. LINEAMENTS AND FRACTURES

Lineaments as important tectonic features visible on LANDSAT images have been discussed in Chapter Three. The original definition of the word lineament by Hobbs (1910) was meant to include topographic lines, soil tonal and vegetation alignments of uncertain origin. Subsequent users (Sonder 1949, Brock 1957) associated lineaments solely to tectonic causes, thus restricting the meaning of the word. Many workers on linear features seen on air photographs relate fractures to lineaments. Lattman (1958) for example, suggested that any fracture trace greater than one mile in length could be referred to as a 'lineament', while the term 'mega lineament' was suggested for a fracture trace over twenty miles in length.

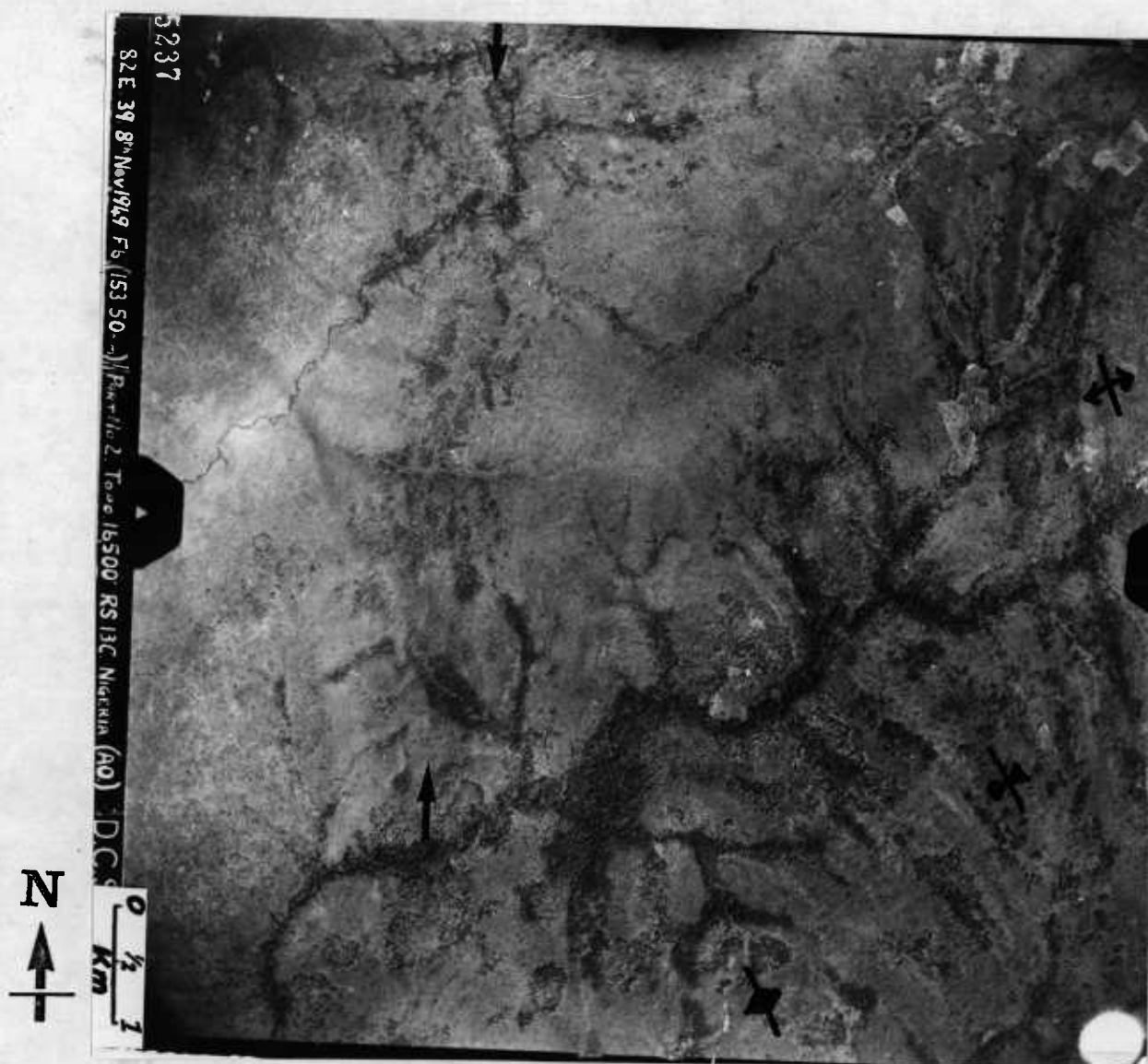
It is obvious that lineaments could originate from

tectonic causes, but this is not always the case. There can be lineaments of uncertain origin. It seems to the writer that a non-genetic meaning should be associated with the term lineament, unless otherwise stated.

4.3.1. Nigerian lineaments and air photo fractures

Very many linear features are visible on LANDSAT images. It is very often difficult without interpretation controls to know which lineaments are not tectonic. In Central Nigeria for example (f, Plate 11) many meta-sedimentary troughs containing resistant quartzites, trend in the same general direction as many lineaments. However image tones and contrasts are helpful in suspecting linear features that may represent relic beds. Where a quartz filled fracture zone within a trough, strikes in the same direction as the trough, it may not be apparent on images, as reflecting a tectonic feature.

Many lineaments within Central Nigeria tend to be broad topographic depressions, sometimes many kilometers across. Such lineaments are not clear-cut fractures as would be expected of faults of the size encountered in field mapping, but are complex fault zones. On air photographs, such complex fault zones sometimes many kilometers across may not be apparent. Plate 9 is an old air photograph covering parts of the contact between the gneissic basement of NW Nigeria and the low grade trough meta-sediments. The photograph shows very little evidence of

PLATE 9

A 1949 RAF photograph showing the closure of the Nigeria F1 folds near Zungeru, NW Nigeria.

Arrows show the trace of a N-S fracture zone visible on LANDSAT images as a N-S lineament.

Note the short distance between two successive anticlines. A full interpretation of this and adjacent photographs is shown in figure 11.

faulting (arrows, Plate 9), whereas on the LANDSAT image (Plate 2), a major tectonic lineament is indicated.

An interpretation of photographs covering the location of a LANDSAT lineament when compiled, tends to show a persistent parallel occurrence of closely spaced photographic fracture traces trending in the direction of the lineament (figure 17a). Vegetation tends to be better developed along lineaments in the more arid northern parts of Nigeria.

4.3.2. Lineament manifestation on the ground

Ground checks on good ground exposures of some LANDSAT lineaments of Central Nigeria indicate that they often form broad negative topographic features generally many kilometers across. A few are positive topographic features while some are in part positive and negative in other parts. Jointing is usually better developed along the location of a tectonic lineament. Streams and rivers may flow along some segments of some lineaments. The Central Nigerian lineaments are characterised by planar silicified mylonites and blastomylonites. Flaser gneisses have been associated with segments of lineaments that now appear to represent lower crustal levels. Over many parts of the Central Nigerian Basement, the lineaments tend to align fold trends referable to different tectonic episodes to a N-S direction. Plate 10a shows a ground photograph of planar silicified mylonites along a lineament

10a



PLATE 10a (top)

A ground true colour photograph of rock exposure within a N-S lineament showing fractures and planar silicification. Note the preferential growth of grass and vegetation along the joints.

PLATE 10b (below)

A ground based true colour photograph of the negative topographic depression as well as porphyritic granite (P) associated with the Nigerian N-S lineaments in the vicinity of Zaria.

10b



while Plate 10b shows the ground topographic expression of a lineament and a marginal porphyritic granite, in Central Nigeria.

4.4. THE THEORETIC BASES FOR RELATING LINEAMENTS

4.4.1. The Conjugate-shear model

The modes of rock fracturing in crustal rocks have been established in laboratory tests under different environmental conditions (Price 1966, Griggs, 1960). Anderson (1951) and Moody and Hill (1956) have supplied some corroborative field evidence. For brittle deformation, fractures within rocks may be related to the principal stresses in the following ways:- 1) They may be conjugate shear fractures oriented such that the acute bisectrix is parallel to the maximum principal compressive stress, σ_1 . 2). They may be extension fractures parallel to σ_2 and perpendicular to the minimum principal compressive stress, σ_3 . The conjugate shear model is of two types known as the pure shear and simple shear structure mechanics (fig. 14a, b). Both simple shear and pure shear mechanics produce conjugate fracture pairs. Some geologists believe that simple shear couple mechanics do not always produce conjugate fracture pairs, but can have tensional fractures arranged at 45° to the differential forces. Uplifts and step faulting have been associated with simple shear couples (Thomas 1976). The tensional fractures associated with simple

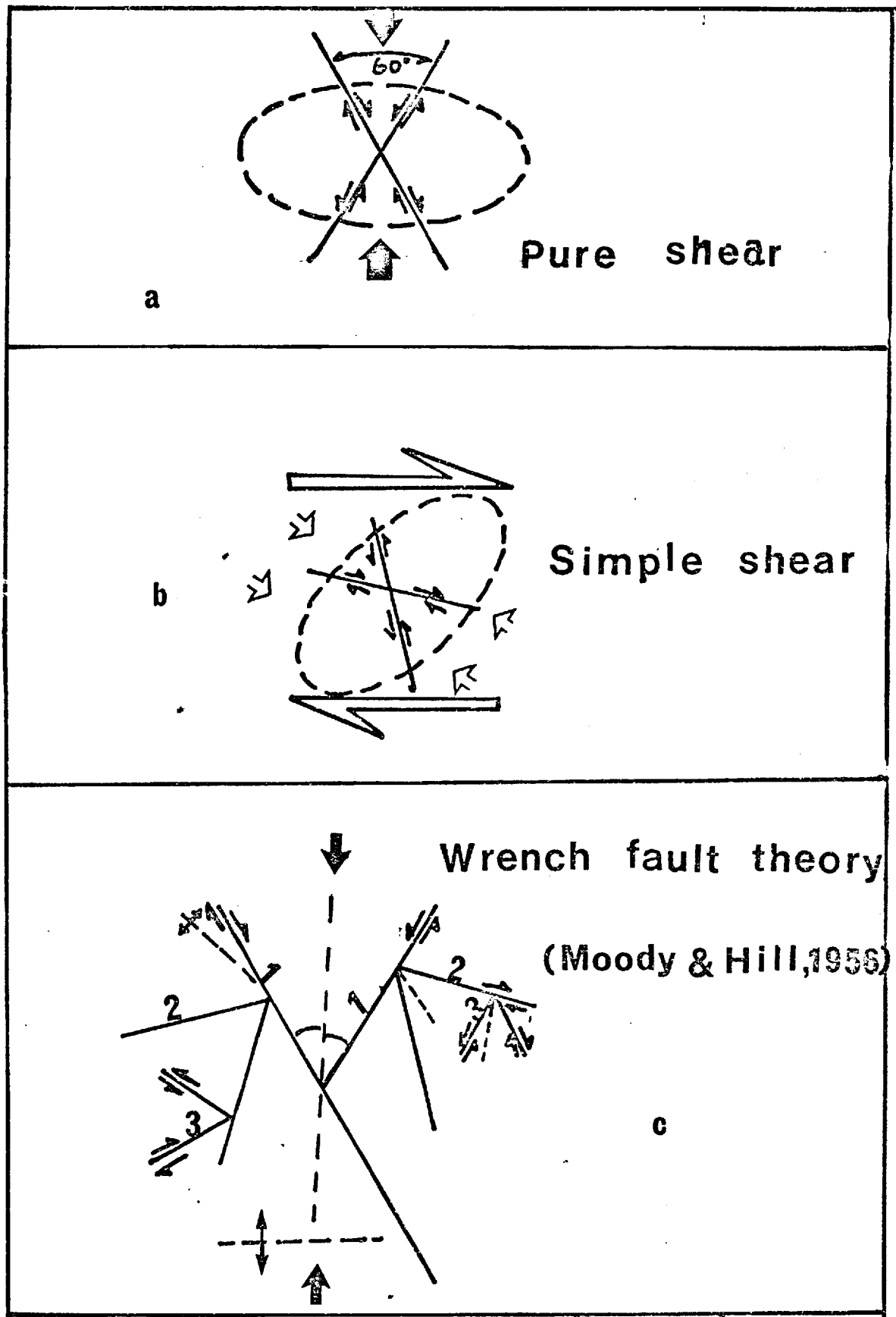


Figure 14

shear dynamics tend to intersect at angles usually greater than 60° . Similar conditions can be produced by pure shear dynamics although some believe that en-echelon uplifts are not usually associated and the intersection angles tend to be less than 60° (Thomas, op. cit. p.543).

The conjugate shear model is useful in relating fractures and lineaments because it helps delineate stress regimes and can suggest areas where fracture patterns are superimposed. It has to be remembered also that the two conjugate pairs may not always be developed, and that orthogonal fractures introduce some ambiguities between σ_1 and σ_3 directions.

Experience from LANDSAT imagery studies has shown that some curved lineaments may locally trend at above 45° with other fractures. Considerations of these curved features in their regional setting often indicate that they may be completely unrelated, in time, with the structures with which they locally appear to be conjugate. It is therefore important that wider photogeological regional settings of fractures and lineaments be known before interpreting conjugate pairs from them.

4.4.2. Other elements of wrench fault tectonics

Each conjugate shear of a simple shear dynamic model is a wrench fault. Studies of the main elements of a wrench fault indicate that four elements are often

associated with them viz: 1) en-echelon conjugate strike slip faults that can produce uplifts, 2) en-echelon tension fractures, 3) en-echelon drag folds and 4) the main wrench fault zone (Wilcox et al. 1973). Second order faults have also been associated with major wrenches (Price, 1966), though this may not always be the case.

Moody and Hill (1956) considered that the concentration of stresses at the ends of conjugate faults can result in the development of important second and lesser order faults, folds and thrusts (figure 13c). The Moody and Hill hypothesis is a useful criteria for relating fractures and lineaments but the formation of third and lesser order folds and faults are now largely discredited (Badgley, 1960).

4.4.3. The plate tectonics model

The Plate Tectonics theory (Sykes and Sbar, 1973; McKenzie 1969) is based on the postulate that the earth's outer surface has a number of strong and rigid lithospheric plates in relative motion. This theory contends that all the major features of the earth are a result of the relative rotation of plates, and that the plate boundaries represent the major seismic zones of the world, (McKenzie, 1969). Continental drift is believed to be a direct consequence of plate motions and the continents are believed to ride passively as the superficial parts of the lithospheric plates. Plates are

changed, or modified only at their margins and three basic margin types are recognised:

(a) The diverging plate margins

Divergent margins are tensional edges located at the mid-oceanic ridges. The lithosphere and the oceanic crusts are believed to be produced at the ridges.

(b) The converging plate margins - or subduction zones are often expressed on the earth's crust as trenches. Trenches are advanced by the model as places where plates collide, over-ride or are destroyed.

(c) Transform faults

Transform faults are lines where plates are neither destroyed nor created, but slide past each other. It is in the relationship of transform faults to oceanic ridges that the plate tectonics model offers a basis for relating lineaments. Figure 15 shows the relationship of transform faults to the mid-oceanic ridges. Right-lateral shear faults are believed to co-exist with and parallel to left lateral wrenches. Some geologists believe that some continental faults may be continuations of oceanic transform faults (Wright, 1976).

There are many inconsistencies in the plate tectonics model. A review of the theory of plate tectonics and orogeny (Smith, 1976) indicate that palaeomagnetic

data, ocean floor magnetic anomalies and least-squares fit of continental edges show that most orogenic belts have formed at or near the borders of continents and island areas. There does not seem to have been large areas of Precambrian ocean floors. They probably have vanished or never existed.

Palaeomagnetic data (Piper, 1974) show that rigid areas of the continental crust have probably been moving as a unit and that some Proterozoic African Orogenic belts may not have originated by plate tectonics processes (Smith op. cit. p.215). There is hardly any geophysical evidence for the existence of Archaean plates.

Some plate-tectonic models appear to be different from the actual orogenic areas they describe. The plate model for most orogenic features appear very controversial. One such unexplained phenomenon is the consistent occurrence of about 800 m.y. radiometric ages along the mid-Atlantic ridge in the vicinity of St. Paul's (Melson et al. 1971) contrary to the plate tectonics contention that very young oceanic rocks should occur at the ridges.

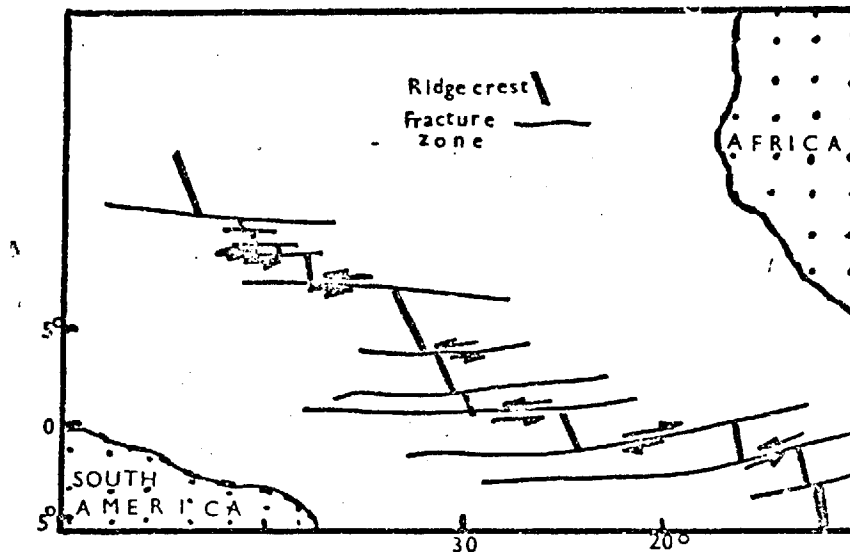


Figure 15. The relationship of transform faults to the Atlantic mid-oceanic ridge. (After Sykes 1968)

There can be no doubt that the plate tectonic model is a good, highly predictive model for explaining many geological phenomena, but a lot of problems like the origin of plates, their driving mechanisms demand some explanation. The application of plate models to Precambrian geology is extremely controversial.

The present regional studies of the Nigerian and West African basements has indicated that concentric fracture zones often forming long narrow troughs containing sediments and metasediments are common. These concentric fractures have been interpreted as resulting from Precambrian meteoritic impacts. Fracturing associated with these large impacts may have fissured through the entire crustal thickness. They may therefore represent sites of volcanism referable to different tectonic episodes.

The 'mobile belts' of the concentric fractures have been suggested to be worldwide and this may form a clue to the origins of crustal plate margins (Norman, Price and Chukwu-Ike, 1977).

P A R T T W O

CHAPTER FIVE

THE CENTRAL NIGERIAN BASEMENT - A CASE STUDY

5.1. MAJOR DISTINCTIVE GEOLOGICAL FEATURES ON NIGERIAN LANDSAT IMAGES

Experience gathered from the study of LANDSAT images of Nigeria shows that band 4 is generally hazy and of little value for geological studies. Band 6 shows features as well as band 7. Bands 5, 6 and 7 have been found to be geologically, the most informative.

Prominent tectonic features appear on LANDSAT images of Nigeria. Some of the more important features are tonal contrasts indicative of major lithological variations, the hitherto unrecognised marginal fractures of the Benue trough, the relationship of the Nigerian ring complexes to other tectonic elements such as the N-S fracture zones and indicated for the first time, the existence of major sinistral shear faults in Nigeria. Previously unknown metasedimentary troughs have also been revealed.

5.1.1. Major lithological changes

Lithological identification from LANDSAT images is extremely difficult. Delineation of major lithological variations based on image tonal changes is the best that can be obtained from these images under the present

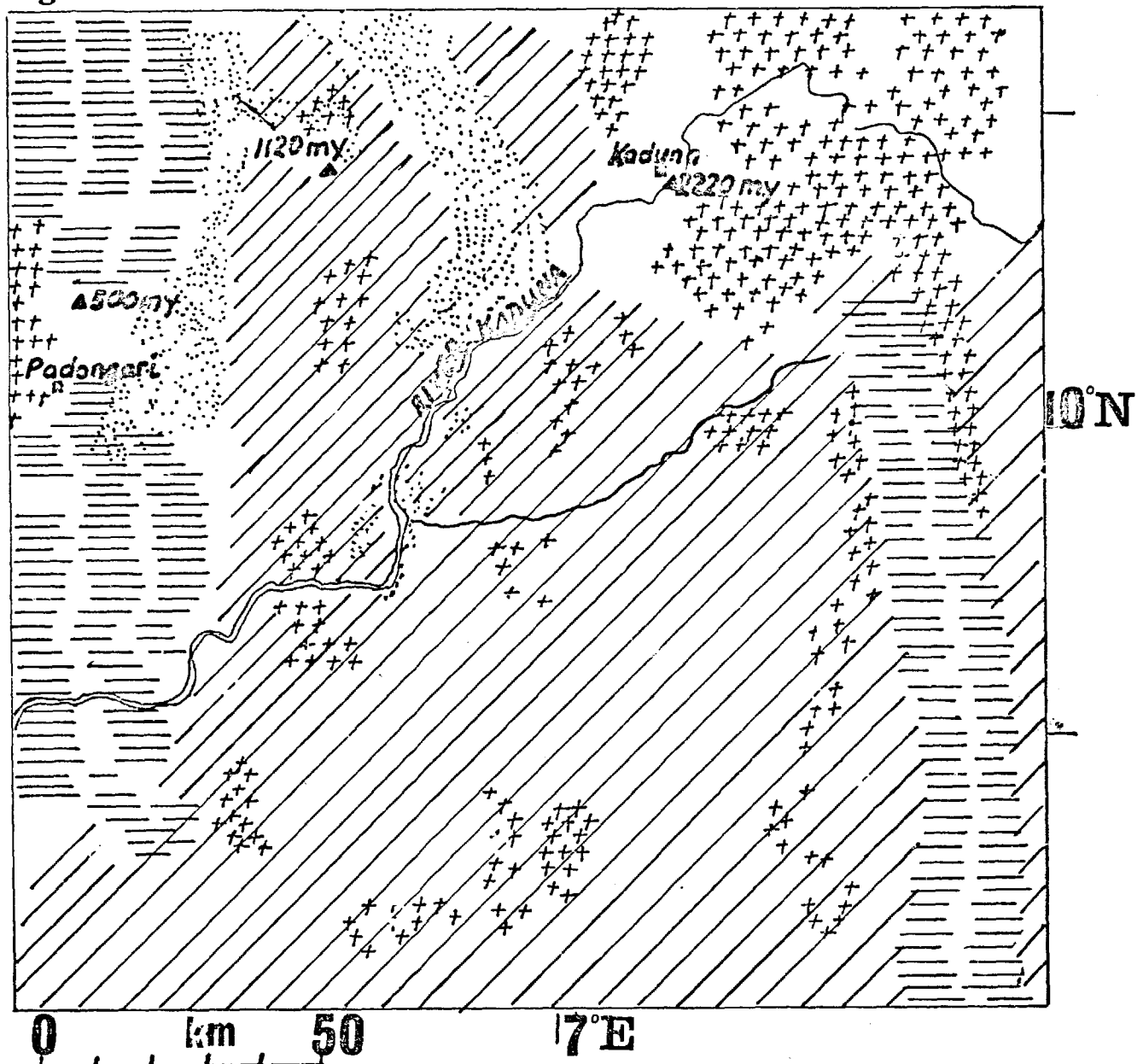
resolution capabilities of the LANDSATS. Plate 2 shows how tonal contrasts can suggest lithological changes. The low grade metasediments, t2, t1, appear distinctly darker in tone.

Flanking the dark toned low-grade rocks in Plate 2 is a belt of patchy rocks some 30-40km wide. This contrasting and patchy belt is even more distinctive on false colour composites (Appendix 1), and is associated with elongate intrusions strongly suggesting the existence of mixed rocks. Field checks confirm that it is a dominantly migmatitic terrain. The dark patches correspond with amphibolites and refolded quartzites apparently older than the rocks within the dark toned low-grade rocks inside the trough.

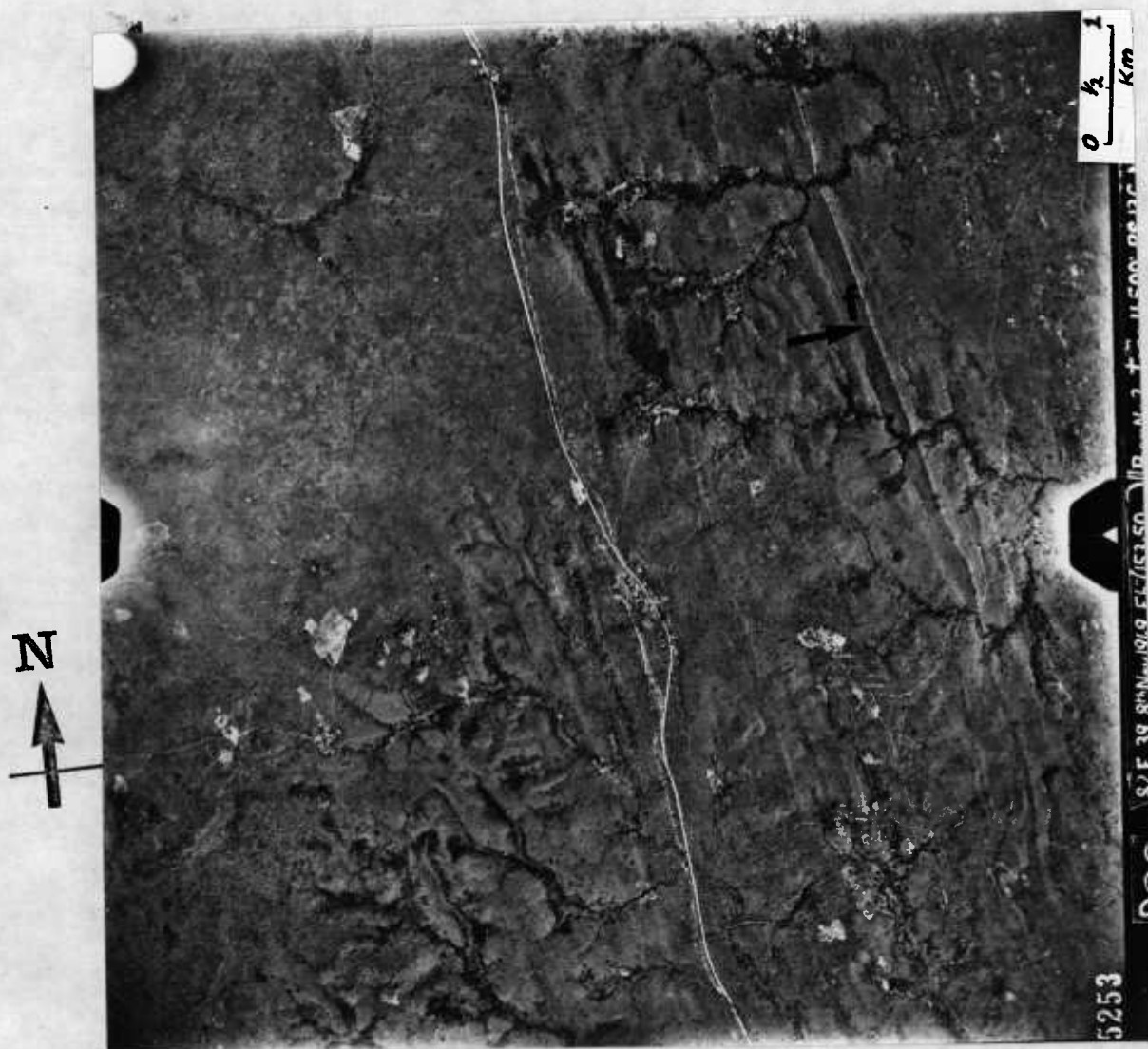
Banded gneisses are easily recognised in the field but good exposures are often rare as a result of soil developments and of lateralisation. They are regarded by some Nigerian geologists as the oldest rocks of the Nigerian Basement Complex (Burke et al. 1976). In Plate 7, faint foliation, f, associated with banded gneisses appear clearly. The faint foliation appear to be folded along an axis bounded by the lineament, L. This configuration resembles the geometry of the structure around Ibadan (figure 5) and suggests that a metasedimentary trough, very similar to that of Ibadan occurs east of the Benue trough but must have been eroded. Scattered remnants of

Groups of Metasediments -NW Nigeria

Figure 16



- ≡≡≡ Metasediment Group B ▲1120my (Rb/Sr Grant 1972)
- /// Older metasediment, A ▲2220my (Rb/Sr Harley, 1966)
- Metasediment Group C ▲500 my (Rb/Sr Grant 1972)
- +++++ Gneissic complex

PLATE 11

An air photograph showing a more prominent quartzite ridge, f, suspected to represent a fracture infilled with siliceous material. The resistant ridge, f, trends parallel to metasedimentary quartzite ridges (RAF 1949)

metasedimentary quartzites are in evidence around this area.

Quartzites are often evident on LANDSAT images. They occur as long continuous trend lines, frequently showing distinct evidence of folding (Plate 2, 5, 6). The sedimentary origin of the quartzites in Plate 2 has been established (Allum 1960). It is still difficult, however, to differentiate metasedimentary quartzites from quartz filled fractures especially when such fractures trend parallel to the metasediments. Plate 5 shows a quartzite ridge, q, whose origin is equivocal, while Plate 11 shows a quartzite ridge, f, trending parallel with the metasedimentary beds but appears to be more resistant to erosion than the metasediments, thus suggesting that, f, (Plate 11) may be an infilled fracture.

5.2. REGIONAL FOLD STYLES OF THE NIGERIAN BASEMENT

5.2.1. The flat-lying, E-W trending (F1) folds

LANDSAT images of the Nigerian metasedimentary areas show large lunate folds sometimes over 50 kilometers long (m, Plate 2). These lunate folds are defined by low ridges of granulitic quartzites in the field. Many such structures have been observed. One of them lies about 20 kilometers NE of Abuja near the village called Igu. Another has been located in Eastern Nigeria near the village of Nkum in Ogoja Province. These structures resemble the major structure mapped at Ibadan (figure 5).

In the field, dip attitudes on the granulitic quartzites and aluminous schists associated with the lunate folds tend to flatten out as the axes of these folds are approached. This suggests that these folds were previously flat-lying. They are associated with axial plane concordant granite-gneisses and minor folds associated with them rarely plunge over 10° from the horizontal.

Apart from the structure mapped at Ibadan, (Grant 1970), the other reference to this style of folding was based on microstructural evidence (McCurry 1973). The present study has located many more of such regional structures. Figures 10 and 11 are photogeological interpretations of the lunate folds. Grant (1970) dated the concordant granite gneiss of the Ibadan structure to be Eburnean in age (1850 ± 250 m.y.) This suggests that the metasediments associated with this type of folding pre-dated the 2000 m.y. cycle.

The identification of many more refolded flat-lying folds within the Nigerian basement enables the present study to establish this type of folding as a distinctive fold style of the Nigerian basement. It appears that flat-lying folds extensively occurred within the Nigerian basement during the Archaean times. It is however not clear whether the flat-lying structures are time equivalents of the banded gneisses. Field relations

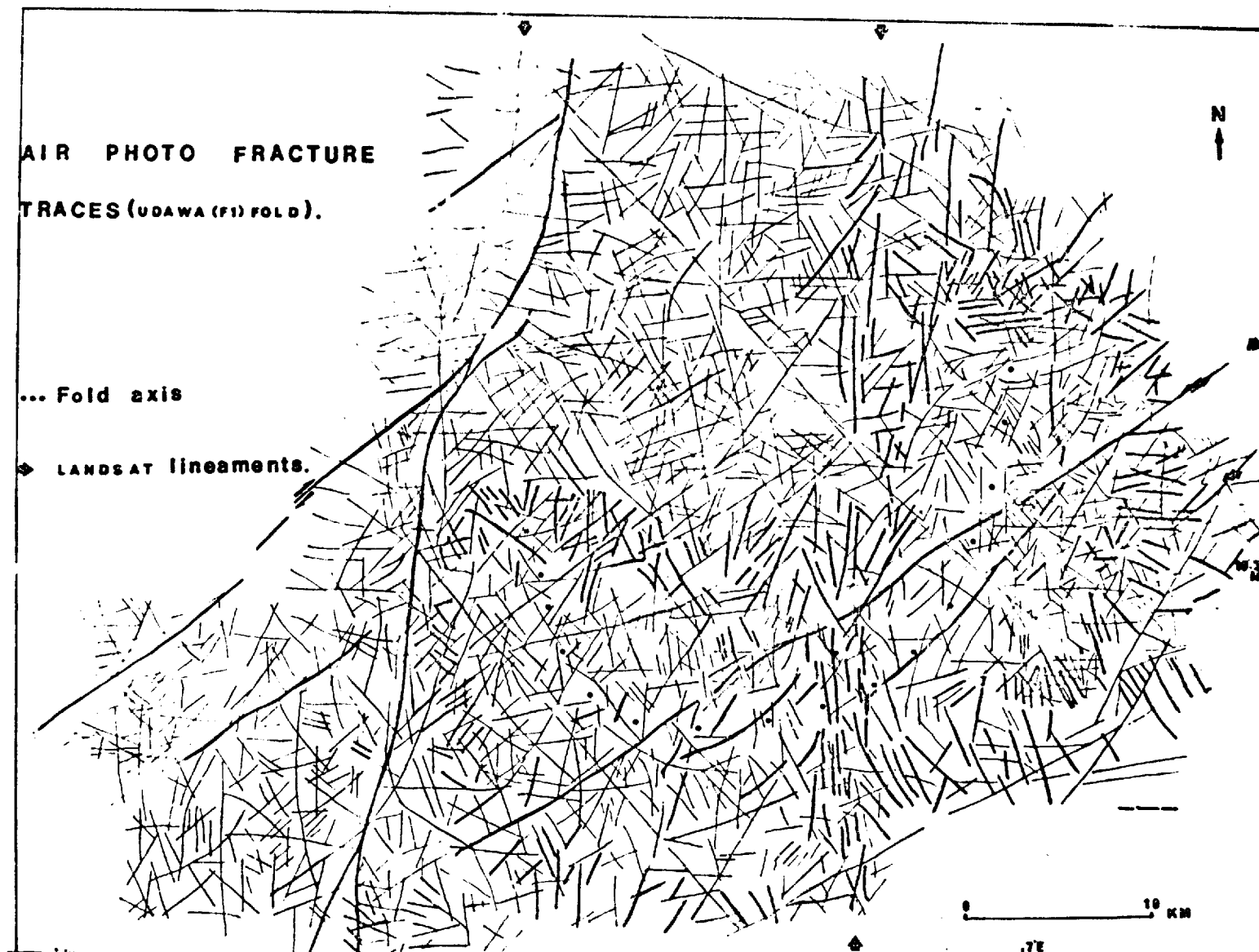
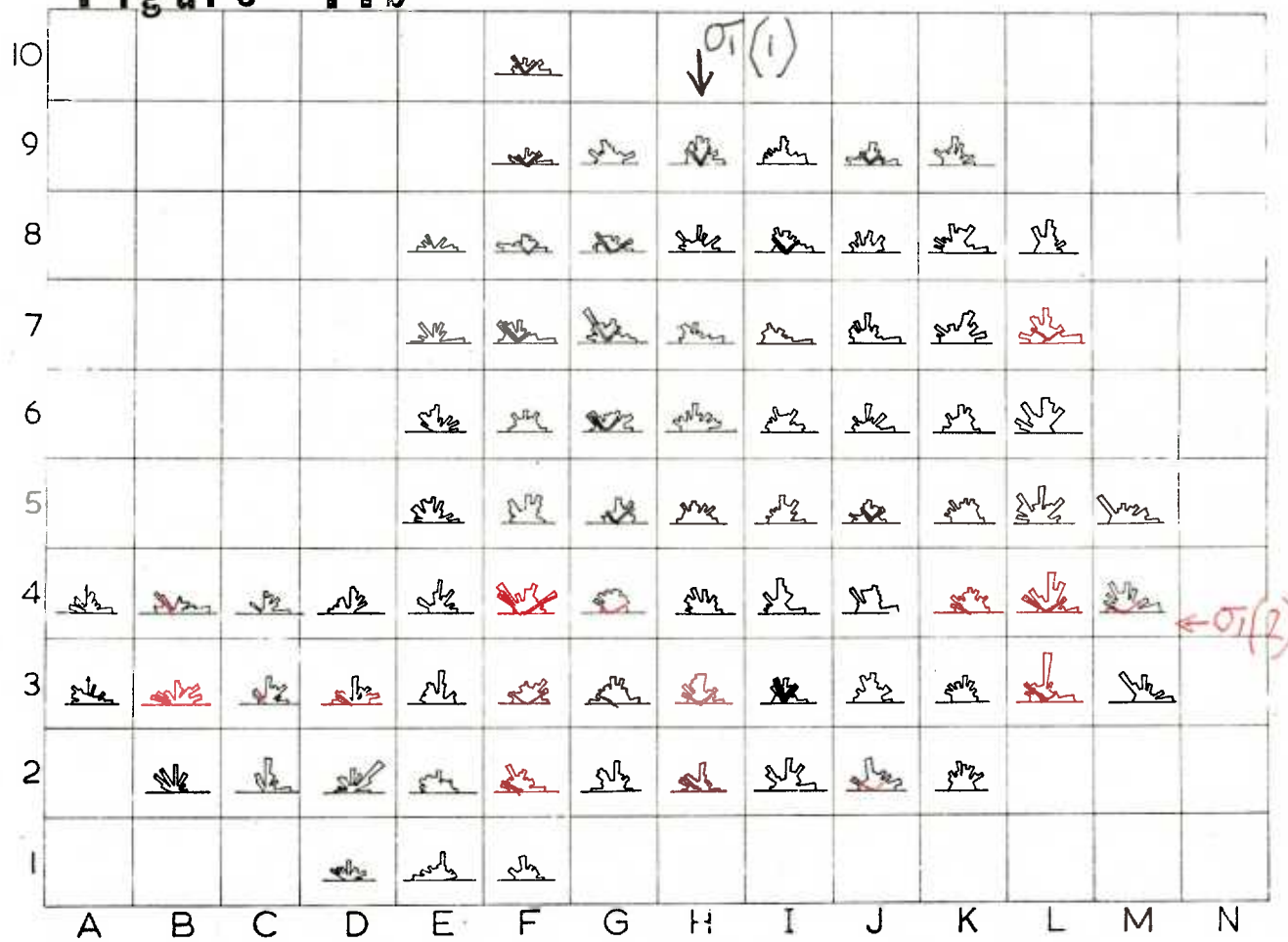


Figure 17a (same structure as in fig. 10)

FRACTURE TRACE DIRECTIONAL FREQUENCY ROSETTES OF THE UDAWA REGIONAL (F1) FOLD

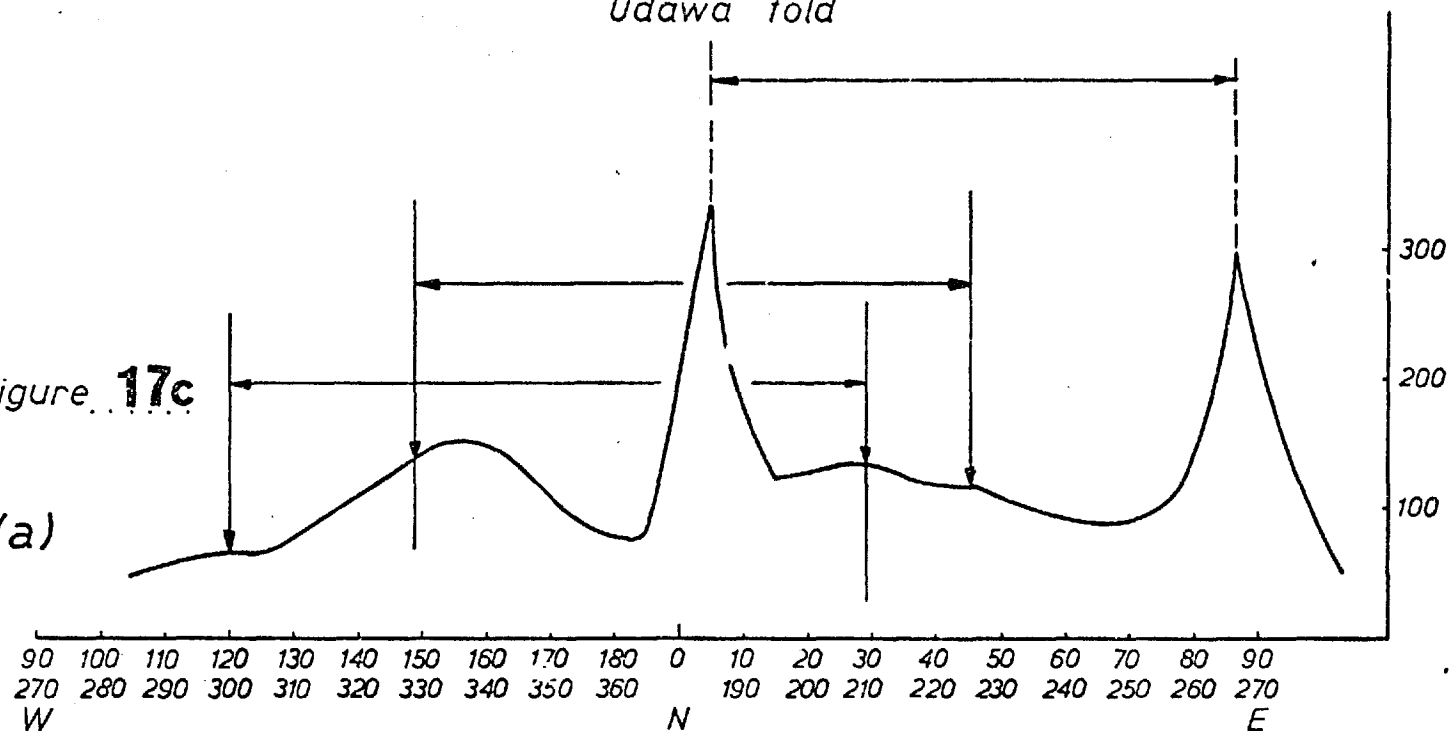
Figure 17b



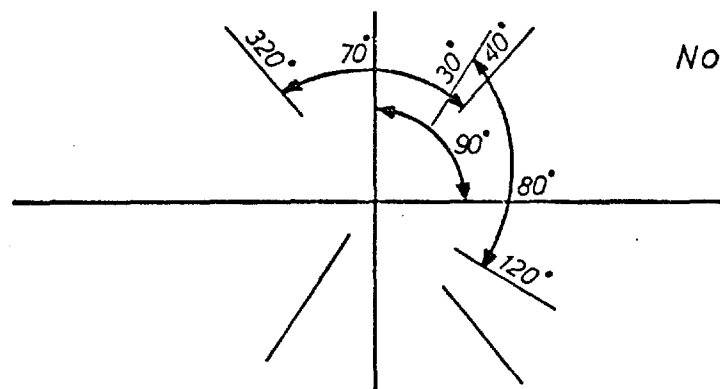
Cartesian plot of near orthogonal fracture sets -
Udawa fold

Figure 17c

(a)



(b)



No. of fractures 2281

are equivocal. It is possible that the flat-lying folds represented the oldest tectonic style very much similar to structures of the horizontal tectonic regimes within the fundamental basements of Greenland (Pulvertaft, 1973).

The flat-lying folds are dominantly refolded plastically. Fractures associated with the refolding tend to fan out from the direction of the principal stress (figure 17a). It has not been possible to identify any fractures associated with the initial formation of the folds. The axes of refolding is dominantly N-S. Plate 9 shows an RAF photograph of the F1 fold closure west of Zungeru (same as figure 11). Fracture trace frequency rosettes associated with the flat-lying lunate folds (figure 17b) strongly suggest a N-S oriented principal compressive stress axis prior to the later E-W stress system. A cartesian plot of near orthogonal fracture sets compiled from figure 17a shows three sets (figure 17c).

LANDSAT image of the Udawa lunate fold (m, Plate 2) indicates that amphibolites are concordantly folded with the quartzites defining the lunate folds. Whether the amphibolites represent metamorphosed equivalents of pelitic rocks or are metamorphosed equivalents of basic rocks is uncertain. It seems to the writer that the amphibolites are metabasic rocks. If this is so, the lunate structures may be remnants of an extensive volcano-

sedimentary sequence that covered most of Nigeria in the Archaean times.

5.2.2. The F2 folds

F2 folds occur within the N-S troughs and on F1 folds also. Within the troughs, F2 structures are tight isoclinal folds. Plates 2, 5 and 6 show parallel folds visible as parallel lines within the troughs. They trend N-S as against the E-W of the F1 folds. F2 folds very often wrap round trough marginal batholiths like those of Minna (r, Plate 2). Figure 11 shows the relationship between F1 and F2 folds. F2 metasedimentary quartzites are restricted to the troughs and are generally not granulitic in texture. F2 folding episode refolded F1 folds along a N-S axis.

5.2.3. The F3 folds

F3 and F2 folds are co-axial (figure 11). They are also seen on older F1 folds. Within the NW Nigerian metasedimentary belt F3 folds appear in places as more open V-shaped folds (o, Plate 2). F3 structures are widely represented in the vicinity of Zuru and along the Nigerian - Dahomey border areas.

5.3. GROUPS OF METASEDIMENTS

The three episodes of folding appear to be related to metasedimentary groups. Groups of metasediments are

mostly recognised on images from fold geometries and tonal characteristics. Three groups of metasediments are recognised in the present study of Central Nigeria, although a fourth belt about 30 kilometers wide trending NE and passing through the village of Zuru, Wasagu and Bena in NW Nigeria (see figure 29) do not show very clear relationships with the three groups recognised here.

5.3.1. Group one metasediments

Group one metasediments based on structures are considered to be the oldest group in Nigeria. This group is represented by the extensive flat-lying lunate folds visible on images (m, Plate 2). Their remnants occur as trend lines in eroded areas. They are associated with concordant granite gneisses in the field and are defined by low granulitic quartzites. The rocks belonging to this group appear to predate the 2,000 m.y. age of the concordant granite gneiss (Grant, 1970). The granite gneiss is known to be significantly younger than the enclosing metasediments.

5.3.2. Group two metasediments

Group two metasediments occur solely within fault bounded troughs. They are characteristically isoclinal, trending N-S and tightly appressed. The quartzites associated with this group are not granulitic. Group two metasediments may locally wrap round trough marginal

intrusions (r, Plate 2). This characteristic is in evidence around the vicinity of Minna and suggests that the stocks have a late tectonic relationship with group two meta-sediments just as the elongate granites, also late tectonic (McCurry, 1973) could be associated with group three meta-sediments.

5.3.3. Group three metasediments

Group three metasediments also occur exclusively without troughs. Folds associated with this group are open and restricted to NW Nigeria and the Nigeria-Dahomey border areas. Group three metasediments are considered to be the youngest of the three groups. Figure 16 illustrates the distribution of metasedimentary rock groups in the parts of NW-Nigeria covered by Plate 2, based on satellite images.

5.4. INTRUSIVE ROCKS SEEN FROM ORBITAL IMAGES

5.4.1. "Eye-shaped" structures

Plate 2 shows an eye-shaped structure, e, associated with group one metasediments. Outcrop-size "eye-shaped" structures have been reported in parts of the Nigerian basement (McCurry 1973). The significance of the "eye-shaped" structures is uncertain.

Field-checks on the eye-shaped structure of Plate 2 shows that it is a gneissic rock (a granite gneiss) surrounded by aluminous schists. The structure lies close

to the axial plane of an F1 fold style. Judging from the way the gneissic rock wedged apart the aluminous schists, the gneissic rock may have intruded into the schists.

"Eye-shaped" structures have been reported in other parts of the world. Windley and Bridgewater (1971) associate eye-shaped structures with granulite facies gneisses within Archaean (> 2500 m.y.) terrains. It is possible that the Nigerian eye-shaped structures represent intrusions associated with the Eburnean orogenic cycle (2000 m.y.). If future radiometric dating of this structure confirms this, then LANDSAT studies has indicated the only well preserved pre-Pan African intrusion within the Nigerian reactivated basement.

5.4.2. The "older granites"

The term "older granite" is used by Nigerian geologists to refer to the Pan African (600 ± 100 m.y.) granite intrusions. The term "older granite" is now regarded by some Nigerian geologists as a misnomer since emerging radiometric dates (Grant 1970, Oversby 1975) indicate that older orogenic episodes affected the Nigerian Basement Complex. The granite gneisses associated with folds and "eye-shaped" structures could be metamorphosed intrusions of this older cycle.

On LANDSAT images, the "older granites" appear pear-shaped or elongate in outline and are mostly associated

with metasedimentary trough margins (1, Plate 2). The longer axes of the pear-shaped intrusions are oriented N-S. The shapes of these intrusions suggest that they were emplaced under an E-W compressive stress system and that the granites were emplaced in a semi-plastic condition. The elongate granites tend to be dominantly porphyritic in the field. Charnockitic granulites have been reported close to some "older granites".

LANDSAT images suggest that the "older granites" are controlled by major N-S lineaments which are located at the metasedimentary trough margins.

5.4.3. The low-grade and higher grade metasedimentary cover contact relationships

Trusswell and Cope (1963) mapped parts of the low grade metasediments and the adjoining higher grade rocks. This area is covered by Plate 2. They recognised the differences in the metamorphic grades but could not identify any unconformity separating the two groups. They therefore proposed that only one orogenic episode affected the Nigerian Basement Complex.

The overwhelming evidence for a polyepisodic evolution of the Nigerian basement as suggested by different radiometric age magnitudes, fold styles and metamorphic grades enabled Oyawoye (1965) and McCurry, (1973) to controvert this conclusion.

Plate 2 clearly shows that the low grade rocks whose tonal characteristic is darker than the higher grade rocks is bounded by a major N-S lineament. Intrusions controlled by the lineaments largely obscure the contact relationships between the two rocks in the field. LANDSAT images of the area therefore proved useful, not only in indicating the controls of the intrusions, but also in showing that the contact between the low grade and higher grade rocks of the Nigerian Basement is tectonic. Field checks indicate strong shearing in the form of silicified mylonites close to the trough marginal intrusions.

5.5. THE NATURE OF THE METASEDIMENTARY TROUGHS

The eastern edge of Plate 2 shows a small metasedimentary trough, t2. The trough relic beds are distinct in the lower half of the image but gradually becomes less distinct northwards. However, vestiges of the trough vg, can still be seen. The clear marginal fractures, to the south, become rather profuse, in the vestigial parts.

The vestigial parts of this trough, t2, is dominantly banded gneisses and migmatites. This area is observed to represent places where the metasediments have been eroded. This interpretation enables the following deductions to be made:-

- (a) That the banded gneisses underlie the troughs.
- (b) That the troughs are therefore ensialic.
- (c) That exposures of banded gneisses along the strike of metasedimentary troughs may be indications of previously lower crustal levels.

Search for the locations of N-S lineaments along areas interpreted to represent lower crustal levels (Kaduna, Plate 2) indicate that the locations of the lineaments are predominantly flaser gneisses on the ground. Local silicifications are also in evidence.

Narrow metasedimentary troughs about 10-20km wide occur all over Nigeria (Plates 2, 5, 6) although in some areas pattern associations indicate that the meta-sediments have been eroded. The vicinity of Keffi, Jos and Beli are such examples of eroded troughs. Meta-sediments are indicated east of Ogoja. There therefore seems to be a suggestion based on images that the Nigerian narrow troughs occurred at intervals all over the country and was not restricted to west of longitude 8° as some authorities contend.

5.5.1. Similarities and differences between Nigerian low grade rocks and the Baberton Mountain-type granite-greenstone terrain

Geologists concerned with the study of the early crust and Archaean terrains (2500+ m.y.) in different continents now distinguish two types of Archaean terrains -

the granite-greenstone and granulite facies gneissic terrains. The granite-greenstone terrains are belts of little metamorphosed well defined basins infilled with volcano-sedimentary deposits and separated from each other by gregarious granitic rocks (Anhaeusser et al. 1969). The gneissic terrains contain granulitic gneisses, aluminous mica schists and high-grade rocks (Windley and Bridgewater, 1971). Some geologists regard modern geosynclines as analogues of Precambrian greenstone terrains (Pettijohn 1970) while others regard the greenstone sedimentary environments as markedly different from those of modern geosynclines. Internal structures within greenstone belts of most continents include upright folds, pillow structures, sedimentary structures and conglomerates. Greenstone belts are metalliferous areas, rich in such minerals as copper, zinc, gold, silver and nickel.

The Nigerian metasedimentary troughs show some close similarities with the granite-greenstone terrain as typified by the Rhodesian Baberton Mountain land (Wright and McCurry, 1971). Common characteristics between the Nigerian low grade rocks and those of Rhodesia include, the low grade nature of the metasediments, the linear nature of the troughs, the marginal trough granitic intrusions and the upright nature of the folds.

The major differences between the Rhodesian rocks and those of the Nigerian low grade rocks lie in the

extremely limited occurrence of basic and ultra basic rocks with the Nigerian low grade rocks. Most importantly, field mapping in Nigeria (McCurry 1973) and structural relationships between the low grade rocks and the adjoining rocks indicate that the Nigerian low grade rocks are not the oldest metasediments in Nigeria. They also do not appear to be as old as the Archaean in age. The marginal fractures to the Nigerian low-grade rocks are clearly evident, at least from orbital images, while in Rhodesia, such marginal fractures have been replaced by granitic rocks.

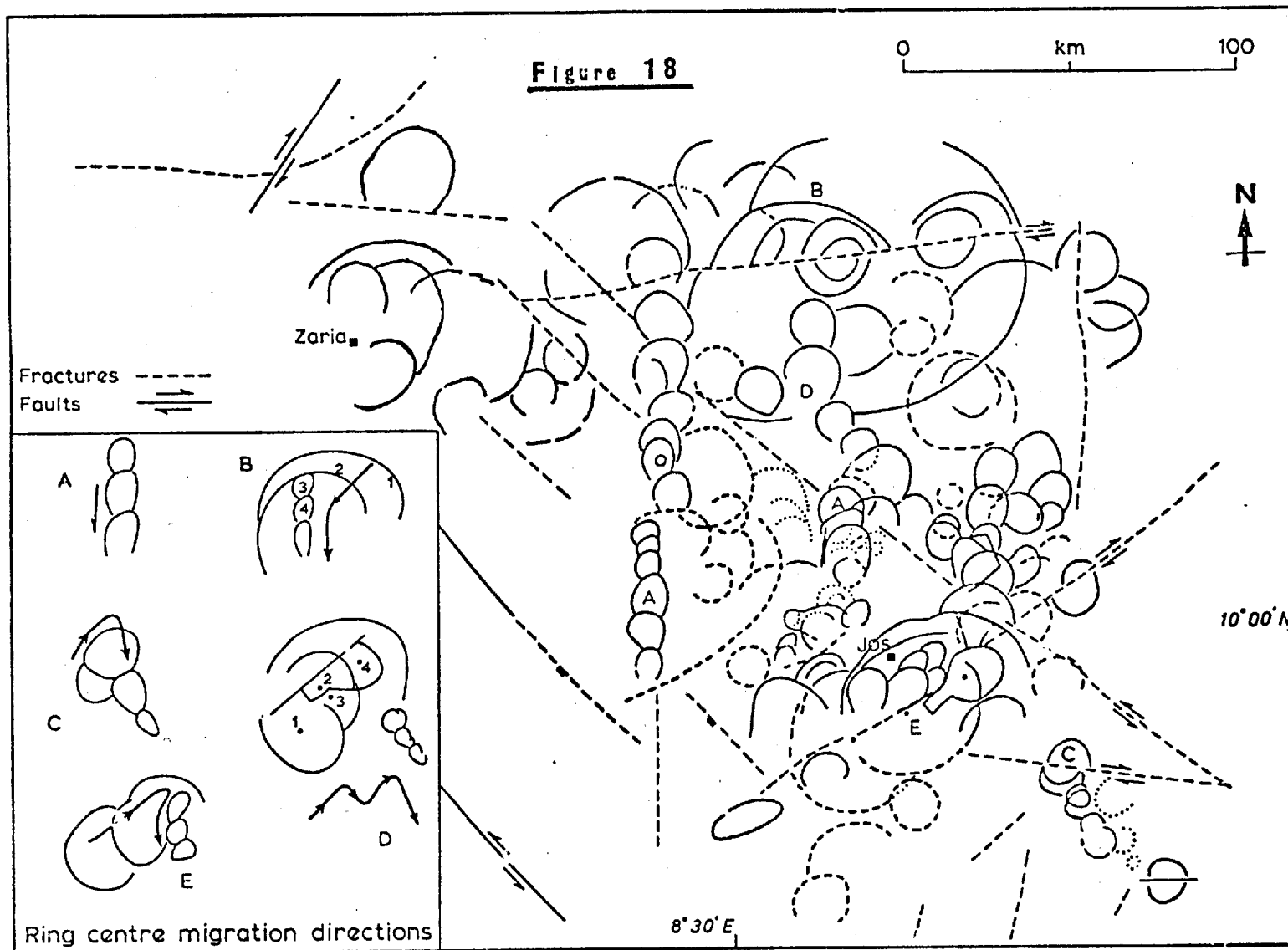
5.6. THE TECTONICS OF THE NIGERIAN JURASSIC RING INTRUSIONS

The Nigerian ring complexes commonly referred to as the Nigerian "Younger Granites" is a belt of ring intrusions some 200 kilometers long by about 100 kilometers wide. The province has received a disproportionate geological attention because of the associated tin, columbite, niobium and tantalite mineralisation. Very little work has been done on the structures of this province.

Turner (1970) suggested that NE-SW and NW-SE crustal fractures controlled the emplacement and mineralisations of the younger granite complexes. While Wright (1970) based on alignments of intrusions argued that N-S lineaments are the controlling structures.

Plate 3 shows a LANDSAT image of about 80% of the province. An interpretation of this frame and the adjacent frames is shown in figure 18. The images of this area show that both NS and NW-SE as well as NE-SW faults are present and important. There is no indication that all the faults are related in time or are due to one stress system. It is very clear on the images that there is a continuous overlapping and younging of many of the intrusions from N-S. The overlapping tendency may often be unbroken for over 100 kilometers in a N-S direction. Also defined in Plate 3 is a less definite alignment of the intrusions in a NE-SW and NW-SE directions. Plate 1 shows that some of the NW-SE lineaments are actually step faults of major importance. The step faults have given rise to differential uplifts and erosion surfaces. The step faults, while having the characteristics of normal faults also show major strike-slip displacements.

Studies of the cross-cutting relations of the complexes (figure 18) suggest that the larger diameter ring complexes formed first and did not show any preferred directions of younging while the relatively moderate and smaller diameter complexes apparently formed later and younged from N-S (figure 18a - d). Some initial E-W direction of younging of the ring complexes is also indicated. The geometry of some complexes such as the Amo-Buji and those just north of Jos indicate that the pre-existing fractures were probably oriented N-S and



Landsat imagery interpretation of some ring intrusions
and circular features — Central Nigeria

that these pre-existing structures exerted some control over the shapes of some of the complexes. The Nigerian ring complexes based on LANDSAT studies had initially no definite directions of younging while the later N-S younging appears to suggest a gradual N-S opening of a pre-existing fracture zone.

The Nigerian ring complexes are therefore largely controlled by N-S fractures with also some NE-SW and NW-SE alignments. The NE-SW and NW-SE lineaments show evidence of strike slip movements. The NW-SE lineaments are dominantly sinistral shears while NE-SW lineaments appear to be dexteral shears. This arrangement suggests a strong E-W compressive stress at the time of formation of the shear fractures and lineaments which may have reactivated older N-S basement fractures along which the intrusions preferentially arose.

5.7. THE BASEMENT TRENDS

The dominant basement trends of the Nigerian Basement Complex is N-S. The trends are defined by basement foliation, as well as relic beds (see figure 28). The basement trends vary in direction from NE through N-S to NW. The N-S direction is the most extensive. The other two directions are associated with basement areas that appear to have been affected by tectonic events older than the 600 ± 100 m.y., Pan African event. LANDSAT

images are particularly useful in indicating where the three trends are associated with one and the same major structure, thereby indicating that a tectonic over printing had taken place. In this respect, LANDSAT imagery studies would help in the correct interpretation of radiometric ages. Radiometric age determinations on structures that have been affected by many episodes would tend to indicate the latest event. This situation often limits the value of the use of radiometric dates in complex Precambrian terrains.

5.8. MAJOR TECTONIC FEATURES OF THE BENUE TROUGH
AS SEEN ON LANDSAT IMAGES

The Benue trough is a 120 kilometer wide intra-cratonic folded sedimentary basin within Nigeria. Its origin is not precisely known. Pugh and King (1952) suggested that the trough originated as a result of rifting and the separation of South America from Africa. This view was shared by Wright (1968) and Uzakpunwa (1974). Wright (1976) critically reviewed the literature on the Benue trough and pointed out that the trough generally follows the structural grain of the flanking basement and that the existing evidence of marginal faulting was scanty and of doubtful significance. Wright (op. cit. p.316) also concluded that it is no longer adequate to attribute the Benue trough structures solely to the distortional stresses consequent on the separation of

1. = Lineaments
2. = Granitic intrusions (c. 600my)
3. = Major volcanic centres
4. = Ka Boragap mylonites
5. = The Benue Trough.
6. = ? Palaeozoic volcanics
7. = Anticlines
8. = Synclines
9. = Basic rocks
10. = Granitic intrusions (60 - 120 m.y.)
11. = Minor volcanic centres.
12. = Mapped faults.
13. = Minor basic and charnockitic rocks
14. = Basement complex
15. = Contact (basement - cover) suggest by LANDSAT images.
16. = Centre points of LANDSAT images covering the area.

Africa and South America. Studies of the Benue trough structures using LANDSAT images indicate the presence of the following hitherto unrecognised marginal fractures and lineaments as well as an apparently older near-meridional lineaments and fracture sets:-

(a) The en-echelon lineaments

Image number E-1193-09044, (Plate 7) covers the trough margin around longitude $E10^{\circ}.30'$ and latitude $N8^{\circ}15'$, and shows Rivers Donga and Taraba to the west and east of the image respectively. A comparison between the LANDSAT image and the existing maps shows some disagreement in the location of the basement-sedimentary cover contact for this locality. Existing maps tend to place this contact well inside the basin, several kilometers away from the contact suggested by band 7 of the satellite imagery (figure 19, symbol 15).

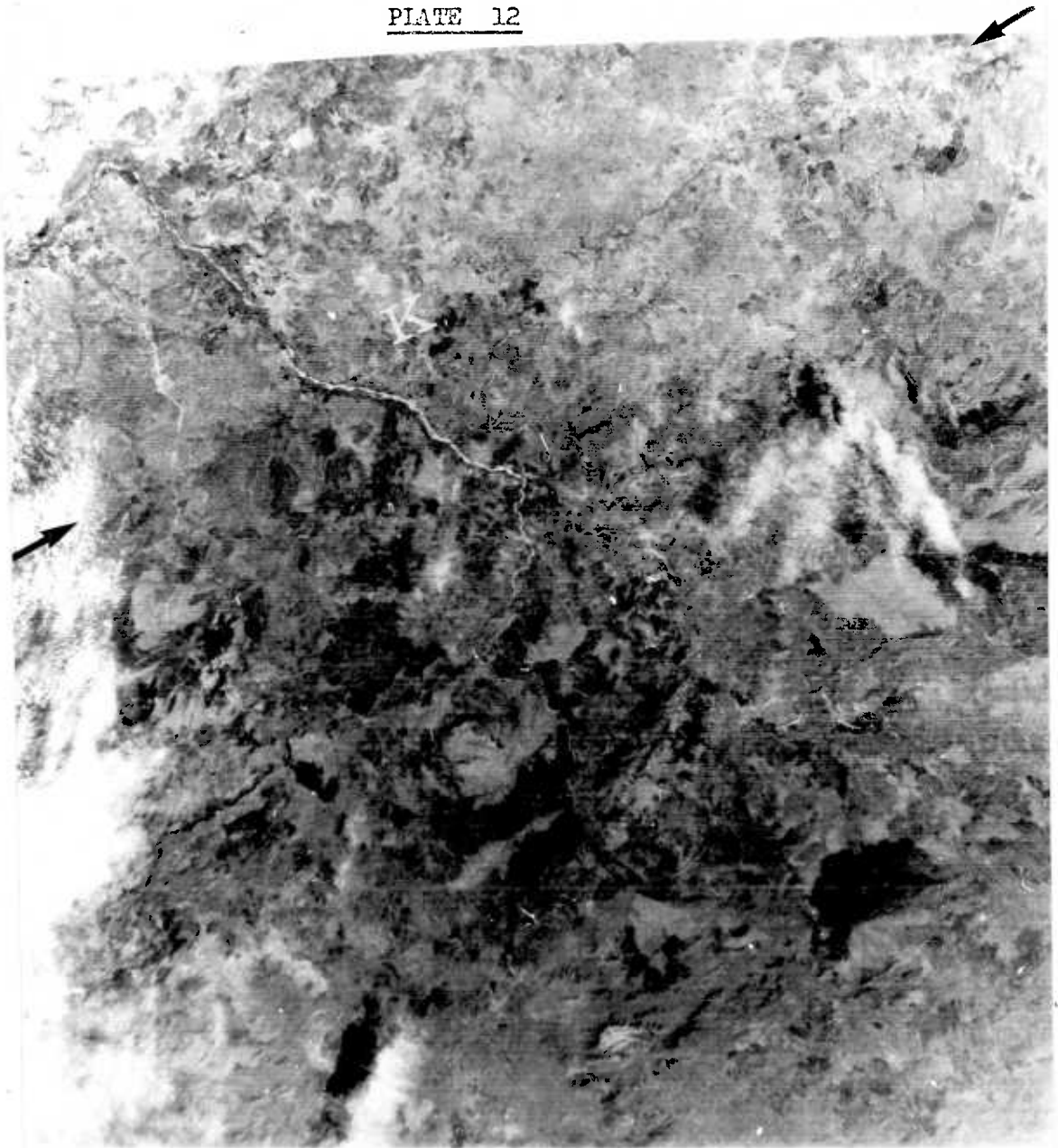
The sedimentary cover, C, as seen on the image (Plate 7) is readily distinguished from the basement B, which in some places indicates a strong foliation, f. This spectral distinction is attributed to vegetation and moisture content differences between the contrasting lithologies. En-echelon lineaments, e, are arranged close to the margin of the trough. Major basement lineaments, L, trending nearly N-S as well as their intimate association with mapped volcanics, V, are also resolved.

A sketch illustrating the arrangement of these various lineaments is shown in the interpretation of Plate 7. The en-echelon lineaments are parallel and trend $N45^{\circ} - 50^{\circ}E$ and are at least each 40 kilometers long. They show no visible transcurrent displacements both in the field and on the images compared with horizontal displacements of over 20 kilometers indicated by NW faults, h, one of which runs along River Taraba.

The en-echelon fracture pattern is 'left-handed' and corresponds to the "italic m" of Yairi (1975). Each en-echelon fracture intersects an imaginary horizontal line, the row, (figure 19b) at about 27° . Field checks confirm that the en-echelon lineaments are prominent scarps, down-towards-the basin, and are characterised by quartz floats. They are generally poorly exposed and may be normal faults. Detailed investigations may reveal more about the nature of these linear features.

(b) Other lineaments

Plate 12 shows a straight segment of a set of generally curved concentric lineaments, K. It is over 200 kilometers long and continues beyond the image. It has been traced to marginal granitic intrusions, south-east of Yola (figure 19). This lineament is not readily accessible but there can be little doubt about its tectonic origin.

PLATE 12

NOV-26/E014-00 N 33/E014-05 MSS 5 R SUN EL 44 AZ 131 188-2487-A-1-N-D-2L NASA ERTS

0 km 60



A LANDSAT-1 image of a marginal fracture zone along the Benue trough, k.

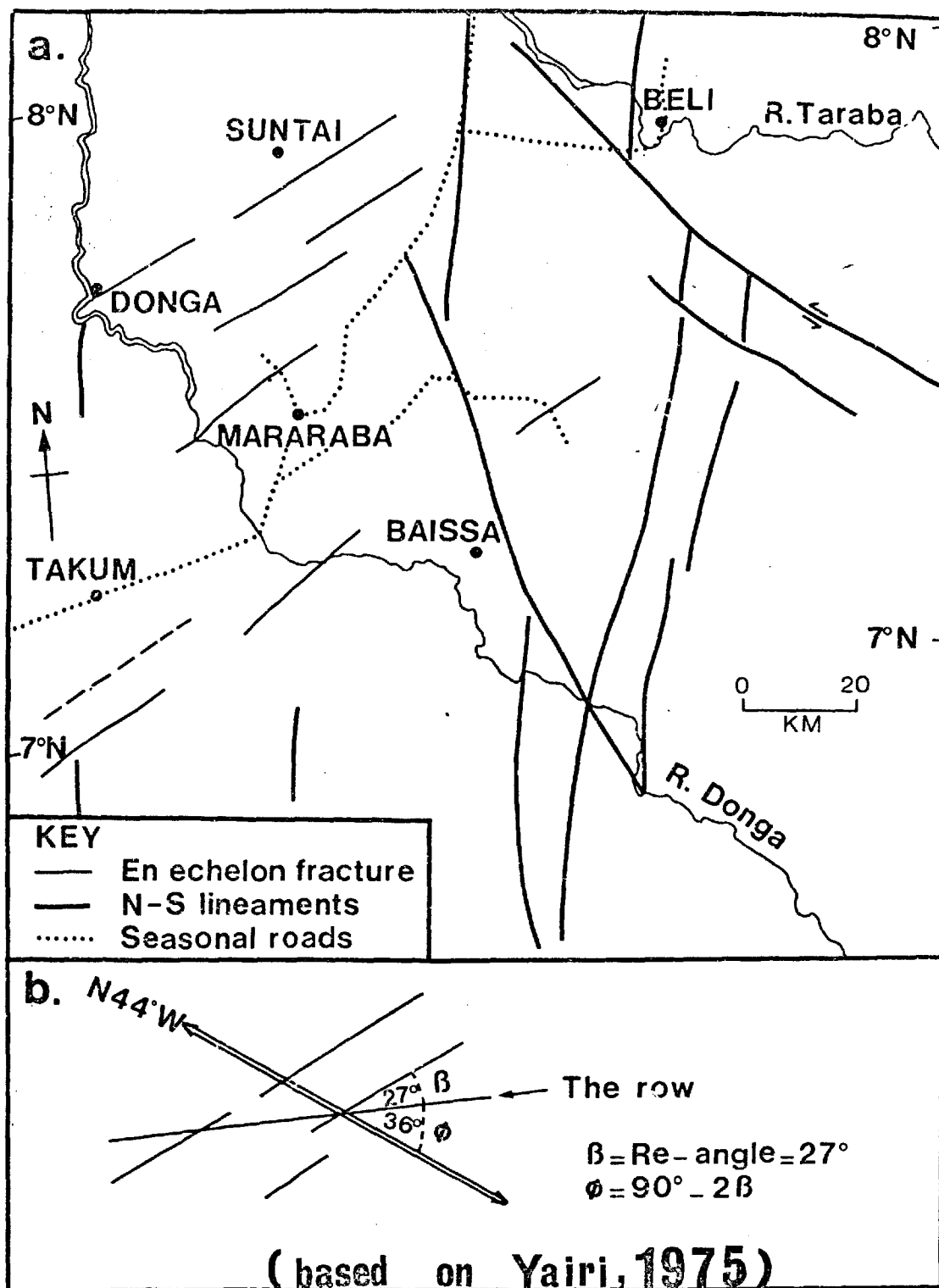
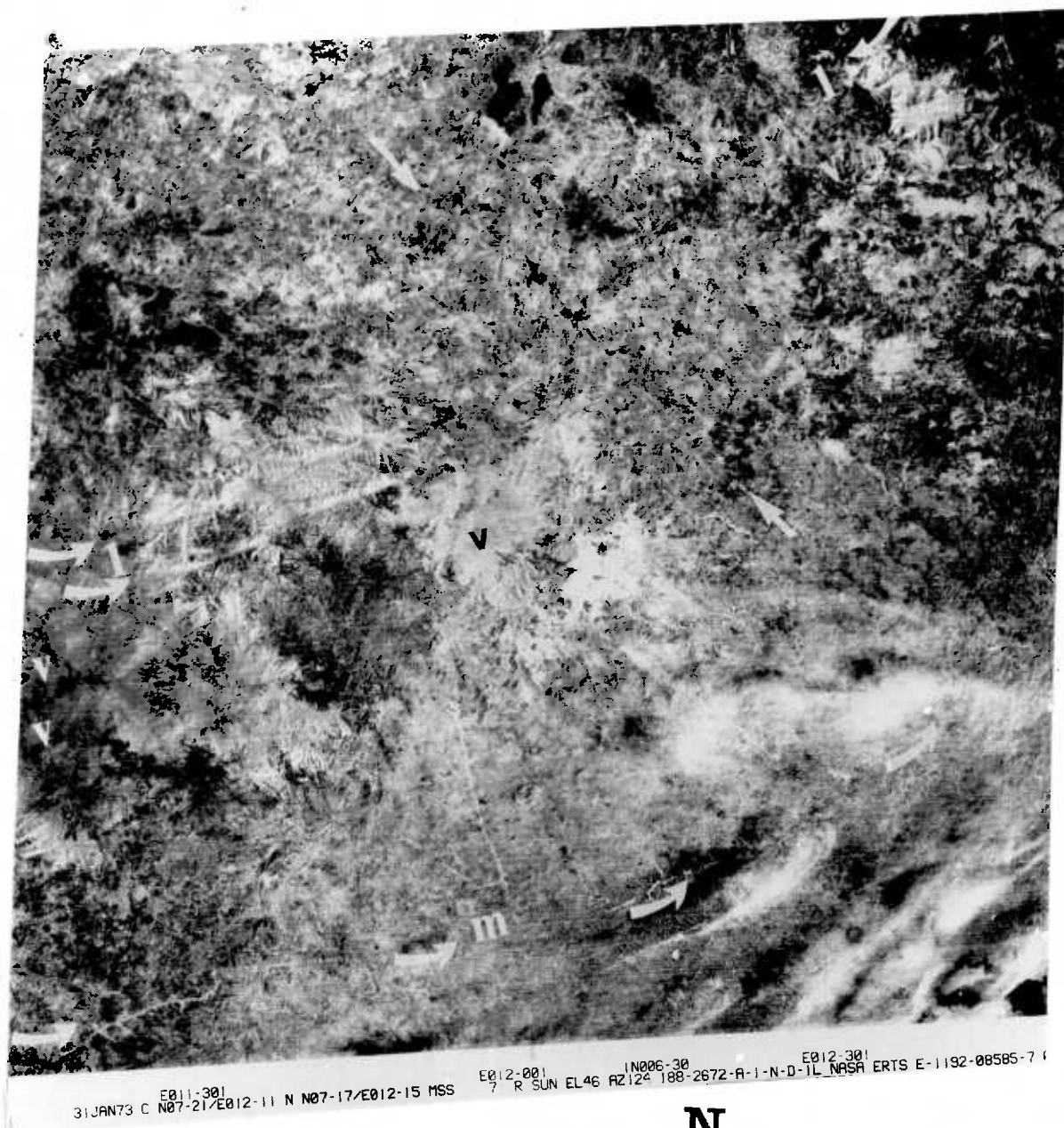


FIGURE 19b

- THE MARGINAL EN-ECHELON FRACTURES & THE N-S LINEAMENTS OF THE BENUE TROUGH.
- CRUSTAL EXTENSION DIRECTION FOR THE AREA.

PLATE 13

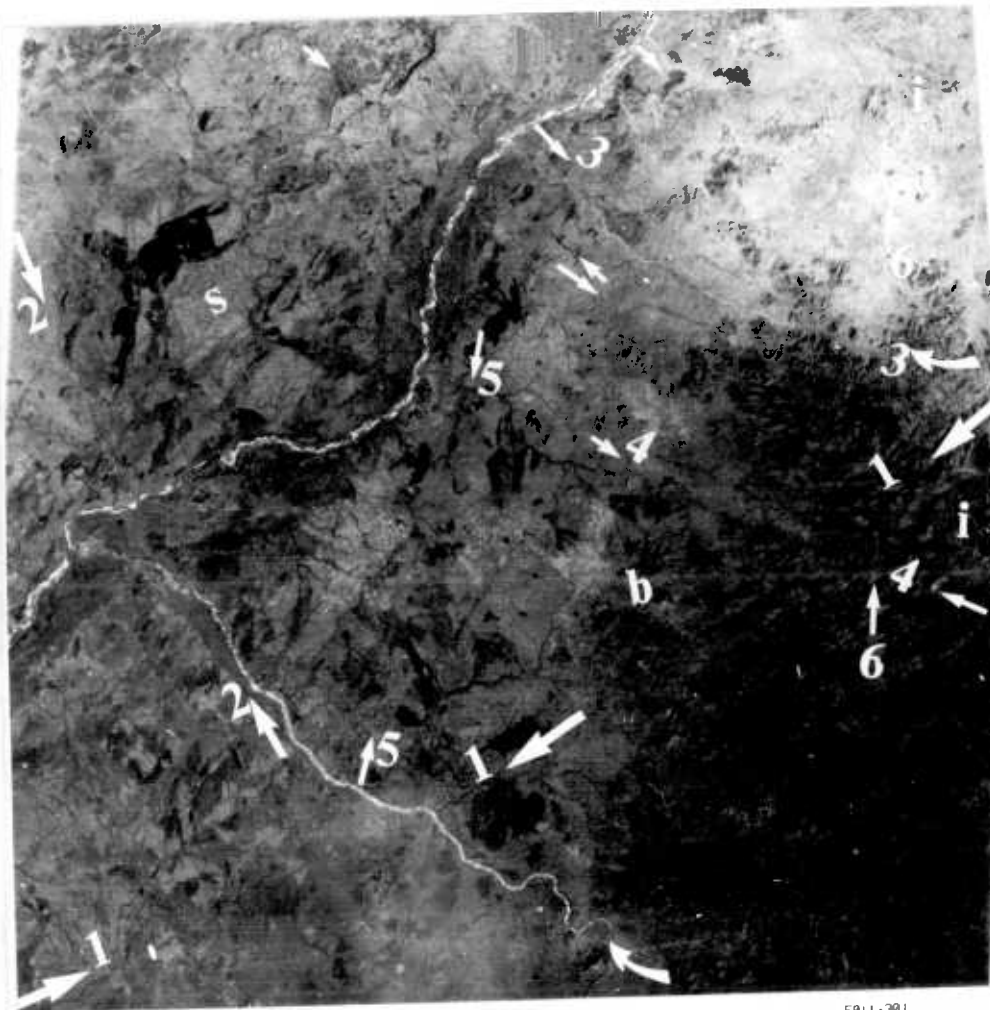
0 km 60



A LANDSAT-1 image of curved concentric lineaments near the Nigerian-Cameroon border, l, m. (curved arrows)

v = volcanics

m = Ka Boragap mylonites



E010-301
 08JUN76 C N00-35/E011-00 N 00-35/E011-04 MSS 5 R SUN EL41 AZ130 189-4889-R-1-N-D-2L NASA ERTS E-2351-00500-5 01
 E011-001
 E011-301

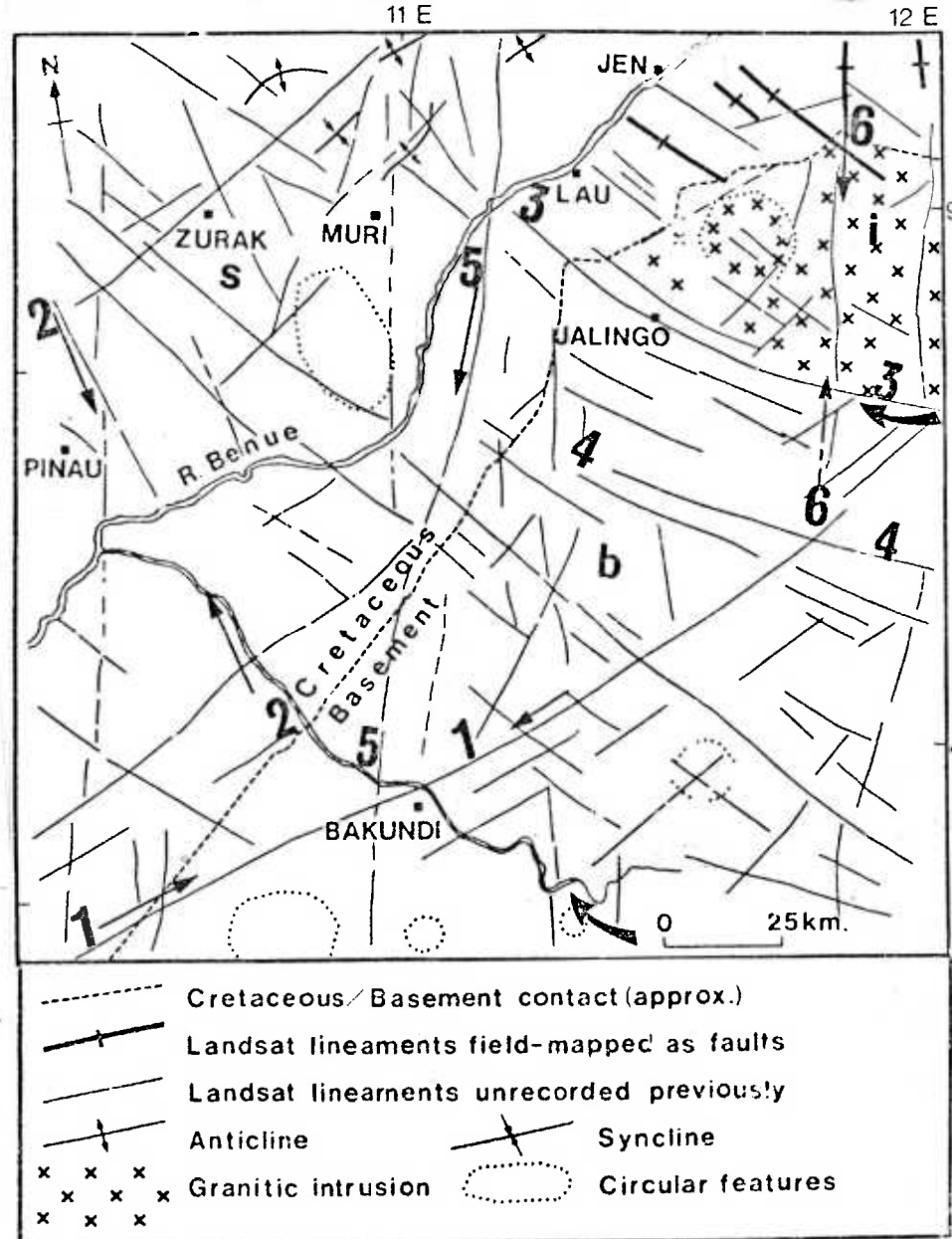


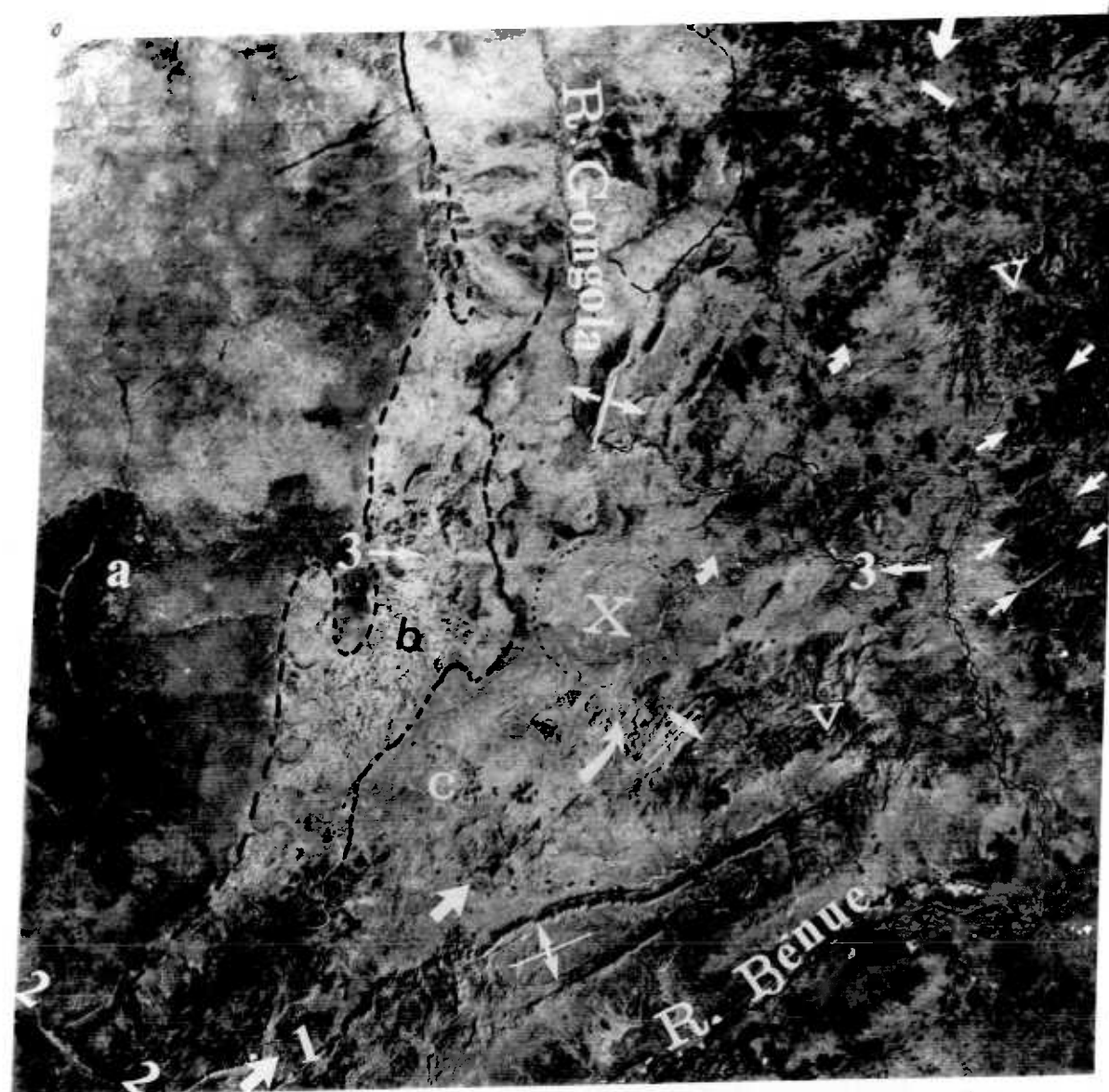
PLATE 14

A LANDSAT-1 image of NW- trending marginal lineament of mid Benue trough areas (left).

- 1, A major curved lineament trending NE.
- 5, 6 N-S lineaments.
- 2,3,4 NW trending lineaments.

A photogeological sketch of the main features of Plate 14 (right)

- s = sedimentary cover
- b = basement
- i = intrusions (granitic)



15NOV75 C N10-09/EB11-27 N N10-09/EB11-31 MSS 7 R SUN EL47 AZ131 185-4136-A-1-N-D-1L NRSA FRIS F-2247-12501-7 01

PLATE 15

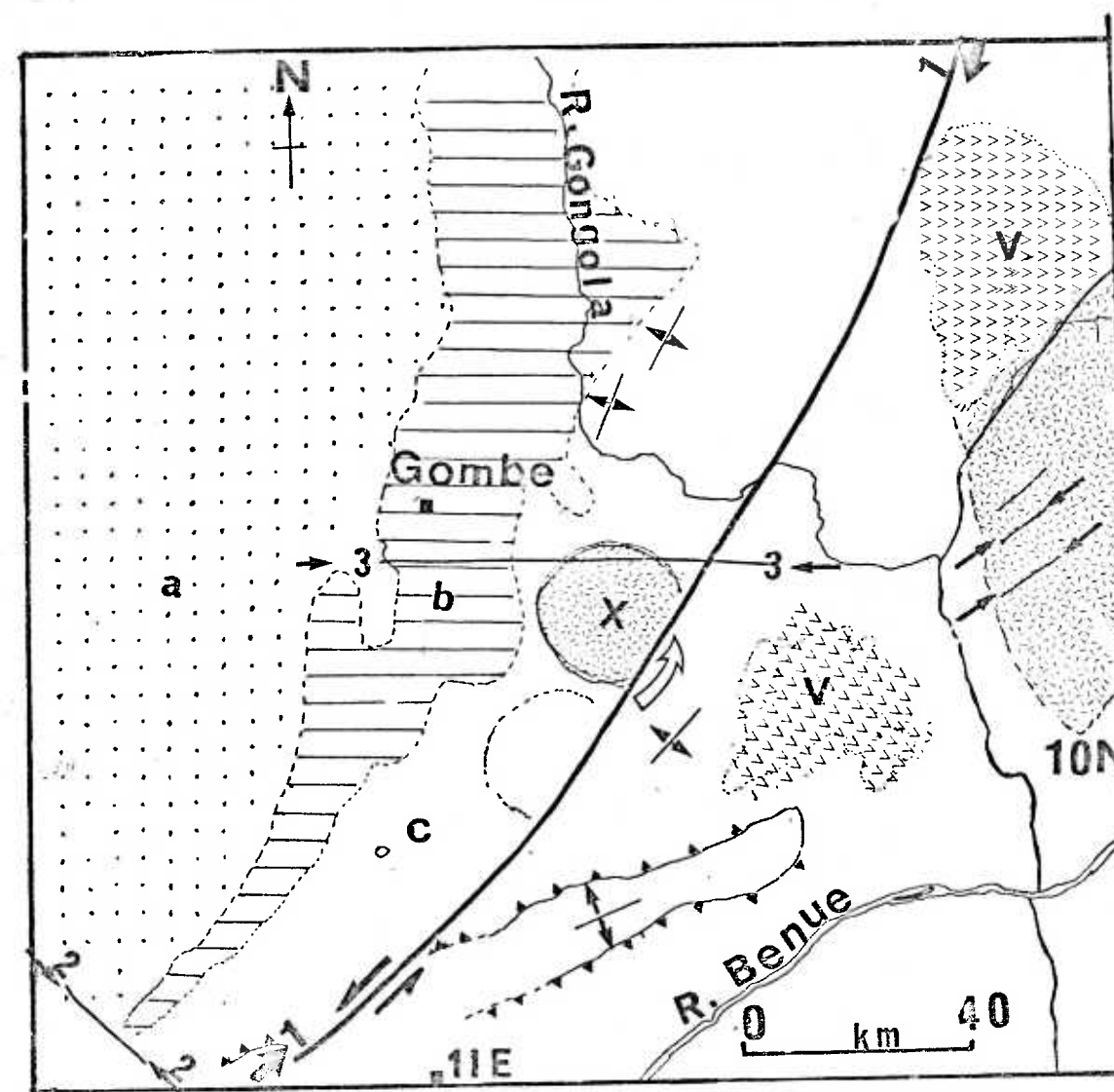
A LANDSAT-2 image of the Benue trough.

Notice how tonal contrasts reflect bulk lithological variations. The Lamude anticline is visible.

a = continental Kerri-Kerri formation

b = Gombe sandstone

c = Bima sandstone



A photogeological sketch of the main features of Plate 15.

1 = A major Benue trough sinistral shear fault, previously unrecognised.

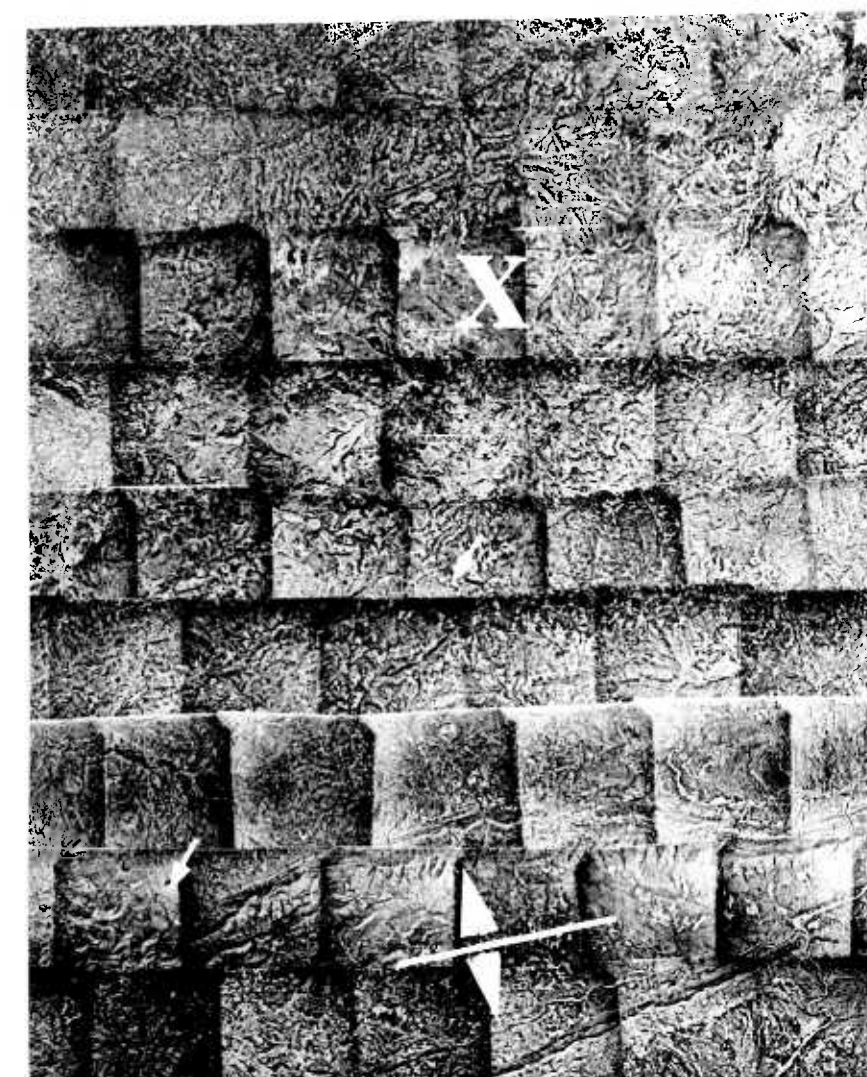
x = Kaltungo basement inlier

v = volcanics

2 = NW trending fracture zone

3 = E-W lineament

Small arrows indicate minor basement fractures.



An air-photo mosaic of the Lamude anticline and the Kaltungo inlier areas.

Arrows indicate the trace of the LANDSAT lineament, 1, (Plate 15).

x = Kaltungo inlier

(c) The NW-trending lineament

The third lineament trend which is commonly observed by field geologists is shown in Plate 14. They trend NW and form perpendicular to the fold axes. They probably initially formed complementary to the NE trending lineaments but became a tensional direction during the Santonian, Benue trough folding. Some NW lineaments are also curved, open and often contain calcite infillings.

Within the trough itself, basement failures through considerable thicknesses of sedimentary cover (Plate 15a) are apparent on the LANDSAT image. The lineament appears on the image as distortions on NE-trending fold axes. Plate 15b shows an air-photo mosaic of the same intra-basin lineament. The intra-basin lineament is curved and extends towards the Chad Basin. This major fracture zone was not recognised prior to the present study.

The advantages of LANDSAT imagery studies are well illustrated in the Benue trough structures. Field mapping did not correctly locate the contacts between the Basement Complex and the overlying cover rocks. LANDSAT images clearly contrasted the sediments with the basement rocks and in figure 19, symbol number 15 is used to show the contact between the sediments and the Basement Complex as suggested by the images. Symbol 1 indicates the LANDSAT lineaments of the Benue trough, while 10, 2 and 11 represent granitic intrusions of different ages.

3, 6 and 13 (figure 19) refer to volcanic rocks also of different ages, and 5 shows the trough sediments, while symbols 4, and 12 show the previously mapped faults.

CHAPTER SIX

THE CENTRAL NIGERIAN LINEAMENTS AND FRACTURES

6.1. THE NEAR-MERIDIONAL LINEAMENTS

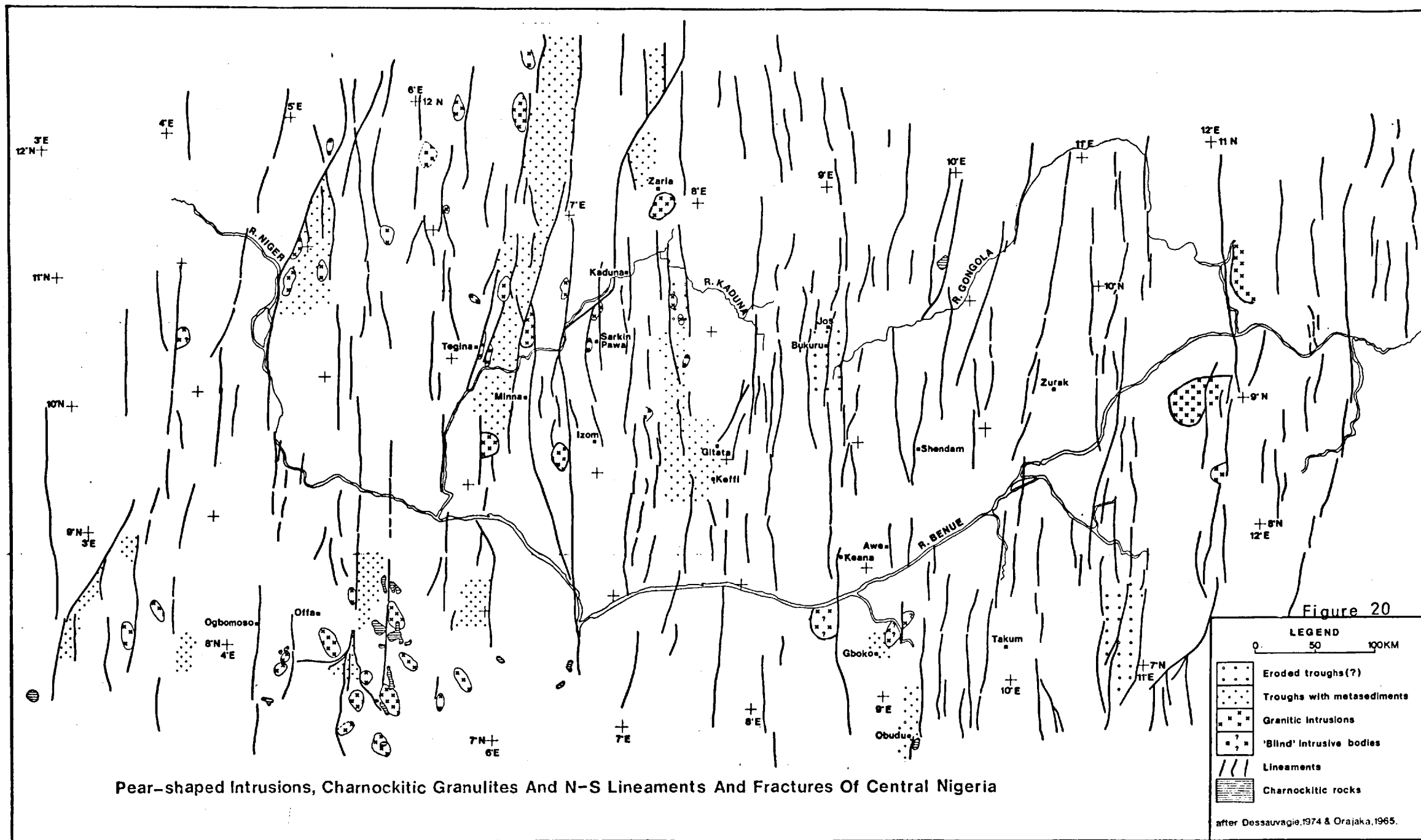
One of the advantages of the LANDSAT and orbital images in general is that they allow one to identify certain new geological factors, that determine the crustal development of a region. One such factor in Central Nigeria, is the occurrence of major near-meridional lineaments ($0^{\circ}\text{N} - \text{N}8^{\circ}\text{E}$) and fracture zones. Some of the near meridional lineaments are not always very obvious on air photographs because they tend to be very wide, thus requiring many air photographs to be discernible.

6.1.2. Lengths and shapes

Figure 20 shows the plot of the LANDSAT near-meridional lineaments of Central Nigeria. They are characteristically straight for several tens and often hundreds of kilometers. Some are branched, a few short and broken. The broken nature of some may have resulted from soil developments along them. Intrusive rocks are frequently aligned along the lineaments, especially the elongate or pear-shaped granitic bodies.

6.1.3. Spacing and ground details

A significant characteristic of the Nigerian N-S lineaments is their spacing. They tend to occur



at intervals of about 40-50 kilometers (Chukwu-Ike and Norman 1977), comparable to the crustal thickness of continents. The reason for the regular arrangement is uncertain but may not be unrelated to the rotational stresses of the earth.

On the ground, the sub-meridional lineaments tend to be negative topographic features. Some are however positive topographic features or partly positive and partly negative. The lineaments very often locally control major rivers. The Kaduna River (Plate 2), tends to follow the N-S lineaments in many places. In some places, the negative topographic expression associated with the N-S lineaments may be as much as 5-10 kilometers across. The intensity of fracturing and jointing in rocks appears to increase as the location of lineaments are approached on the ground. The jointing often trends in the same general direction as the lineament.

The lineaments tend to have extensive soil cover. Rare exposures associated with some show that they are intensely fractured zones. The lineaments appear to be intensely fractured zones that are closely spaced. Mylonitisation and silicifications are associated with them (Plates 10a and 10b). Flaser gneisses are associated with the N-S lineaments in areas that appear, on the images, to represent previously lower crustal levels.

6.1.4. The relationship between the lineaments,
metasedimentary troughs and migmatisation

The several narrow N-S metasedimentary troughs of Central Nigeria are related to the N-S lineaments. In most places, LANDSAT images clearly show that the Nigerian troughs are bounded by gregarious granitic intrusions clearly linked by N-S lineaments (Plate 2, 5). Figure 20 also illustrates the relationship of the N-S lineaments with granites.

It is evident on LANDSAT images that intrusive rocks tend to follow the lineaments closely. The N-S fracture zones appear to be important tectonic axes along which granitic intrusions and volcanisms preferentially followed. Appendix 1 (same as Plate 2) shows a colour composite of the NW Nigerian low grade rocks. The image tones at the locations of the marginal intrusions indicate that heat associated with the rise of the granitic intrusions affected the supracrustal rocks. The cover rocks here appear patchy in tone. Ground checks confirm that the trough marginal areas are dominantly migmatitic terrains. The lineaments appear to represent fractures that extend to the base of the crust that may serve as lines of high heat and magma flows. Cover rocks are as a result intensively migmatised. The N-S lineaments are tectonic lineaments. Major E-W folds of the Nigerian basement tend to be re-aligned N-S indicating that the N-S lineaments may have been shears at

some geological time. Judging from present erosion levels, vertical movements appear to be dominant along these lineaments. (Chukwu-Ike and Norman 1977a).

6.1.5. The age of the N-S lineaments

It is difficult to determine an age for the origin of a fracture system or lineament along which movements and igneous activities may have occurred at different geological periods. A lineament may exist for a long period of time without igneous activity and may later be reactivated, but the relationship between lineaments and other basement features can provide some help in dating lineaments.

In Central Nigeria, photogeological evidence and field work suggest that the near-meridional fracture zones and lineaments determined the location of N-S metasedimentary troughs. The flay-lying E-W trending folds are always refolded along these troughs. This suggests that the E-W folds predated the N-S troughs. Radiometric dating of concordant granite gneisses along the E-W folds indicate an Eburnean ($2000 \pm \text{m.y.}$) age. (Grant 1970). The volcano-sedimentary sequence that was tectonised to give rise to the E-W folds therefore appear to date back into the Archaean.

Elongate porphyritic granites associated with the N-S lineaments in Nigeria are Pan African ($600 \pm 100 \text{ m.y.}$)

in age (Jacobson et al. 1964, Grant 1970). This shows that the N-S lineaments were active about this time. The granites appear to be late tectonic (Wright and McCurry, 1972). This suggests that the trough sedimentation probably stretched into the Kibaran orogenic cycle ($1,000 \pm$ m.y.). The Nigerian near-meridional fracture zones may probably have formed between the 2000 m.y. Eburnean cycle and the 1000 m.y. Kibaran event.

6.1.6. Geophysical evidence for the existence of the N-S lineaments

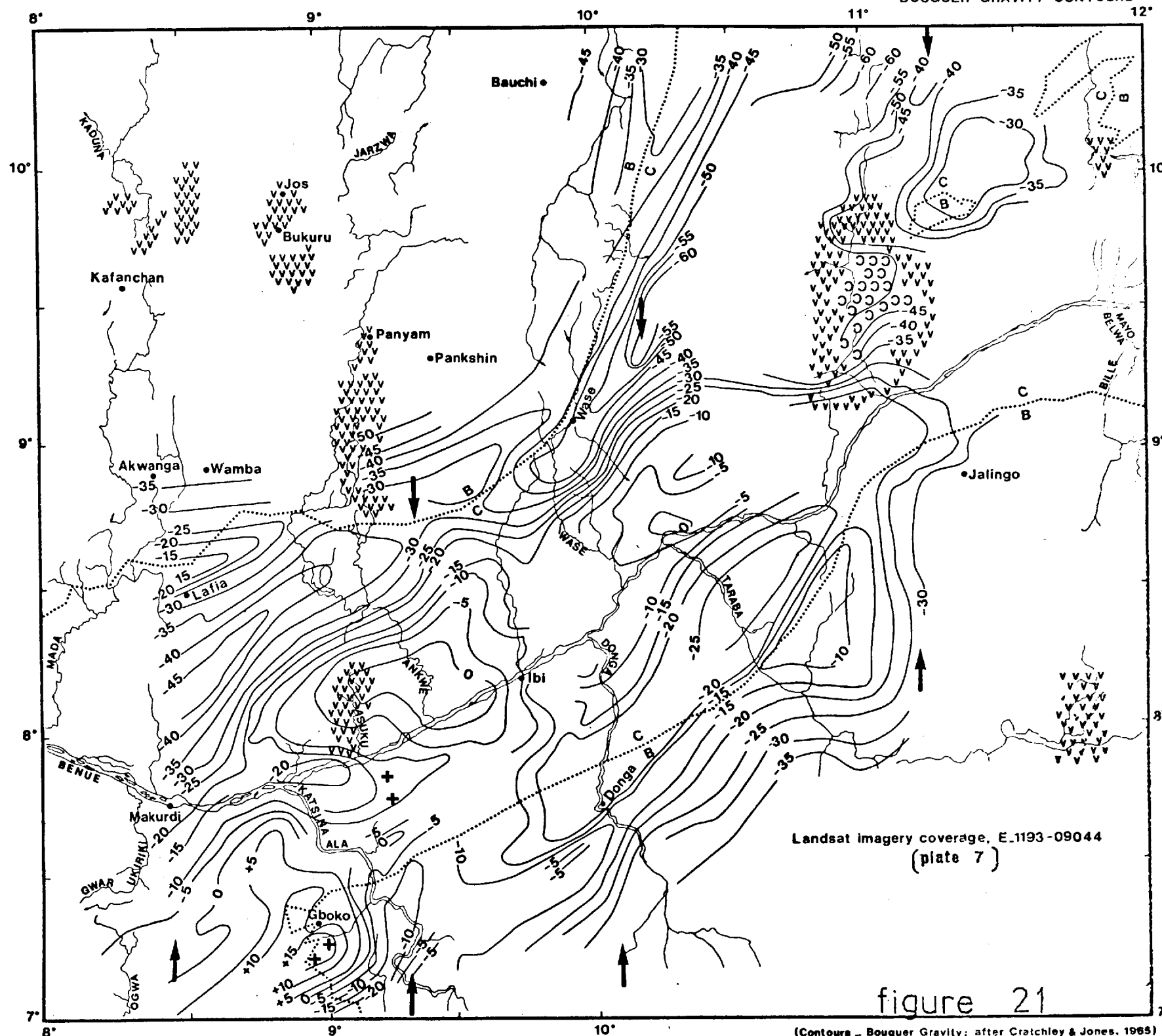
Aeromagnetic data over the locations of the N-S lineaments do not appear to have a consistent pattern. An aeromagnetic anomaly is a record of the contrasts in the magnetic properties of rocks. Lithological changes as well as geological structures, such as faults may produce magnetic contrasts. The causes of aeromagnetic anomalies are therefore many and varied.

Aeromagnetic contours of parts of Central Nigeria (figure 29) show that frequently negative regional magnetic values are associated with the N-S lineaments. The alignment of negative magnetic contours along the lineaments may be indicative of the granitic bodies associated with the lineaments.

. Bouguer gravity contours appear to be more significant in their relationship with the N-S lineaments.

BENUE VALLEY

BOUGUER GRAVITY CONTOURS



Landsat imagery coverage, E.1193-09044
(plate 7)

figure 21

(Contours - Bouguer Gravity; after Cratchley & Jones, 1965)

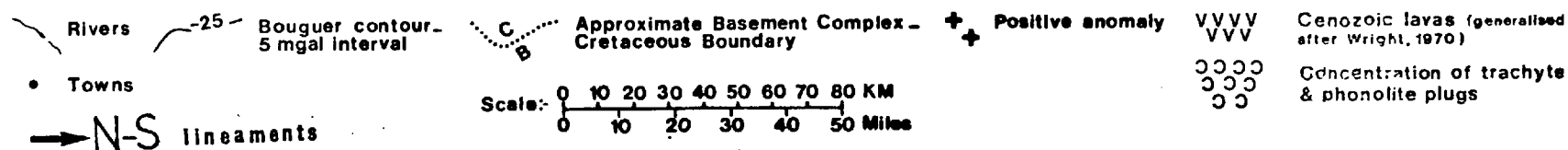


Figure 21 shows a regional gravity map of the Benue trough. The gravity contours tend to be deflected along the locations of the N-S lineaments. The deflections occur on both sides of the trough corresponding with the traces of the lineaments on LANDSAT images. This evidence argues against the suggestion that the Benue trough represents a subduction zone or a crustal suture (Nagy et al. 1976) since there appears to be no mismatches in the trends of these old fracture zones on both sides of the trough (Chukwu-Ike 1977).

6.1.7. The possible origin of the N-S lineaments

The regularity in the arrangement of the N-S lineaments and their spacing and lengths, suggest that they may have required enormous stresses for their formation. It was suggested elsewhere (Norman and Chukwu-Ike 1977) that changes in the rotational speeds of the earth may have resulted in the formation of the N-S fracture zones. Later stresses may have reactivated them from time to time.

6.2. THE NE AND NW TRENDING CURVED CONCENTRIC LINEAMENTS

The NE-trending lineaments constitute a prominent set in Central Nigeria. Two types of NE-trending lineaments are recognised - the straight NE trending set exemplified by Plate 12 and the curved concentric lineaments

DRAINAGE MAP OF CENTRAL NIGERIA

Figure 22

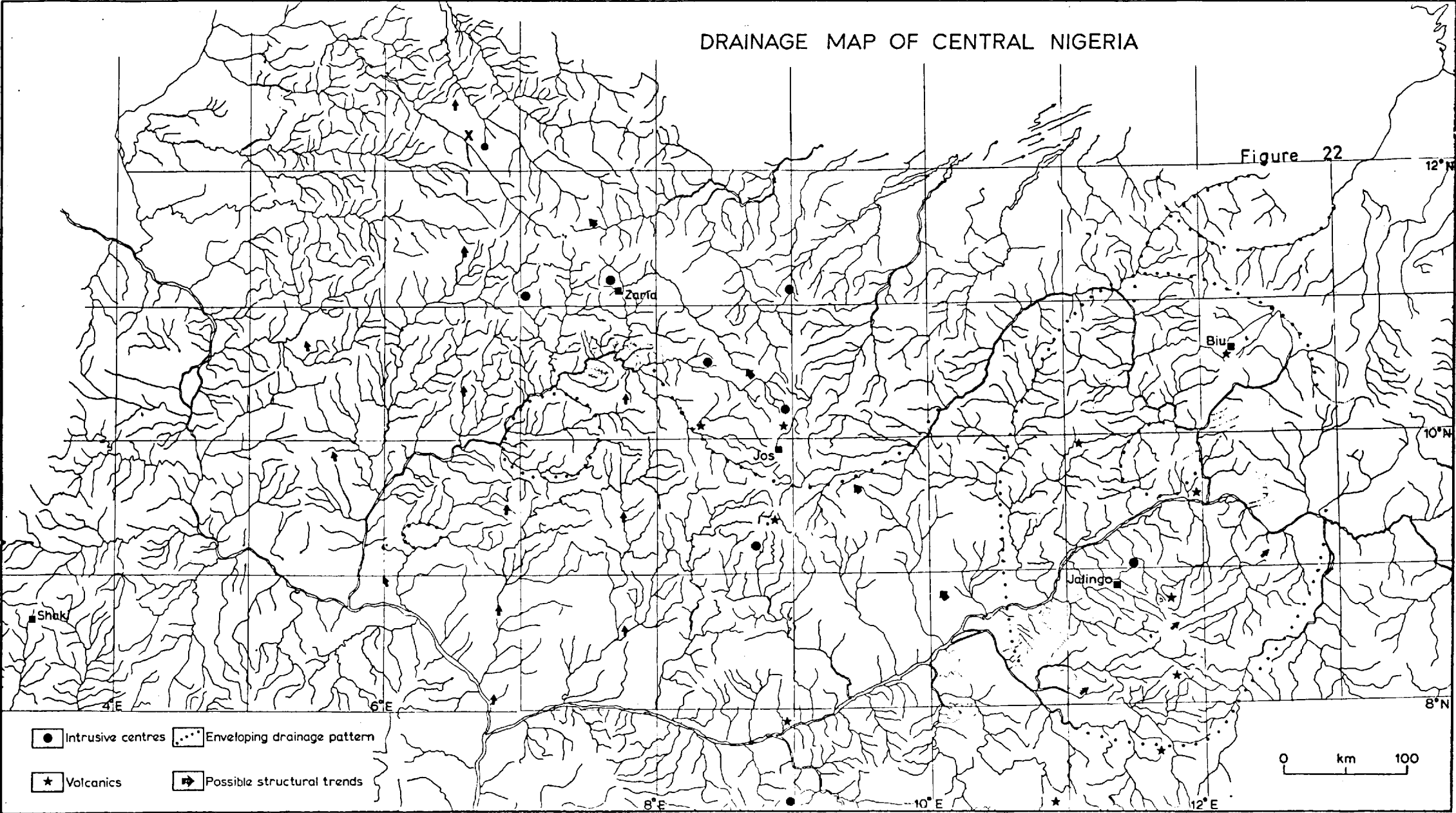
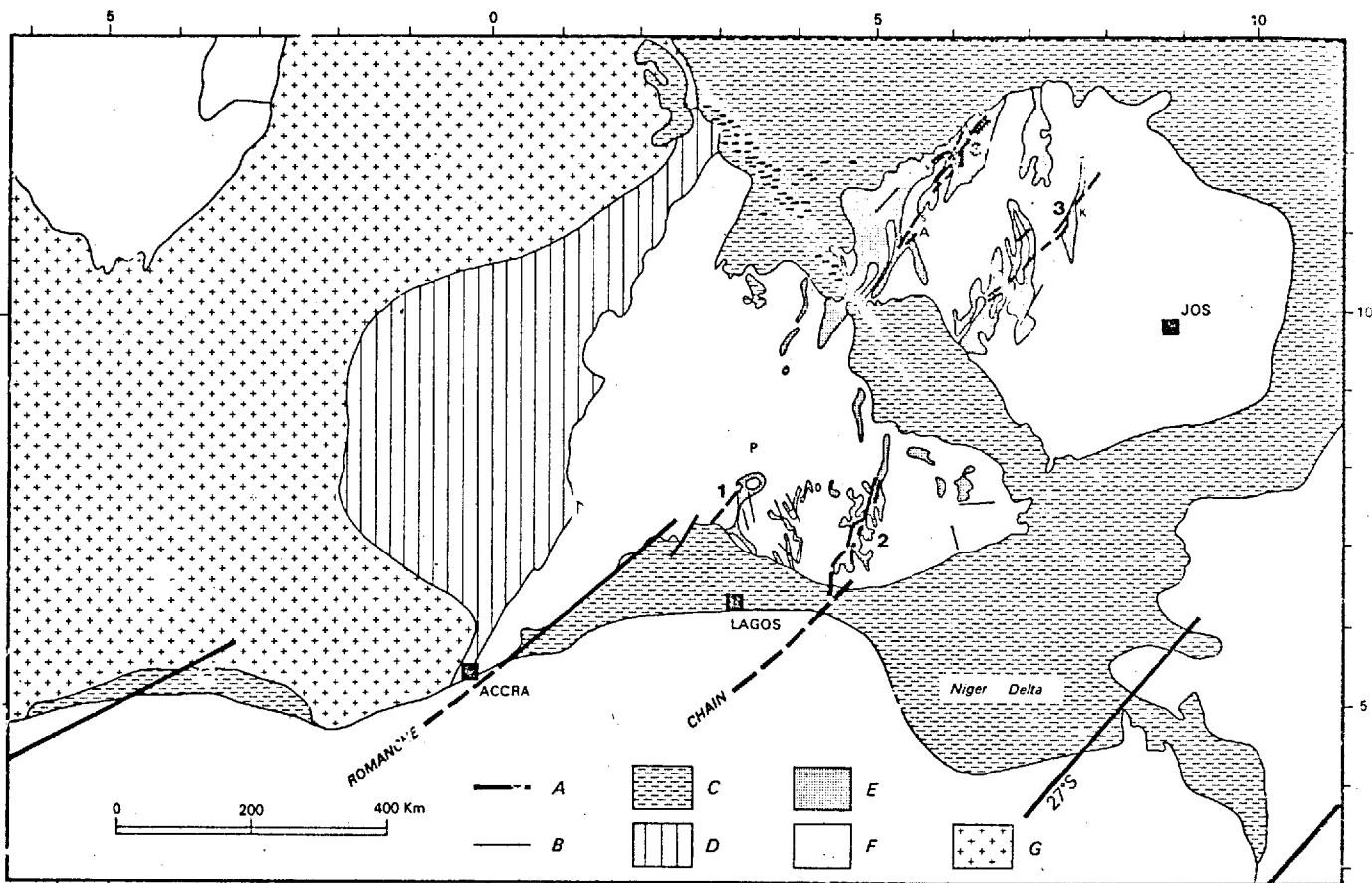


Figure 23



A correlation between some Nigerian faults and Atlantic transform faults suggested by Wright (1976).

A, Major fractures; B, minor fractures; C, cretaceous and younger sediments; E, metasedimentary belts; F, gneisses; D, Buem-Togo-Voltaian sediments.

exemplified by Plates 4 and 13.

6.2.1. The concentric lineaments

The concentric lineaments vary in diameter from a few tens of kilometers to over a thousand kilometers. The smaller concentric lineaments are reflected in the enveloping drainage pattern of the region (figure 22). The larger diameter concentric lineaments are associated with major igneous centres, major tectonic features such as grabens and linear volcanic lines such as the Cameroon volcanic line. Wright (1976) correlated two curved continental faults in Nigeria with some Atlantic transform faults (figure 23) thus suggesting that the Nigerian fracture zones may be continental equivalents of ocean fractures, along which Africa and South America are believed to have separated. Two of the fracture zones he correlated with Oceanic fracture zones are visible on LANDSAT images. Wright's correlation appears to be an over-simplification of the actual traces of these faults.

6.2.2. The characteristics of the curved concentric lineaments

The NW trending and NE-trending lineaments occur in a very complex criss-crossing pattern. In some places however the relationship between different radii of a concentric set are well preserved to allow a close study. Plate 16a illustrates a curved concentric lineaments set

near the Walvis Bay in S.W. Africa. The centre point of this set is a sedimentary basin inside South Africa.

From the centre of the basin outwards, the innermost (smallest, diameter) arcuate lineament is separated from the second lineament, (2, Plate 16a), by the Precambrian basement and Precambrian metasediments. The third and fourth rings are associated with intrusions and volcanic rocks. The S.W. African curved lineaments are defined by tonal contrasts.

In Nigeria the trace of arcuate lineaments are represented on the ground by distinct morphotectonic features such as graben. The Benue graben along which many arcuate lineaments could be traced is over 50 kilometers wide in many places. Broad mylonitic zones and concentrated igneous activity are some of the characteristics of some arcuate concentric lineaments. A geometric examination of the Benue concentric lineaments shows that the centre is situated at the Toudeni Basin ($11^{\circ}30'E$, $21^{\circ}N$) in Mauritania. This basin is about 1000 kilometers from North to South and contains sediments and metasediments of different geological ages.

Geological literature about the Toudeni Basin shows that it is defined by concentric lineaments and fractures (figure 24a). This structure is very similar to the structures resulting from the explosion of 500 tons of T.N.T. in a series of experiments conducted on flat-

16c

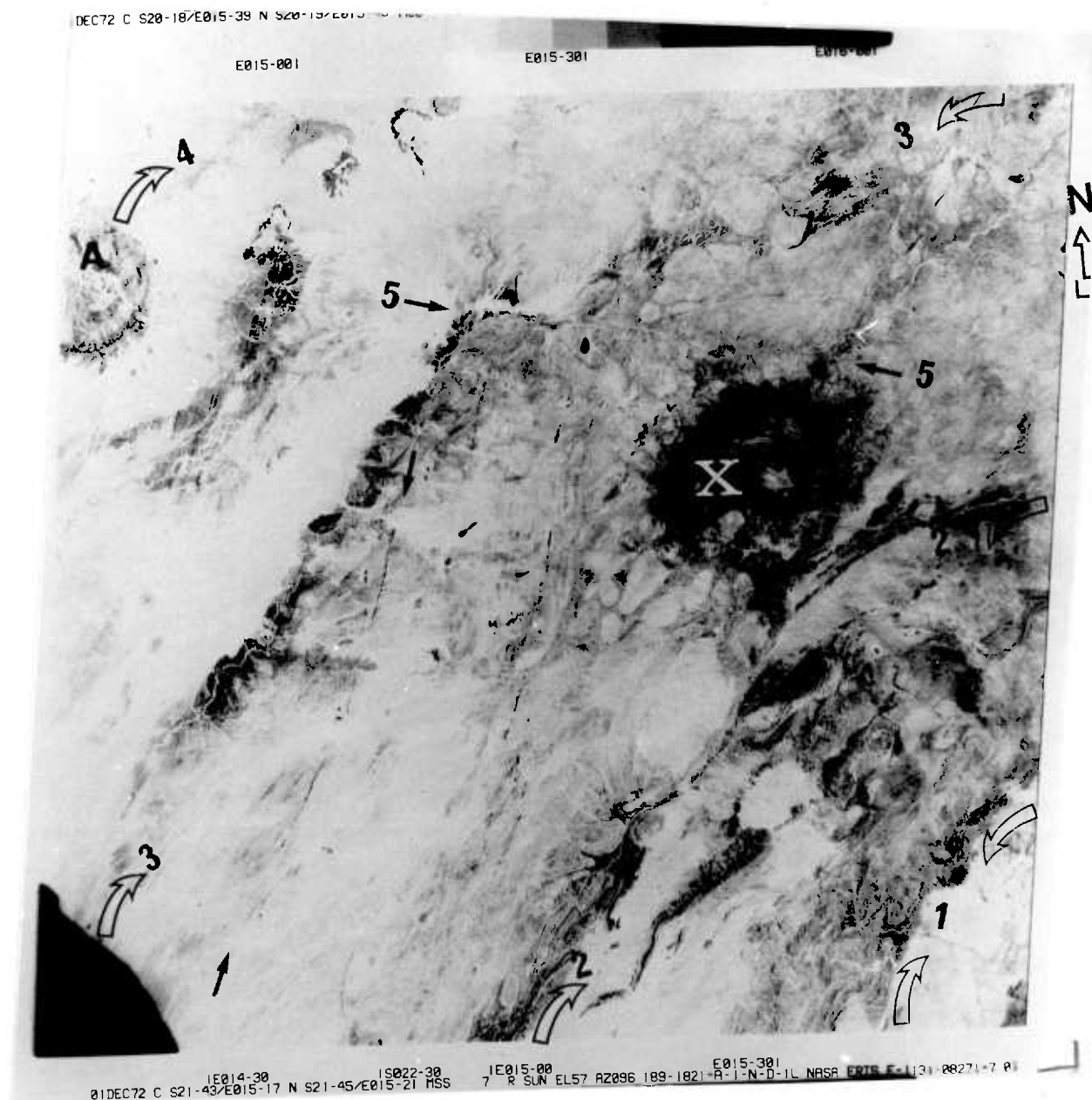


PLATE 16a

A concentric set of lineaments near Walvis Bay, S.W. Africa

1, 2, 3, 4 concentric lineaments

5 = E-W lineament

A, X intrusions.

16b

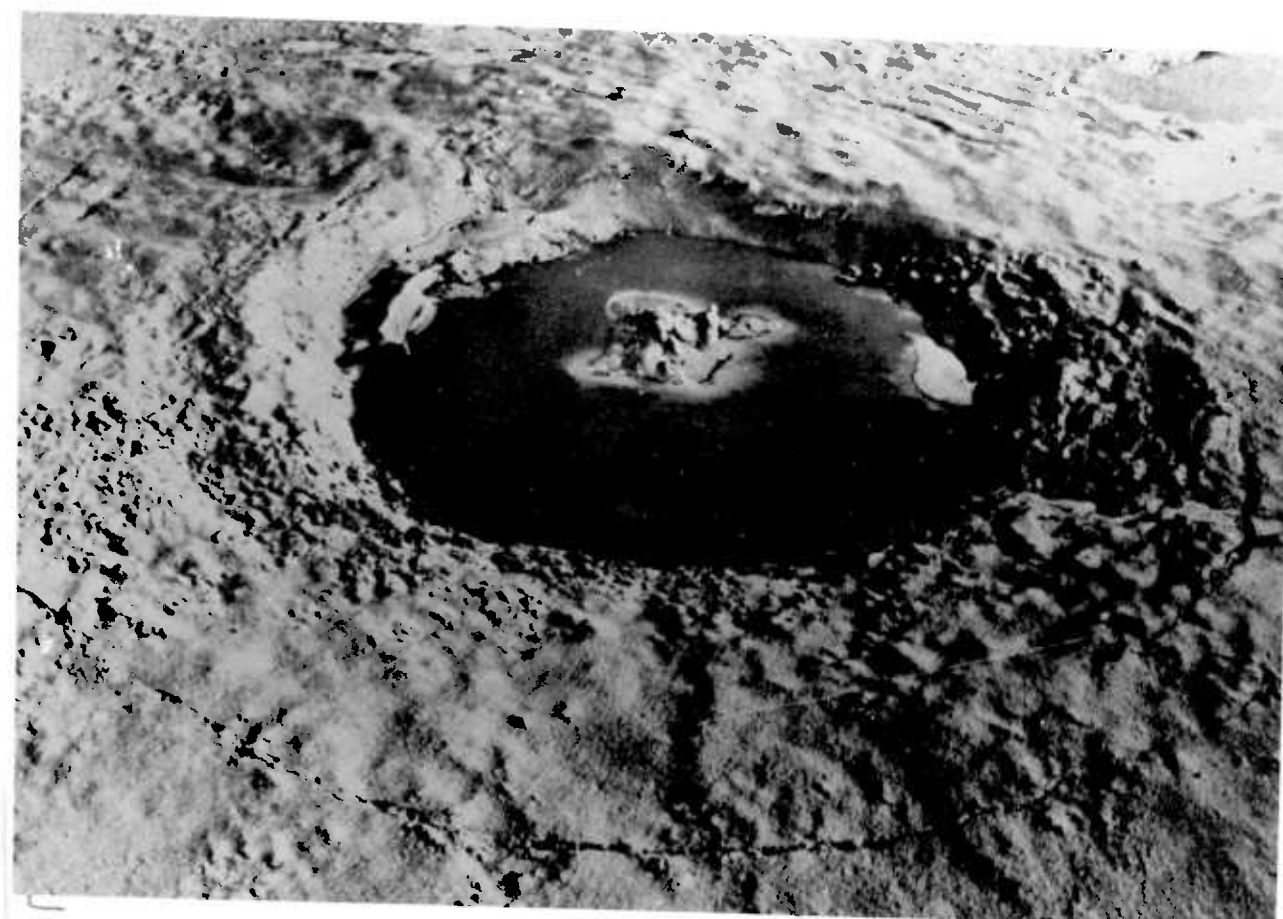


PLATE 16b

A concentric set of lineaments obtained by G. Jones (1966) showing a central depression and associated circumferential graben.

(See figures 24a and 24b)

a

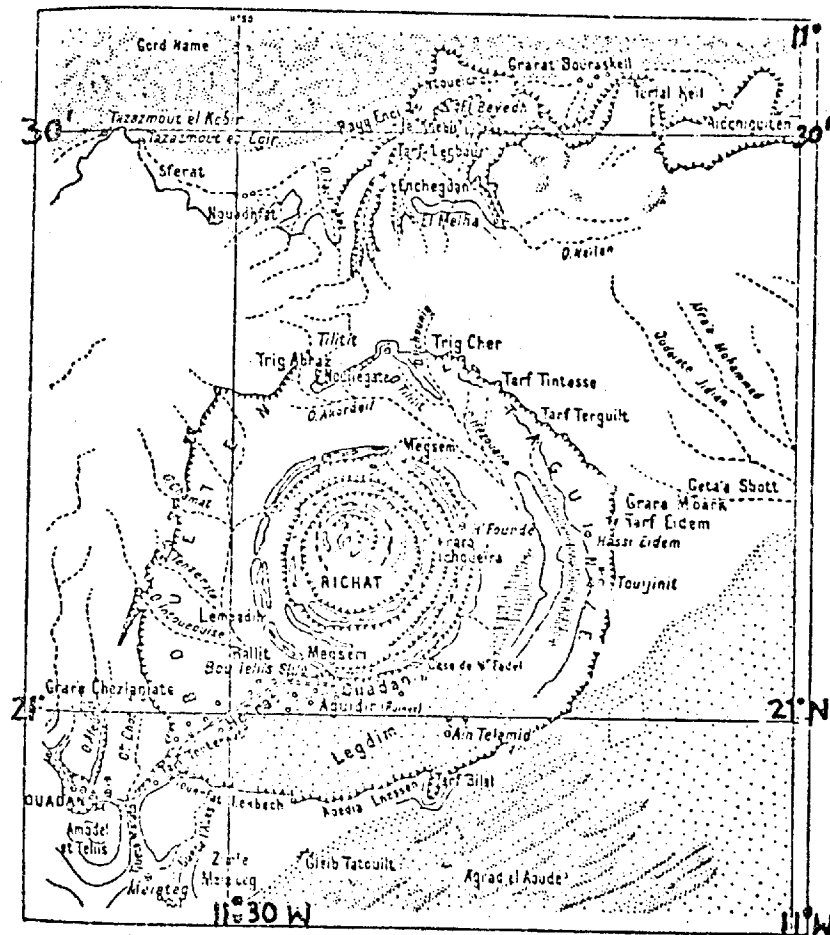
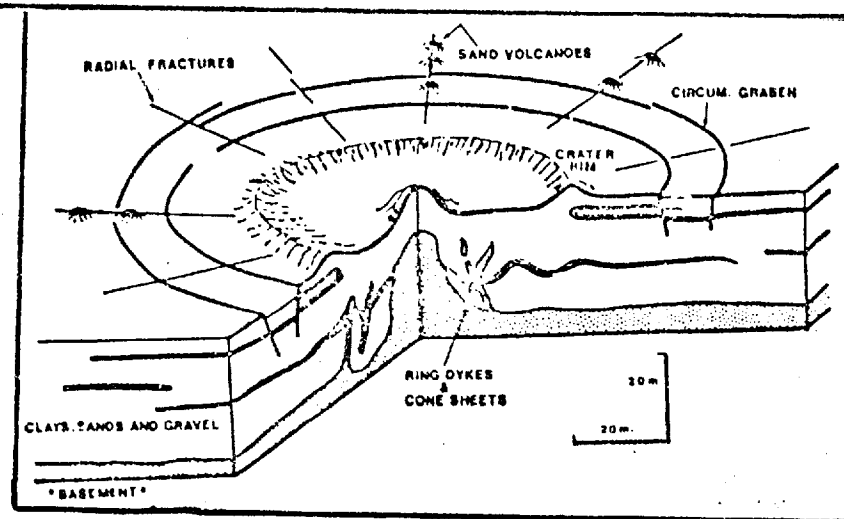


Figure 24

- (a) A structure within the Toudeni basin showing concentric fractures (After T. Monod, 1952): In *Tectonics of Africa* (UNESCO, Choubert ed. 1971 p.271).
- (b) Diagrammatic representation of the main structural features revealed by sub-surface exploration of crater shown in Plate 16b.
(After N.J. Price 1975).



b

Figure 24

lying sediments in Alberta reported by G.H.S. Jones (figure 24b).

The geological map of Africa published by UNESCO in 1971 shows that there may be very many circular basins of this type in Africa. Calculating the centre points of other Nigerian curved lineaments clearly shows that they are either in Lake Chad area or somewhere off the coast, S.E. of Lagos.

This observation prompted the search for clues for the possible causes of the circular lineaments and the associated basins. Regional gravity data over the Toudeni basin shows a marked positive gravity anomaly (Girdler 1975) suggesting that the circular basin is an area of mass concentration. A similar structure in the Congo (the Congo basin) is also an area of mass concentration.

The characteristics of the concentric lineaments can be summarised as follows:-

- (a) Their centres are marked by sedimentary and metasedimentary basins.
- (b) Very little igneous activity is associated with the smaller radii lineaments closer to the basin.
- (c) A Precambrian craton, scarcely deformed, may separate the basin from the larger diameter lineaments.

- (d) The larger radii curved lineaments are geologically active. They are marked by graben, igneous activities and sedimentary troughs.
- (e) The rings of a concentric set may be complicated by other concentric sets having different centres.
- (f) Where two major curved lineaments intersect, igneous activity is usually pronounced.
- (g) Lineaments may radiate from the basin centre in some cases.
- (h) The concentric lineaments sometimes mark edges of step-like features away from the centre.
- (i) Horizontal movements along some concentric lineaments may reach 10-20 kilometers, although vertical movements appear to be dominant.
- (j) A study of the smaller fractures and lineament patterns within a crustal block between two concentric lineaments (Plate 16a) indicates that strong horizontal compressive stresses radial from the centre may be a characteristic phenomenon.

The cause of the concentric lineament is speculative. It has been suggested elsewhere (Norman, Price and Chukwu-Ike, 1977) that the arcuate lineaments helped to shape the present coastlines in many parts of the world. We also suggested that the circular lineaments are very similar to lunar impact features and that the

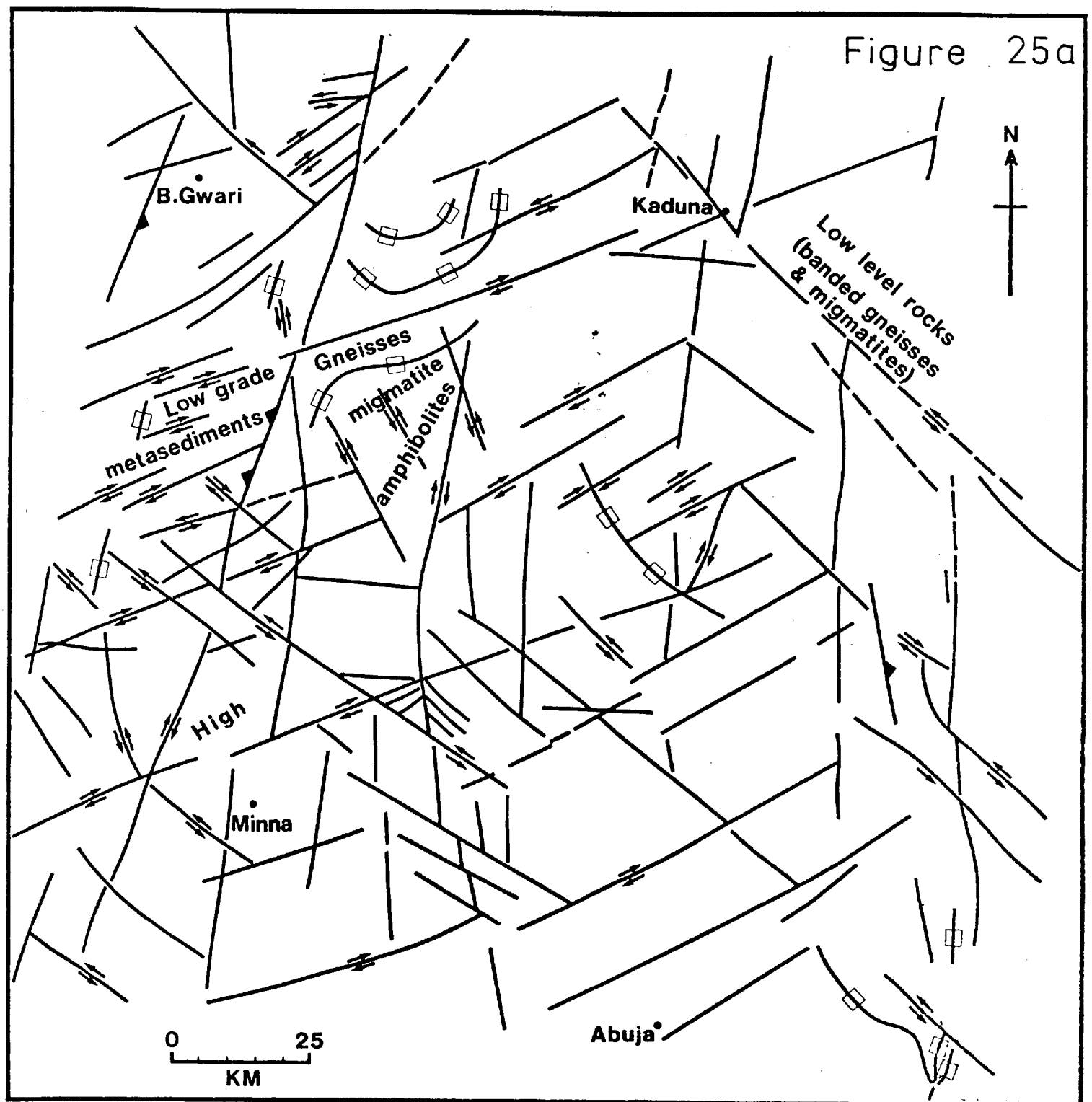
Earth must have been bombarded by even more meteorites than the moon. Fractures created by this bombardment probably gave rise to the concentric lineaments and may have determined the location of parts of some crustal plate margins. Plate 16b shows an experimental structural pattern by Jones (1966) showing a close similarity with circular features seen on LANDSAT images.

6.3. THE INTERSECTION PATTERNS OF STRAIGHT LINEAMENTS AND FRACTURES OF CENTRAL NIGERIA

The Nigerian lineament and fracture intersection patterns fall under two main categories. One category represents intersections subtending angles of 60° or less and the second category generally subtends intersection angles greater than 60° . The 60° dividing line is chosen because laboratory experiments show that conjugate fractures produced by compressive rock deformation stresses tend to subtend angles of 60° . In practice, however, the intersection angle ranges between 45° and 55° and seldom approaches 60° . The great majority of the Nigerian straight lineament intersection angles are over 60° .

It has been stated in the previous sections that the N-S lineaments appear to be unrelated to the concentric sets. It has also been noted that if only one or two LANDSAT images containing these features are studied, there is the tendency to regard some segments of the

ZUNGERU — KADUNA SHEARS, FAULTS AND LINEAMENTS



- Lineaments
- ◻ Fold axes
- ≡ Faults with movements
- ◄ Normal faults & downthrown side

arcuate lineaments as straight lineaments forming at 45° to the N-S lineaments. This danger can be avoided by studying many images of an area before deciding which lineament sets are conjugate or related in time.

6.4. PALAEOTECTONIC STRESS PATTERN DETERMINATION FROM LANDSAT LINEAMENTS OF NIGERIA

Based on the works of Anderson (1951), Price (1966), Huntington (1975), Zwain (1976), the orientation of palaeotectonic principal stresses can be deduced from the study of fractures and other structures. Photogeological palaeostress determinations usually employ statistical methods. It tends to be a regional approximation and takes very little cognizance of minor features associated with major faults. For the scale of study, the method appears very helpful in isolating anomalous areas (Norman, 1976). In some cases en-echelon fractures in sedimentary rocks overlying a major basement fracture zone may be detected on satellite images (Plate 7) and can be useful in stress pattern construction.

Photogeological fracture traces are statistically plotted as rose diagrams and the arrangements of the maxima studied for consistent patterns.

North-west Nigeria is covered by Plate 2 and is an area of polyepisodic deformation. It is also an area where metasedimentary relic beds are preserved. The

displacements along relic beds, the fold axes and the geometry of plastically emplaced intrusions - the elongate granite bodies - provided additional data in the stress pattern analyses of NW Nigeria. Displacements of features on major wrench faults like the Kalangani fault (Trusswell and Cope, 1963) and the Yaribori fault (McCurry 1973) are visible on LANDSAT images and have been considered in the stress pattern construction. However, only the latest movements on these faults are obvious. Movements referable to older orogenies are uncertain. This leaves the fracture patterns as the most significant criteria for inferring the directions of an older principal stress direction.

Figure 25a illustrates the displacements of features along lineaments observed on Plate 2. The interpretation was carried out on 1 : 500,000 enlargement of Plate 2, and figure 25b shows the latest principal stress trajectory constructed for this area based on the geometry of fractures on figure 25a. The interpretation draws largely on the pure shear hypothesis illustrated in figure 14a. Figure 25b shows that the latest principal stress direction over Central Nigeria Basement Complex acted in a general E-W direction.

6.5. SOME MAJOR LANDSAT LINEAMENTS OF CENTRAL NIGERIA

Figure 26a illustrates the total lineament field

of Central Nigeria outlined in the present study. The representation of the lineaments on figure 26 reflect their different degrees of clarity on images. The more obvious lineaments are represented as bold lines. The clarity of a lineament on an image may not necessarily reflect a greater tectonic importance.

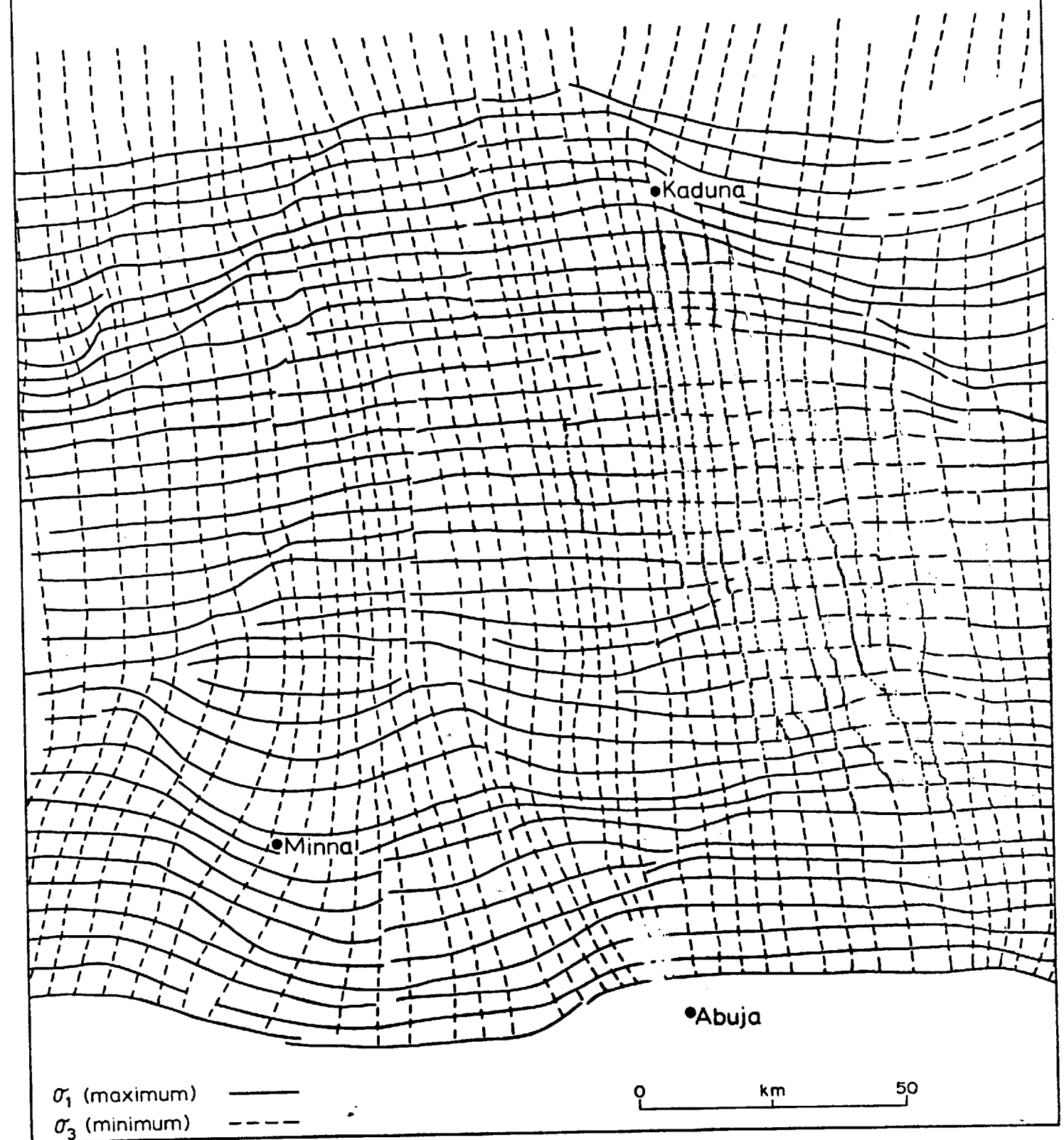
A short description of Central Nigerian lineament for which names have been proposed can be seen in Appendix 2.

The directional statistics of Central Nigerian lineaments and fracture zones show that there are four important straight trends, N-S, E-W, NW-SE and NE-SW. Based on fracture patterns these four directions may not have resulted from one single stress system. Also clearly resolved on LANDSAT images of Nigeria are sections of curved, concentrically arranged lineaments. The concentric lineaments were not included in the directional statistics. The concentric lineament are interpreted to represent probably mantle-tapping fractures resulting from Precambrian meteoritic impacts.

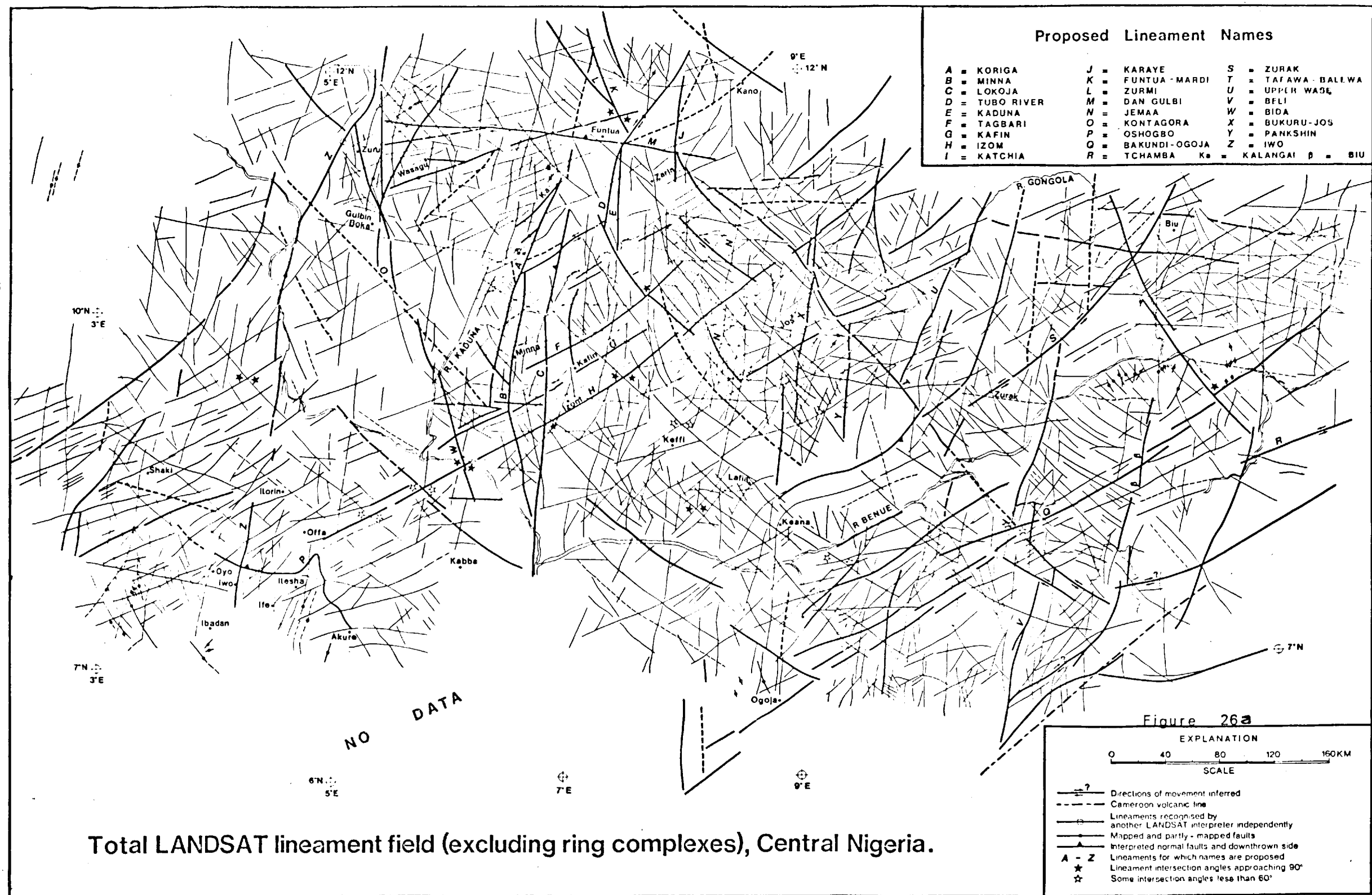
6.6. THE RELATIONSHIP BETWEEN THE KALANGANI AND YARIBORI FAULTS

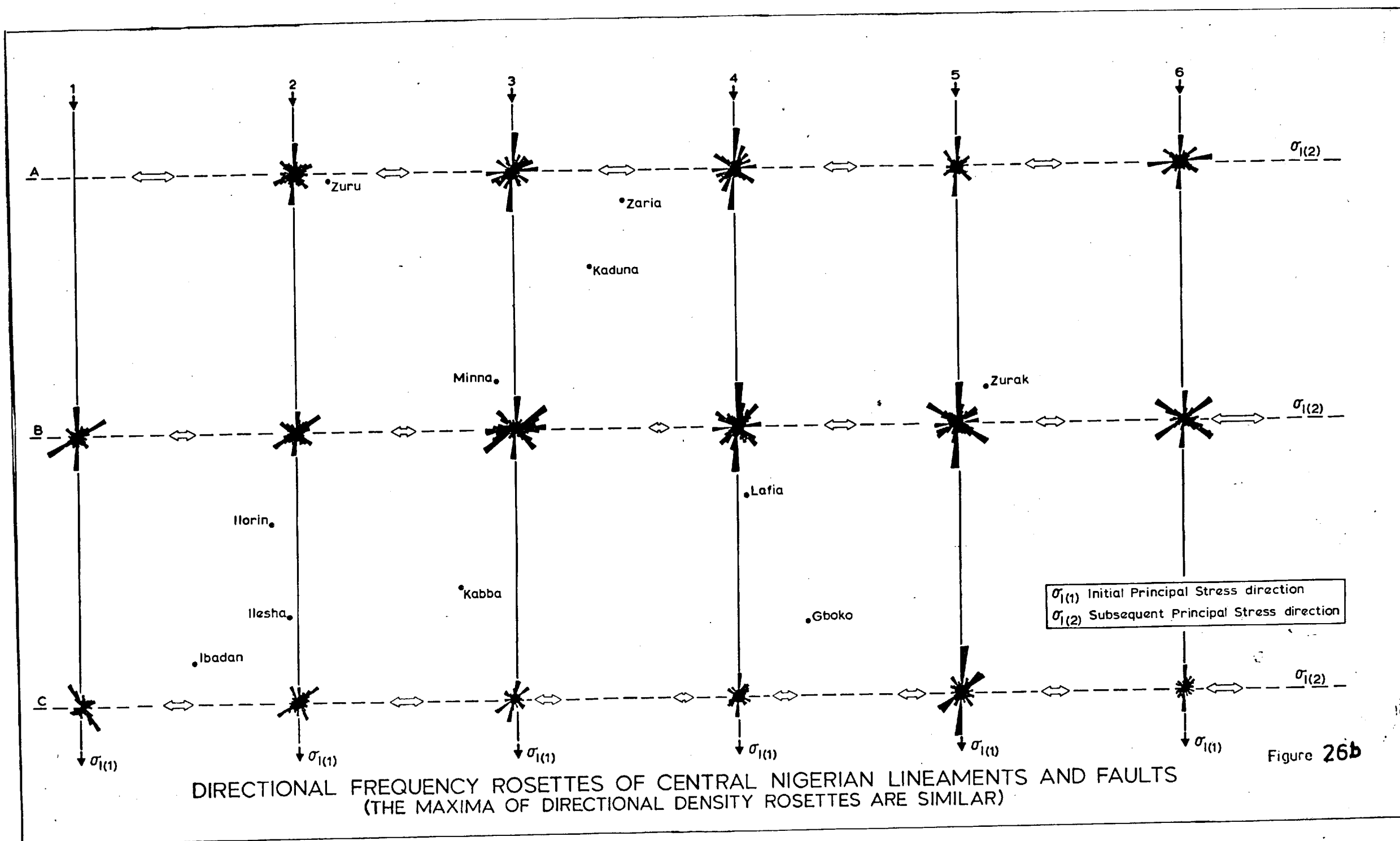
Only two shear faults, the Kalangani shear fault (Trusswell and Cope, 1963) and the Yaribori shear fault (McCurry, 1973) were known prior to the present study. Both are dexteral wrenches having displacements of about

Figure 25b



Latest Maximum & Minimum principal compressive stress trajectory of Zengeru-Kaduna area, Nigeria (σ_1 based on fault movements and fold axes)





A tectonic map based on landsat images

176

fig. 27

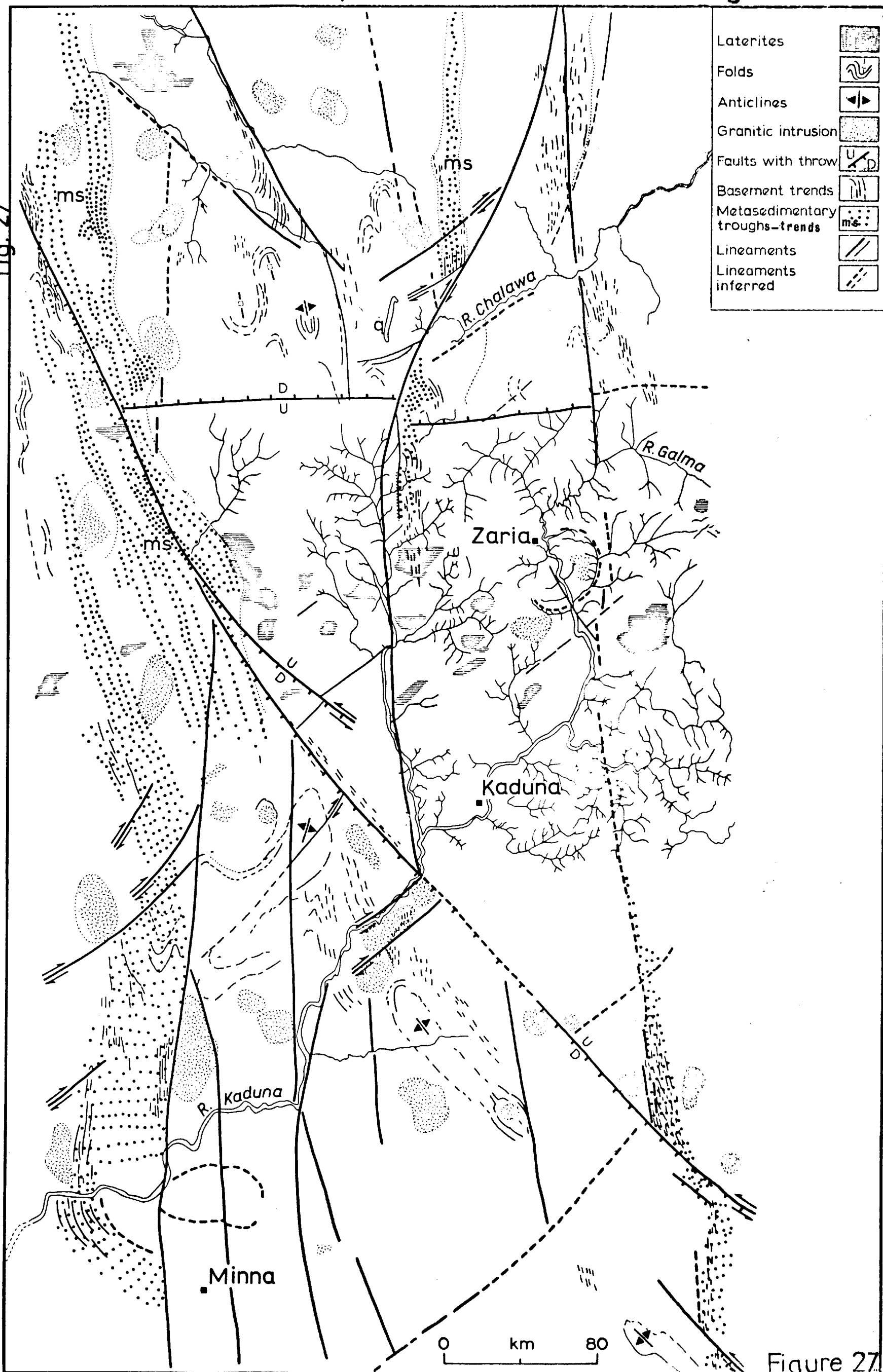


Figure 27

10 kilometers. Both the Kalangani fault (f, Plate 2) and the Yaribori fault (l, Plate 5) appear curved on images. Wright (1976) suggested that the Kalangani and the Yaribori faults are one and the same fault and that they are the continental equivalents of the Chain fracture zones in the Atlantic Ocean (figure 23).

The imagery studies of these faults suggest that the above proposition (Wright, 1976) is an over simplification of the tectonic situation. It is clear that many major continental fracture sets extend to the coast. These tend to follow to a large extent, older N-S fractures. The N-S fractures tend to exert great influence on the NE trending and curved lineaments. Figure 27 illustrates the trace of the two faults over most of NW Nigeria. They both curve into N-S lineaments thus complicating the possible simple relationship between the two faults.

CHAPTER SEVEN

TECTONIC PROVINCES OF THE NIGERIAN BASEMENT

The photogeological approach to elucidating the tectonics of a complex and large shield area as suggested by Hepworth (1967) was adopted for the present study. This method involves distinguishing basement areas in which structures formed during particular tectonic events appear dominant. It is an imprecise method as pointed out by Hepworth (1967) but very useful in gaining an insight into the complex tectonics of a basement.

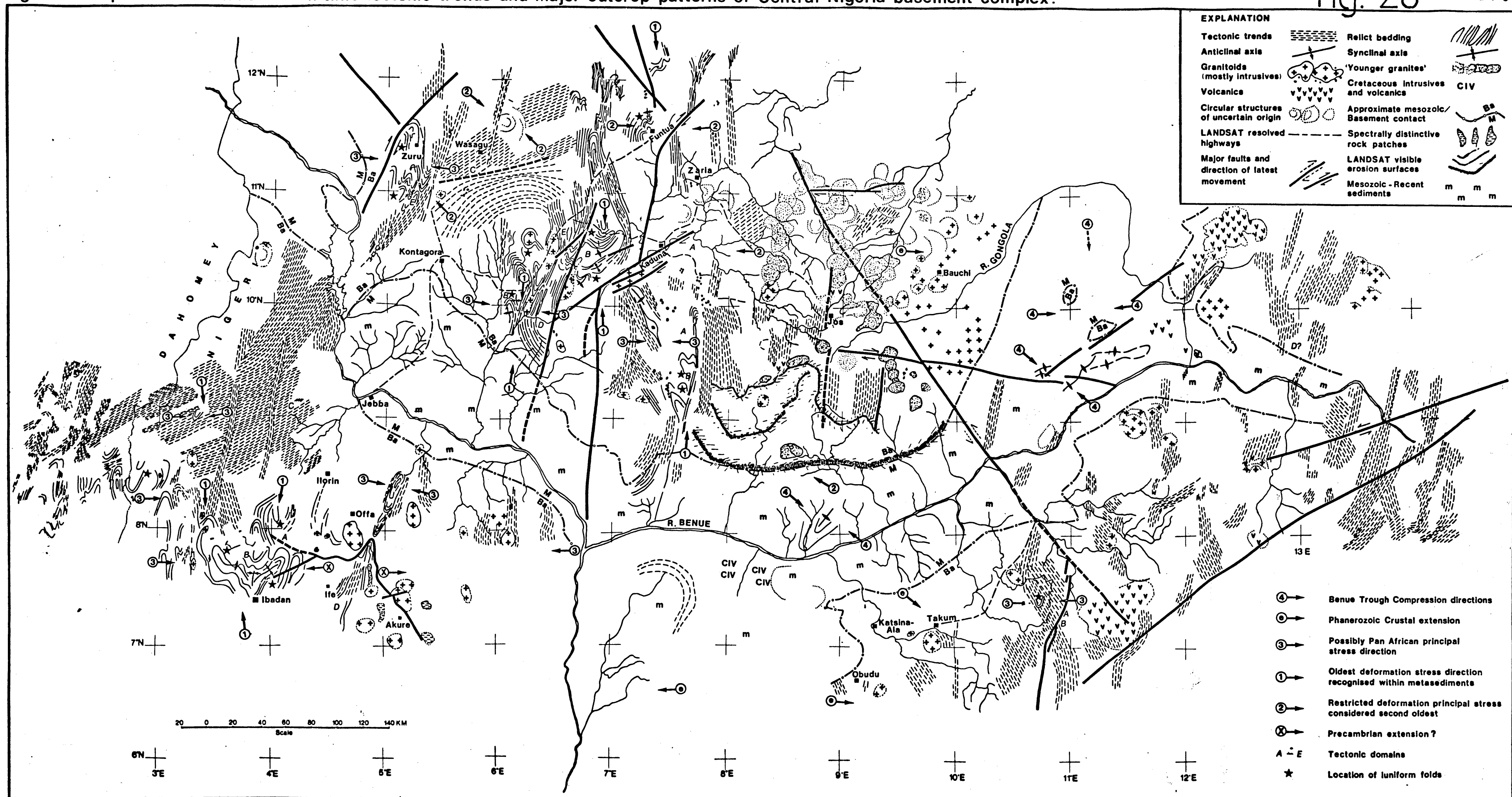
The criteria used collectively in defining a domain by Hepworth (1967) include basement trends or grains, fold trends, metamorphic grades, tectonic styles and tectonic sequence. Each criterion is inadequate for defining a domain. The term 'tectonic style' refers to the total characteristics of a group of related structures in a rock.

The Nigerian domains are numbers A-F. This arrangement does not necessarily reflect the tectonic sequence or chronology (Figure 28).

The 'A' domain

The 'A' domain does not appear to have a peculiar image characteristics. It can however be recognised or suspected from associated features. In Plate 2, the

Fig.28 Principal stress variations with time tectonic trends and major outcrop patterns of Central Nigeria basement complex.



Kaduna area is seen to have a better defined drainage pattern. Metasediments are absent here and where metasediments previously existed (vg, Plate 2) can be inferred on the image. In the field, Kaduna area is dominated by banded gneisses. The 'A' domain appears to represent lower crustal rocks now exposed as a result of uplift. It appears that the banded gneisses underlie metasediments of all ages in Nigeria. The 'A' domain refers to the parts of the Nigerian Basement complex in which the dominant rock type is banded gneiss (Figure 28).

The 'B' domain

The 'B' domain often co-exists with 'A' domain. The 'A' and 'B' domains coexist at Ibadan. Around Kaduna Plate 2, the 'B' domain is recognised by the patchy light and dark tones adjacent to the 'A' domain. It is a strongly migmatitic terrain. The 'B' domain is characterised by large luniform folds (m, Plate 2). The folds are evidently refolded structures. In the field the lunate folds are defined by low-ridge granulitic quartzites with axial plane granite gneisses. The plunges on associated small folds rarely exceed 9° from the horizontal indicating that the lunate folds were originally flat-lying. The wavelength between two adjacent lunate folds is characteristically short (Plate 9).

The 'C' domain

The 'C' domain is represented only in the NW corner of the investigated area. The fold axes and basement trends of this belt are NE. This belt resembles the 'Atacorian' metasediments of Ghana in structural style. The Nigerian 'C' domain passes through the villages of Bena, Wasagu and is over-printed at Zuru by a N-S trough. The 'C' domain contains granulitic quartzites and charnockitic granulites have also been reported in the vicinity of Bena (Sacchi, 1965). Aeromagnetic trends of the 'C' domain support the distinct character of this area (Figure 29). LANDSAT images of this area, although hazy, indicate that a major NE-trending lineament separates the 'C' from 'A' and 'B' domains. The 'C' domain appears to be a narrow (about 30 kilometers) ancient sedimentary trough bounded by deep fractures.

'D' and 'E' domains

The 'D' and 'E' domains are associated with low grade metasedimentary troughs. The imagery evidence for distinguishing 'D' and 'E' domains are as follows:-

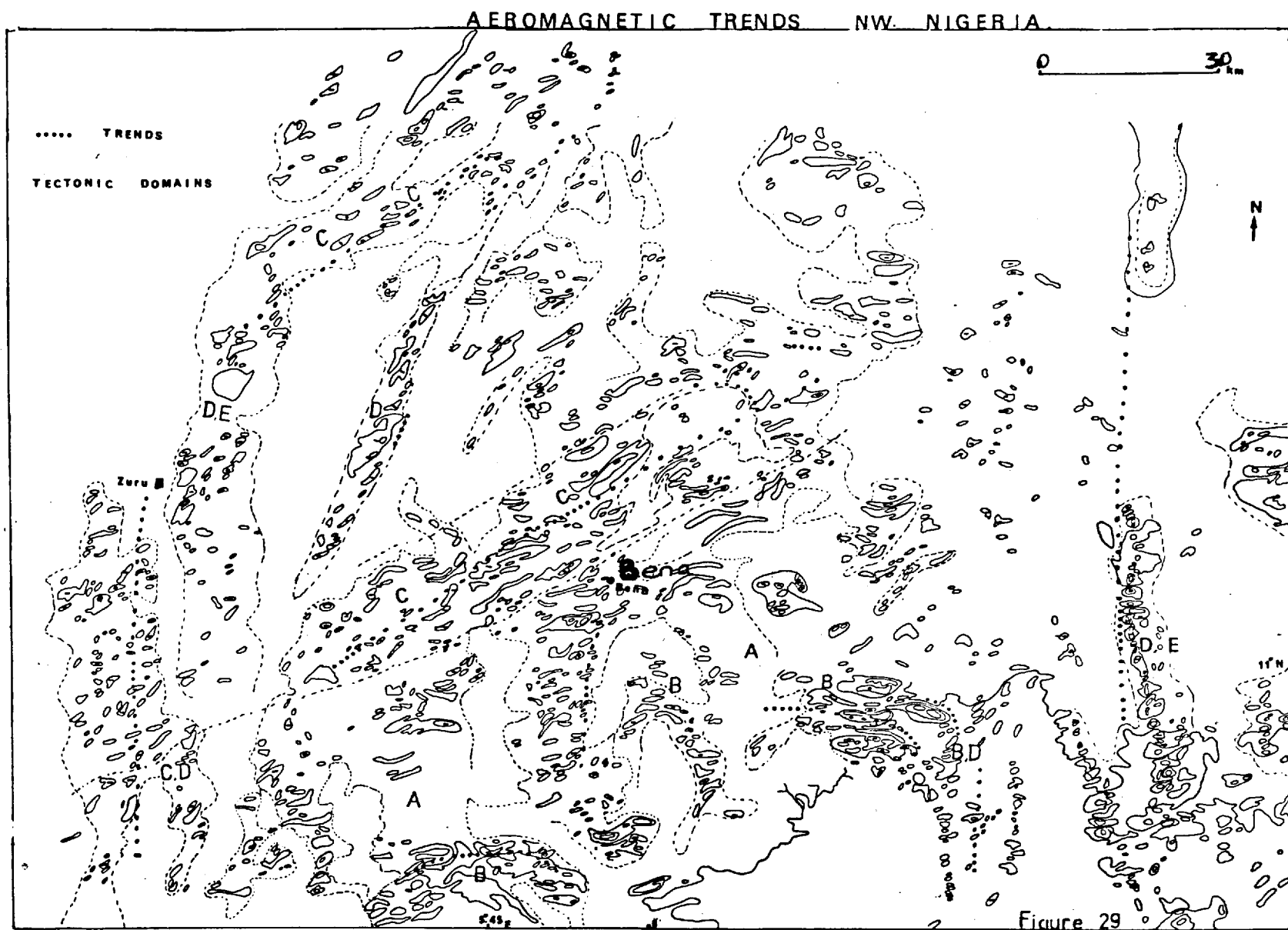
1. The 'D' domain is associated with very tight isoclinal N-S folds. Trough marginal stocks like those of Minna (Plate 2) wrap the 'D' domain metasediments round them. Plate 2 illustrates the wrapping of 'D' domain relic

beds around trough marginal stocks. Plate 11 is an old R.A.F. photograph of quartzites belonging to 'D' domain in the same area as in Plate 2.

The 'E' domain is more restricted in occurrence than the 'D' domain and also occurs within the meta-sedimentary troughs. The folds associated with the 'D' domain are less tightly folded. The fold style associated with the 'D' domain occur east of Birnin Gwari and in the vicinity of Zuru in North-western Nigeria.

7.1. AEROMAGNETIC TRENDS OF NW-NIGERIAN DOMAINS

Figure 29 shows the regional aeromagnetic map of NW-Nigerian metasedimentary belt. The magnetic anomalies over the Nigerian lineaments tend to be poorly defined although the N-S lineaments tend to be represented by a N-S alignment of negative magnetic anomalies in some places. It appears that if a basement failure does not bring rocks of contrasting magnetic properties into juxtaposition, it may not be detected easily on an aeromagnetic map. Where formations having different magnetic properties and trends occur, they are well defined. In figure 29, for example, the 'C' domain has a distinct NE trend while the 'B' domain is represented by arcuate magnetic trends. 'D' trends are aligned N-S. The differences in the magnetic trends



are probably a reflection of the differences in the magnetic properties of the relic quartzites belonging to these different groups of metasediments.

7.2. STRUCTURAL CORRELATION GUIDES FROM LANDSAT DATA OF NIGERIA

Over a Precambrian terrain like the Nigerian basement, it is often difficult to find diagnostic criteria for relating the tectonics of distant parts. LANDSAT studies of Central Nigeria has indicated that because of the small scales of these images and consequently their large areal coverages, that major regional features can be identified to the exclusion of more localised tectonic disturbances. The following tectonic styles have been found consistent over many parts of the Nigerian basement:

(a) The Large flat-lying refolded folds

The Nigerian metasedimentary areas show a number of large folds generally over 50 kilometers long that have the following characteristics:-

- (1) They may not be evident on the ground in some places because the ridges defining them are low and often wide.
- (2) They tend to form large antiformal structures defined by granulitic quartzites and the gneissic basements appears to have participated in this folding.

- (3) They are all luniform in shape.
- (4) They are all refolded along a N-S axis, and may show evidence of more than two episodes of folding.
- (5) The large folds occur both within and outside the metasedimentary troughs.
- (6) The dips along their flanks tend to flatten out as the axis is approached and the plunges of some minor folds associated with them rarely reach 8° from the horizontal.
- (7) Some amphibolites may be concordantly folded with the quartzites defining the luniform folds.
- (8) Axial plane granite gneiss is commonly a feature of the large folds.
- (9) The wavelength between two such antichines are generally small compared to their sizes.

Only one such structure has previously been recognised at Ibadan by Grant (1970). LANDSAT images of Nigeria show that this fold style occurs practically everywhere and that it is a distinctive deformation style of the Nigerian basement. The concordant granite gneiss known to have an intrusive relationship with the flat-lying structure at Ibadan yielded an Rb/Sr isochron age of 2205 ± 70 m.y. (Burke et al. 1976). This suggests that the metasediments defining the flat-lying structures are probably Archaean in age.

(b) Linear features

Closely associated with the flat-lying structures are peculiar linear features visible on some LANDSAT images (f, Plate 7). The geometrical shape of the linear features resemble the refolded structures even when no associated metasediments are in evidence. In Plate 7, for example, the foliation feature, f, occurring in banded gneisses define an arcuate geometry.

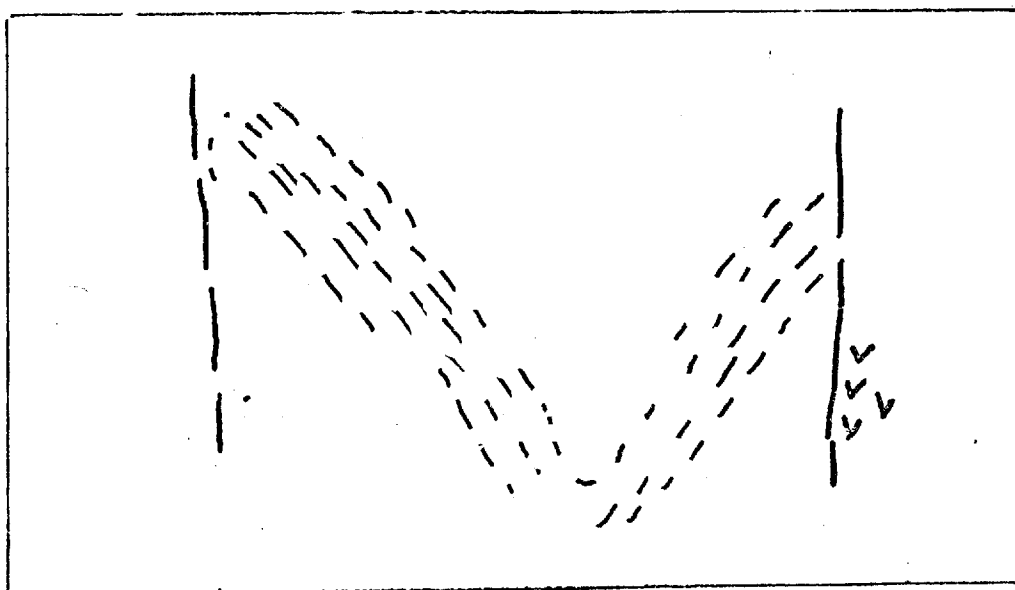


Figure 30. A sketch illustrating the geometry of foliation trends in banded gneiss along a possibly eroded metasedimentary trough, as interpreted from Plate 7.

It is close to a prominent N-S lineament which appears to parallel the axis of the U-shaped trend. Such foliation features in banded gneiss appear to be common where metasediments have been stripped off by erosion. The foliation trends appear to be a pointer to where a narrow metasedimentary trough previously existed, and may be suggestive of previously lower crustal levels, now exposed.

(c) The N-S tight folds

Discrete N-S metasedimentary troughs are a feature of the Nigerian basement. These troughs contain N-S tightly folded isoclinal folds. The flat-lying structures are always refolded along these troughs. The troughs and the N-S folds, based on deformation styles appear to post-date the arcuate folds. This characteristic is a distinct tectonic feature of the Nigerian Basement Complex.

7.3. REGIONAL DEFORMATION SEQUENCE OF CENTRAL NIGERIA AS SEEN ON LANDSAT IMAGES

Based on the patterns of features and their relationships as seen on LANDSAT images, it appears that the gneissic basement represents the oldest rocks in Central Nigeria. The sequence of events as interpreted from these images are as follows:-

1. The sialic basement is now represented by banded gneisses or the gneissic basement. Its age may be in excess of 3,000 m.y.
2. The deposition and development of flat-lying folds and volcano-sedimentary succession on the sialic crust. This deposition may locally be contemporaneous with the formation of the sialic crust (> 2500 m.y.).
3. The development of the N-S fractures.

4. The formation of some concentric fractures and further deformations of earlier folds.
5. The formation of linear N-S sedimentary troughs controlled by N-S fractures, possibly about 1800 m.y. initial sedimentations and subsequent folding (perhaps about 1000 m.y.).
6. Possibly renewed subsidences and a later episode of folding within the troughs culminating in the Pan African 600 m.y. orogenic event.

It is not clear whether some circular fractures formed before the N-S fractures and lineaments. This aspect remains obscure principally as a result of the tendency of older fractures to be reactivated by later events, and the tendency for some fractures to be inactive over a long geological interval.

CHAPTER EIGHT

BROADER PERSPECTIVES

In Chapter Six, the different lineament types occurring in Nigeria were discussed. In a study like this, it becomes very tempting to compare the tectonic features of other areas with the new data derived from LANDSAT, especially if currenent geological opinion holds that two such areas are related. LANDSAT images of the North African Hoggar Mountains, S.W. Africa and parts of South America were also examined for tectonic similarities.

8.1. PRINCIPAL STRESS DIRECTIONS IN PRECAMBRIAN NIGERIAN BASEMENT

Fold axes are oriented at right angles to the principal compressive stress responsible for their formation but folds in Precambrian terrains are not always well preserved and very often criteria for differentiating structures belonging to different structural levels are lacking. Regional lineament and fracture studies and their symmetrical arrangements are useful in suggesting where multiphase deformation has occurred.

Figure 26b shows a statistical plot of the directional lineament frequency of the total lineament field of Central Nigeria (figure 26a). Two directions of principal stresses are indicated from the symmetrical

arrangements of the rosettes:-

(a) The E-W stress direction

The existence of conjugate fractures in NW Nigeria (figure 25a) suggests that an E-W stress system has operated. The other corroborative evidence include tightly folded N-S oriented, isoclinal folds. The isoclinal structures occur mostly within the metasedimentary troughs. Along trough margins elongate intrusions having their longer axes oriented towards the North also support an E-W stress system. The E-W stress system appear to be a later event than the N-S stress system.

(b) The north-south principal stress system

The frequency rosettes (figure 26b) suggests that a strong N-S compressive stress may have operated within the Nigerian basement. E- W trending flat-lying folds appear to support this contention.

8.1.1. Evidence for a revived E-W principal stress system

The two regional fold styles discussed earlier occur widely within the Nigerian low-grade troughs. The image tones belonging to the two styles show marked contrasts. The first style of folding within the troughs tend to be tightly appressed, while the second style tends to be more open (Plate 2). The axes of the two fold styles trend N-S. Image evidence suggests that they

may have resulted from two different sedimentary and tectonic cycles. The second cycle probably increased the tightness of the earlier trough folds. This suggests that the E-W compression responsible for the foldings may have been revived at two different geological periods. Two dominant radiometric age magnitudes obtained with the low grade sedimentary areas seem to support this observation. The age groups fall into 1000 ± 200 m.y. and 600 ± 150 m.y. (Grant, 1972).

8.2. SIMILARITIES BETWEEN THE DEFORMATION PATTERNS OF NIGERIA AND THOSE OF THE AHAGGAR (HOGGAR), S.W. ALGERIA

Very little work has been done on African basement areas in general. This situation makes it difficult to attempt a comparison between basement rocks of two distant locations. Some considerable work has been done by French geologists in the Ahaggar (Choubert and Faure-Muret (1971), Bertrand and Lasserre (1976), Black and Girod, (1970). From these studies a lot of structural and radiometric data on the Ahaggar is available. A few radiometric data on Nigeria are available but there has been no regional structural data previously. The results of the present study enables some close similarities to be drawn, between the two areas. Owing to inadequate structural data on the Nigerian basement, some Nigerian geologists believe that although there are marked correspondences in the

geochronological data and some degree of lithological similarities between the two places, these similarities are not accompanied by structural similarities (Grant, 1977 in press).

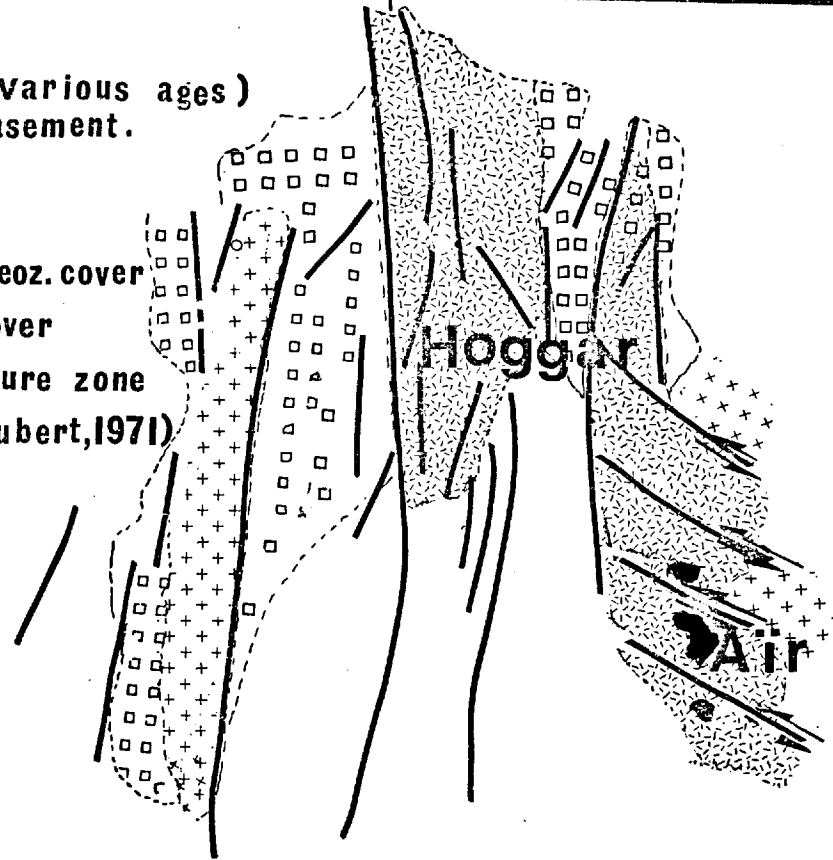
The present study evaluates the similarities between the two places in the light of the new satellite imagery data and the evidence suggests that the two places had re-acted as a unit to tectonic deformation during the Proterozoic. Figure 31 illustrates the major geological features of the Ahaggar and the relative locations of the Hoggar and Nigeria while figure 32 is a LANDSAT image interpretation of the structures of the Air mountains which lie within the vicinity of the Hoggar. Table 4, summarizes the previous geological data on the two places and includes data from the present study.

There are therefore very many geological and geochronological correspondences between Nigeria and the Hoggar, to justify the conclusion that the two areas have behaved as a coherent landmass though most of the Precambrian times. The differences in the volumes of low grade metasediments between the two places may be attributed to the evidence that Nigeria and the Cameroons represented an emerged landmass during the Palaeozoic and early Mesozoic times (Black and Girod 1970), a situation which led to the erosion of a good proportion of the soft low-grade trough rocks.

A Generalised Geological Map Of Nigeria-Hoggar Areas

- 1, Cratons
 - 2, Metasediment (Various ages)
 - 3, Reactivated basement.
 - 4, Ring dykes
 - 5, Fault zones
 - 6, Precamb.-L. Palaeoz. cover
 - 7, Phanerozoic cover
 - 8, Akwapian fracture zone
- (based on Choubert, 1971)

20°N



1
2
3
4
5
6
7
8

Phanerozoic cover

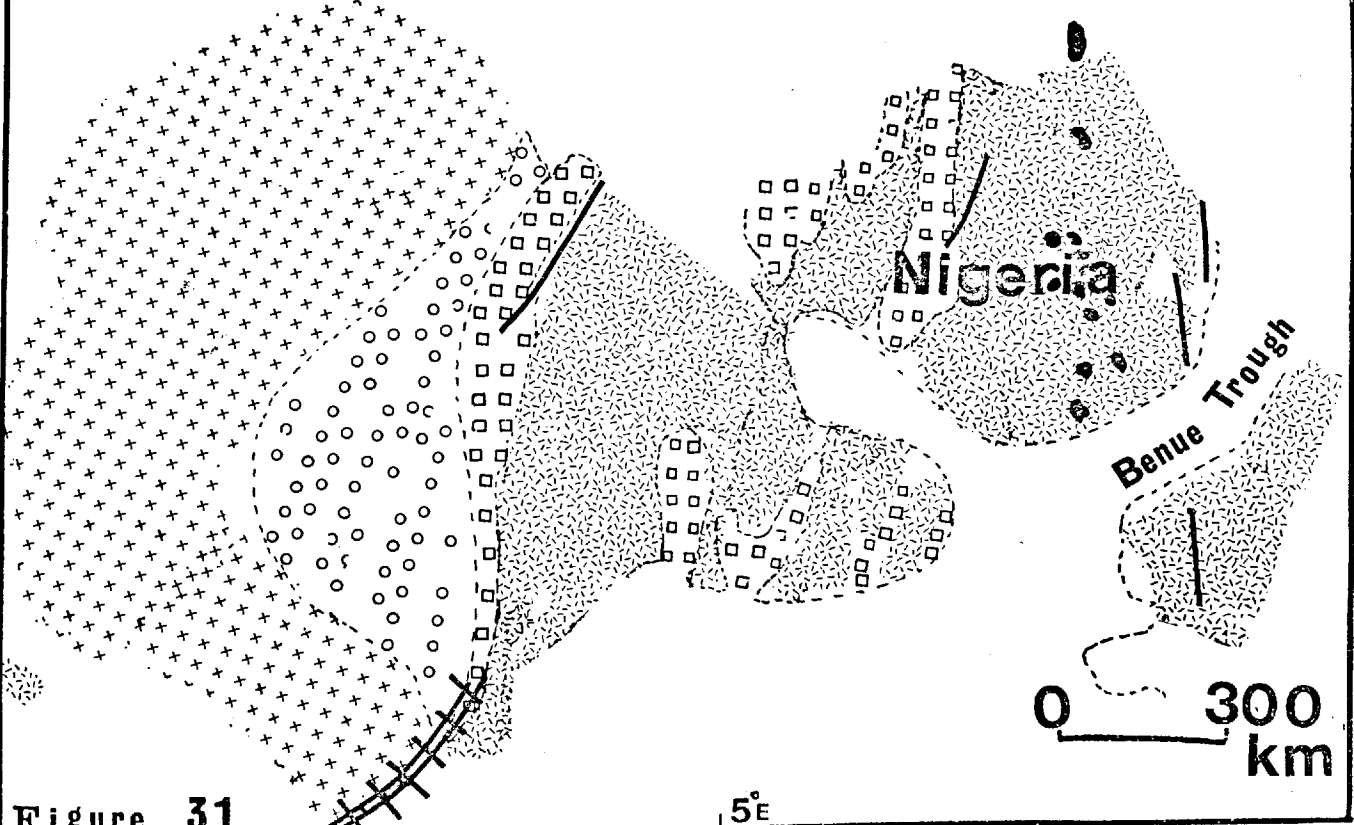
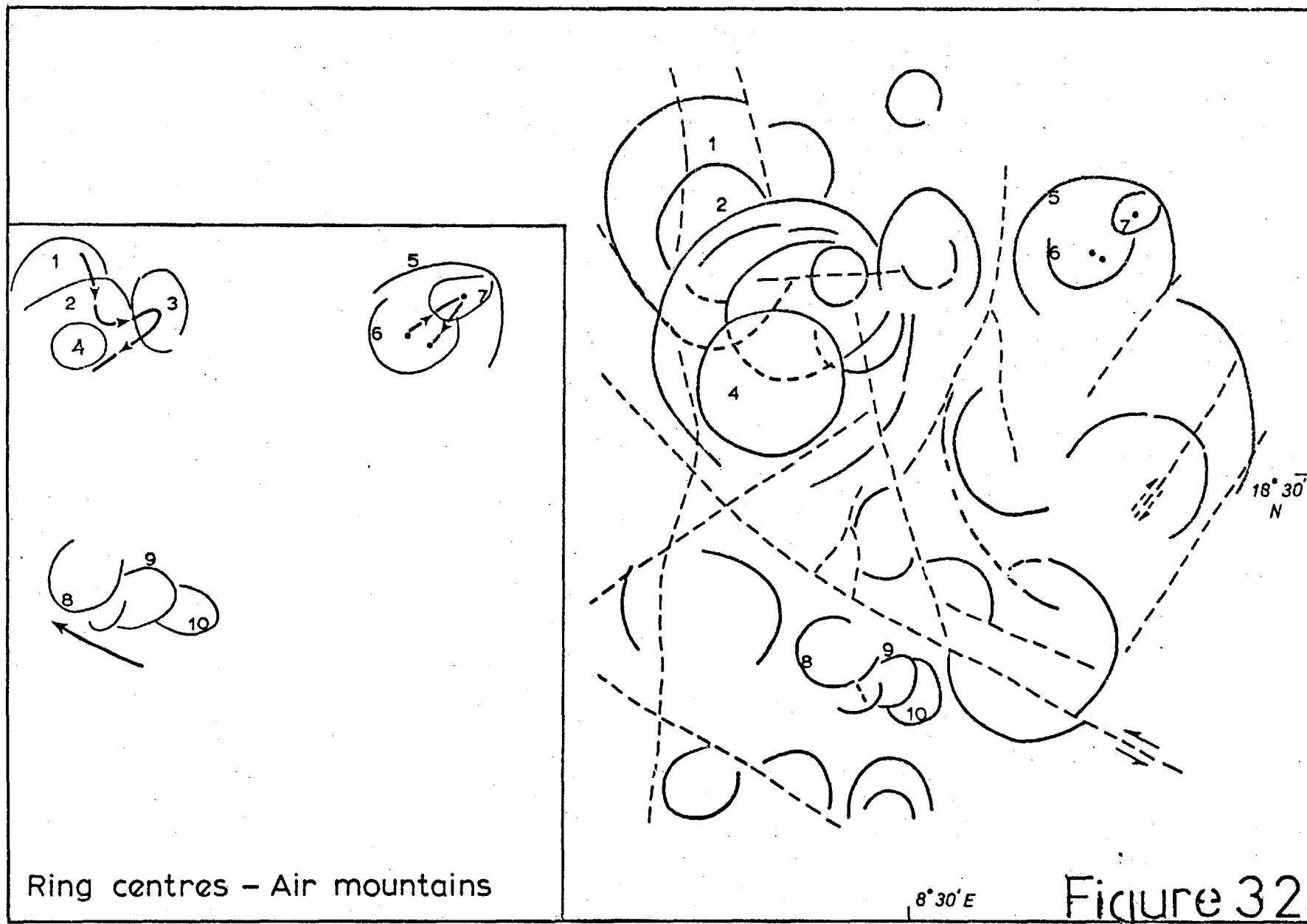


Figure 31

5°E

TABLE 4. SIMILARITIES BETWEEN GEOLOGICAL DATA OF NIGERIAN
BASEMENT AND THOSE OF THE AHAGGAR

Geological Information	The Hoggar	Nigeria
A. Radiometric ages		
1. 600 ± 100 m.y.	Recognised (Bertrand and Lasserre 1976)	Recognised (Grant 1970, Jacobson et al. 1964)
2. 1100 ± 100 m.y.	Recognised as the Egere-Alekkod domain (Bertrand 1976)	Suggested, based on Rb/Sr data (Grant 1972)
3. 1800 ± 200 m.y.	Well known (Choubert and Maure Muret 1971)	Established (Grant 1970, 1972, Hurley, 1966)
4. 2750 ± 300 m.y.	Known as the Ouzallian (Bertrand et al. 1976)	Recognised (Oversby 1975, Ogezi, personal communication)
B. Narrow N-S meta-sedimentary troughs	Known	Known
(1) Tightly appressed folds	Known (Bertrand 1976)	Known (McCurry 1973)
(2) More open folds	Known "	Recognised in the present study.
(3) Angular unconformity within this trough	Known to be tectonic in most places	Recognised in the present study to be tectonic.
C. Major N-S fracture zones	Well known (Choubert et al. 1971)	Clearly visible on Nigerian LANDSAT images (Chukwu-Ike and Norman 1977)
D. Elongate intrusions along major fracture zones	Recognised (Bertrand and Lasserre 1976)	Recognised (Chukwu-Ike and Norman 1977)
1. Late trough marginal stocks along troughs	Known (Bertrand et al. 1976, Boissons et al. 1969)	Clearly visible on Nigerian images (around Minna Pl. 2)
2. Metasedimentary troughs wrapped around stocks.	Recognised (Boissons et al. 1969)	Plate 2 in the present study (r, near Minna) shows this.
E. Major NW-trending sinistral wrenches	Known (Black and Girod, 1970). Links the Hoggar with Air	Identified in the present study (Plate 2), connecting Jos Plateau and NW Nigeria.
F. Major dexteral wrenches	Recognised (Black and Girod 1970)	Recognised (Trusswell and Cope 1963, McCurry 1973)
G. Strong Precambrian E-W horizontal compressive stress	Known (Black and Girod 1970)	Recognised in the present study.
H. Low grade meta-sediments.	Known	Known
I. Ring intrusions	Well known	Well known.



Ring dykes and circular features of the
air mountains, N. Africa

8.3. SOME SIMILARITIES BETWEEN LINEAMENT PATTERNS
OF NIGERIA AND THOSE OF S. AMERICA

The two prominent lineament sets recognised in Nigeria are the regularly spaced straight N-S and concentric lineaments. The shapes of W. Africa and South America have been used to prove that continental drift and sea-floor spreading has taken place. It therefore became tempting to look at the satellite imagery coverage of some parts of Brazil to see whether the same lineament patterns could be discerned. LANDSAT imagery interpretation of parts of Brazil indicated that a prominent set trends at about $N.60^{\circ}E$. This set was found to be comparable in many ways with the Nigerian N-S lineaments. The possibility that S. America rotated about 52° relative to Africa was suggested (Norman and Chukwu-Ike 1977).

Circular structures, very similar to those of West Africa are equally well expressed in the Brazilian shield. Kloosterman (1975) reported that three "ring volcanoes" with diameters of hundreds of kilometers have been active in the Guiana shield during the early Proterozoic, with their central calderas filled with sediments. The circular structures of Brazil, like its coastline, appear to be continuations of the West African circular features.

8.4. THE ASTRONS

In the discussion of the characteristics of the circular and concentric lineaments in Chapter Six, it was stated that next to the circular depressions, are usually a disc of old rocks. Such discs have usually been plastically welded, and are generally surrounded by circumferential fracture zones. The term 'astron' is an elision of the geological terms astrobleme and craton coined to signify a central depression filled with sediments, and also associated structures believed to have resulted from meteoritic impacts (Norman, Price and Chukwu-Ike, 1977).

8.4.1. Other possible causes of concentric features

Although the characteristics and experimental data favour the impact origin of the concentric lineaments and fracture, some other possible causes are worth noting:-

- (a) Some geologists believe that the formation of circular and concentric lineaments may be related to large scale magma movements within the crust and other endogenic processes. The cross-cutting relation of concentric lineaments in Nigeria and the variations in sizes of the central depressions is difficult to justify by any systematic mantle movements such as convection currents.
- (b) Some followers of the theory that the earth is

continuously expanding believe that circular features are caused by chemical transformations within the core. The chemical differentiations within the core result in the addition of new materials and layers to the crust from the mantle. Major earth structures like those of the Aleutian arc, Pacific Ocean fracture zones and the frontal arc of the Himalayan Mountains have been attributed to the differentiation and transformation of the earth's core, adding layers to its exterior (Mouritsen 1975).

The chief flaw in this hypothesis is that the oldest crustal rocks would be at the surface. This is incompatible with the field geological relation of rocks and with accepted stratigraphical principles.

- (c) Some geologists relate curved features on earth to the earth's rotation and spinning. The patterns and relationships between the concentric features do not appear to support this idea, because there does not appear to be any uniform variations in the diameters of the circular and concentric fractures.
- (d) The Precambrian plate tectonic model suggests that small convection cells were characteristic

of the Archaean (Fyfe 1974) and that probably these smaller cells gave rise to the circular features on earth. It is pertinent to note that some circular features have diameters in excess of 1000 kilometers and there does not appear to be any regularity in their diameters.

It appears that large circular features on earth may have resulted from similar processes that gave rise to those of the Moon, Mars and other planets. Since the gravity field of the earth is about 6 times that of the moon, the earth must have received a greater proportion of meteoritic impacts. These impacts would produce deep fracture. It is possible that igneous activity and earth tides would tend to reactivate these impact features from time to time. Figure 33 illustrates the locations of some suggested 'astron' structures in Africa, based partly on satellite imagery lineament patterns and on the geomorphology and alignments of sedimentary and metasedimentary basins.

8.4.2. Geological implications of the impact concept

It has been suggested elsewhere that arcuate, coastlines, inland circular basins and narrow extra cratonic grabens may be reflections of major impact features (Norman, Price and Chukwu-Ike, 1977). This conclusion is based on satellite imagery observation and

the similarities of these structures with Jones' experiments. Studies of fracture zones in West Africa (Blundell 1976, Wright, 1976) indicate that some continental fracture zones are related to oceanic transform faults. Blundell (1976) also suggested that the Akwapian fault separating the slightly deformed cratonic rocks of West Africa from the Palaeozoic sediments in Ghana is currently active and has been so over a long geological period. He suggested that the fault zone represents an incipient plate margin. The West African fracture zones are related and appear concentric with a centre in the Toudeni basin. It appears that the concentric fractures have the following characteristics, based on the West African and Brazilian examples:-

1. They appear to be potential plate boundaries.
2. They are sites of igneous activity over long geological periods.
3. They may probably be mantle-tapping fractures.

It is tempting to suggest that the concentric lineaments were lines along which crustal plates formed, prior to spreading. If so, the shapes of some coastlines would reflect the geometry of these fractures. In the Precambrian times however, the circular fractures appear to have been dominated by vertical movements, narrow sedimentation along the peripheral graben and in-situ deformation. Renewed igneous activities along the graben may have led to stress revivals.

8.4.3. Thermo-tectonic events, and in-situ deformations

The 600 ± 100 m.y. orogeny in Nigeria is dominantly a thermal event. A characteristic feature of impact structures is that the brittle deformations occurs some distance away from the point of impact. This distance depends on the nature and momentum of the impacting body. For a large meteorite (300 km in diameter), the shock wave generated on impact will deform rocks plastically outward from the point of impact. At a certain distance, after a considerable energy dissipation, these waves will start to produce brittle deformation.

The Pan African thermo-tectonic event (600 ± 100 m.y.) is properly represented in West Africa just east of the Akwapian fracture zone in Ghana. This radiometric age magnitude is unknown west of this fracture zone. Burke and Dewey (1970) consider that this fracture zone is a crustal suture between the so-called reactivated areas to the east and the unaffected areas to the west, (Figure 31). It is pertinent to note that the same fracture zone is considered to be an incipient plate margin (Blundell 1976). It seems to the writer that the Akwapian fracture zone is a fundamental curved fracture zone and marks the line along which the shock waves consequent on a major West African impact changed from plastic deformation to brittle deformation.

The West African basement appears to have been

one unit and the Pan African domain marks the areas of influence of the outer concentric fracture zones associated with a huge (> 1300 kilometers diameter) West African impact (Norman et al. 1977). Similarities in radiometric age magnitudes, support this view. Precambrian polar wandering curves (Piper 1974) of Precambrian Africa do not appear to support the existence of Proterozoic plates. In-situ deformation seems to have been the dominant Precambrian deformation pattern in Africa. The so-called mobile belts appear to be related to peripheral troughs or intersections of peripheral graben related to large Precambrian concentric fracture systems and graben. Radiometric age determinations of rocks in all the so-called mobile belts in West Africa and many other parts of Africa yield the same radiometric age magnitudes as the so-called older cratons (Coward and James, 1974).

8.4.4. Dating the impacts

Sedimentary and metasedimentary rocks within the central basins suggested as having resulted from impacts indicate that they all predated the Kibaran sedimentation (1500 m.y.). The duration of a sedimentary deposition could extend between 500 and 1000 m.y. or more. The time of development of the hydrosphere in the Precambrian and erosion as we know it today is not properly understood. It is possible, as in the case of the Akwapian

A map suggesting some African Astrons

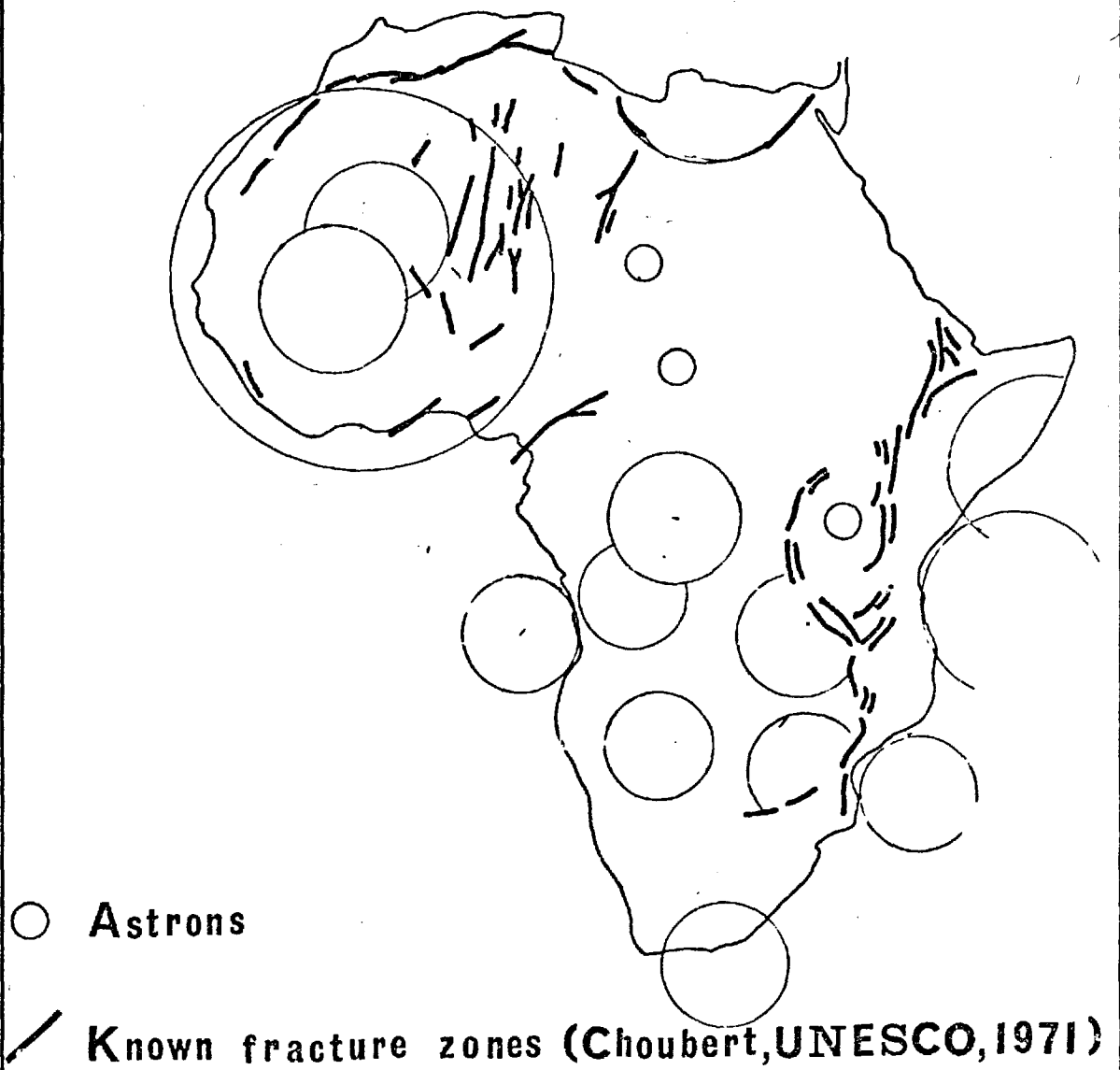


Figure 33

fault zone that the concentric fractures and lineaments may have existed for hundreds of millions of years before the development of the sedimentary basins. Most importantly, it appears that impact structures may have occurred at different geological times possibly more frequent in some periods than in others.

8.5. THE RELATIONSHIP BETWEEN LANDSAT LINEAMENTS AND MINERAL DEPOSITS

Controls of mineralisation vary considerably but geologists generally agree that the following factors are possible guides for mineral exploration:-

1. Favourable lithologic units or formations.
2. Pre-existing geochemical culminations within the earth's upper mantle.
3. Particular geological periods.
4. Certain erosion levels.
5. Nearness to igneous intrusions.
6. Nearness to major and minor geological structures such as faults and fractures.
7. Some stages in the tectonic cycle of a region.

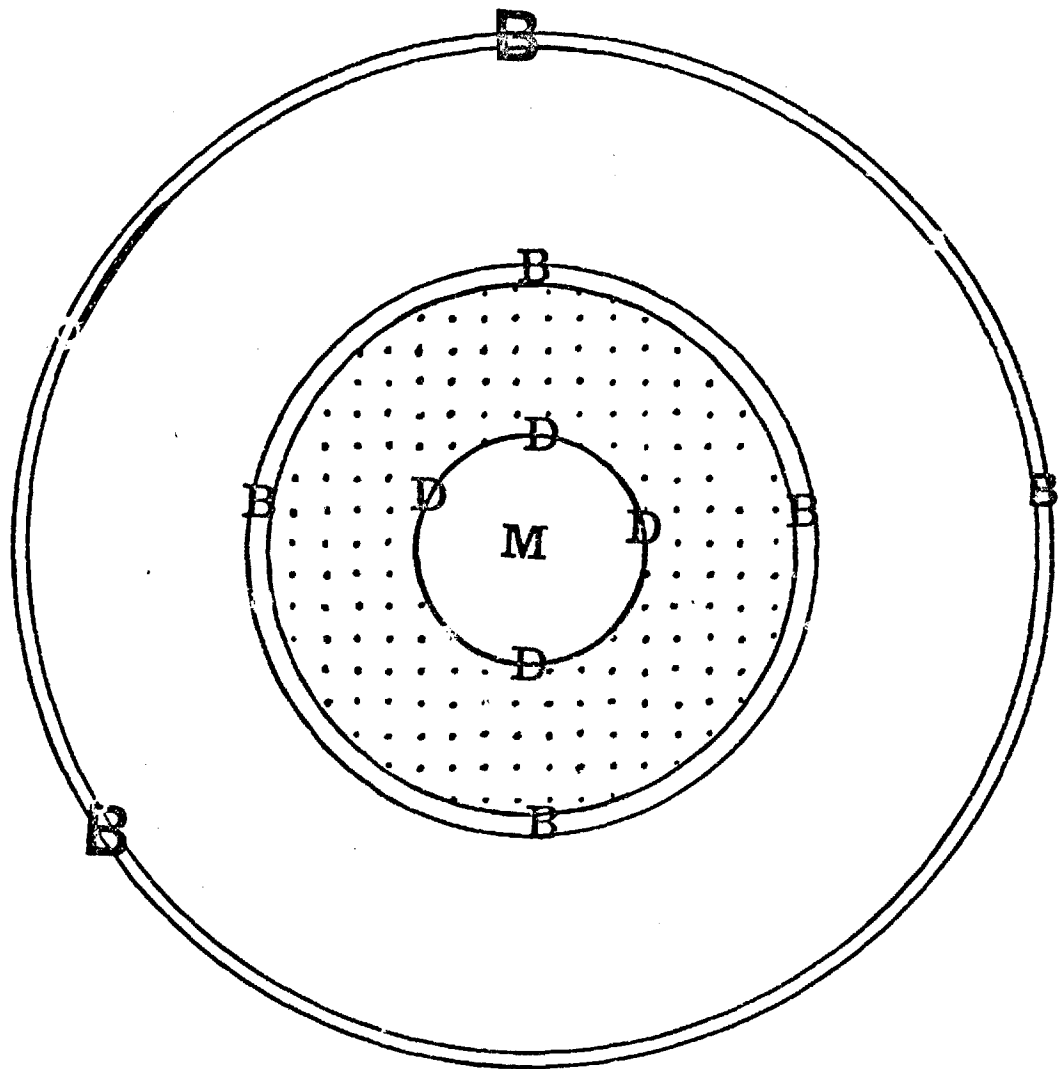
Experience from LANDSAT studies of Nigeria indicates that provided the feature of interest is within the resolution capabilities of the satellite sensors, favourable lithologic units (quartzites for example) can be discriminated. Relative erosion levels have also been interpreted from images of Central Nigeria. Exposed and

concealed intrusive centres on images of Central Nigeria as well as the relationships of such intrusions to fracture zones and lineaments are often clearly resolved. The control of tin and other Nigerian base metal mineralisations by N-S lineaments have been suggested (Chukwu-Ike and Norman 1977).

Many major lineaments have been located in Nigeria and these may prove useful in mineral exploration programmes. Large sialic plutons have also been located marginal to the low grade metasediments and connected to one another by N-S lineaments. Recent exploration in Canada shows that large batholiths adjacent to greenstone belts are favourable for porphyry copper and molybdenum mineralisation. Gold mineralisation has also been reported within the Canadian greenstone belts near their contacts with marginal batholiths. During this study LANDSAT images have indicated that major lineaments border the Nigerian low grade rocks and they may be useful in future mineral exploration within the Nigerian metasedimentary belts. Many hitherto unknown narrow metasedimentary troughs have been observed on the images.

Circular and concentric lineaments are no less useful as guides for mineralisation. Studies of mineral associations with concentric fracture of possible meteoritic impact origin suggest the following patterns:-

A diagram illustrating the pattern of economic mineralisation associated with some African Astrons
(Not to scale)



M, Central basin

D, Diamond bearing ultrabasics and diatremes.

B, Base metals, Cu, Pb, Zn, Co; & Sn, W, Be, and U.



Plastically welded rocks.



Basement

Figure 34

1. Kimberlite pipes, diatremes and diamonds are associated with the smaller radii circular fractures, marginal to the central depression. It appears that impacting bodies often penetrate deep into the crust and perhaps down to the mantle, thus enabling mantle rocks to rise up diapirically in that vicinity (Price personal communication).
2. Base metals are associated with fractures formed away from the impact point, especially where the impact waves change from plastic to brittle deformation. The more important minerals are lead, zinc, copper, uranium and tin.

Figure 34 illustrates a diagrammatic sketch of the general association of minerals with circular LANDSAT features believed to have formed from meteoritic impacts. The diagram (figure 34) is based on the pattern and arrangement of minerals along the circular fractures of Plate 16a as well as the pattern along the Benue trough and other West African concentric lineaments. It appears that only astrons structures of diameters in excess of 200 kilometers tend to be associated with significant mineralisation.

Lineament intersection points have also been

associated with mineralisations. The plot of lineament intersections of NW Nigeria shows some relationship with known mineralisation. The gold deposits of NW Nigeria are largely alluvial. The main producing areas lie around major lineament intersections and around stocks associated with lineaments. Lineaments and major fracture traces intersection points need closer geochemical studies.

8.6. DISADVANTAGES AND ADVANTAGES OF THE USE OF LANDSAT IMAGES FOR REGIONAL GEOLOGICAL STUDIES

The main reasons advanced by NASA for embarking on the LANDSAT programme are to test the following geological hypotheses (Goetz et al. 1975):-

- (a) "That the multi-spectral images, properly recorded would prove useful in the mapping and remote recognition of rock types, geochemical anomalies and alteration zones.
- (b) That some geological features may be visible depending on the angle of illumination.
- (c) That large geological structures on the surface of the earth, by virtue of their sizes and subtle expression have gone unrecognised.
- (d) That dynamic processes like erosion, deposition and flooding could be better understood."

The criticism of the use of LANDSAT images ought

to take cognizance of what the entire programme was initially intended for. Generally speaking the first motive outlined above has not been satisfactorily met while the last three have generally been considered satisfactory. The geological information content of some cloud-free LANDSAT frames is considerable but for general geological purposes the use of LANDSAT images have been found useful in the following:-

(a) Geomorphology

Many geomorphic features, whose tectonic significance may not have been obvious can be recognised on LANDSAT images. The 200 kilometer long scarp in N. Nigeria, Plate 5, is one such example. Erosional and depositional features have been studied by many workers using satellite images.

(b) Structural geology

LANDSAT images, in the hands of a competent interpreter, can provide unique structural and tectonic information. The regular N-S lineaments and the concentric lineaments that are likely to be global features, are good examples of new data from orbital images of Nigeris. Faults, fractures and foliations are often clearly indicated.

(c) Lithology

Lithological identification from images is

extremely difficult and nearly impossible. Spatial variations in lithology, however, can be recognised from tonal contrasts on images.

(d) Stratigraphy

Major structural elements that can be useful in the correct stratigraphic placing of unrelated rocks may be indicated on images. In NW Nigeria, a group of unrelated rocks have been lumped together in the field. LANDSAT images suggested that there is a strong distinction between the two groups and that the unconformity separating them is strongly tectonic.

(e) Superficial geology

Sand dunes, moving and fixed, and areas of alluvium may be observed on images. LANDSAT images are also useful for planning field work, mineral exploration and high ways.

8.6.1. Limitations of LANDSAT images

Uncertainty often attends the interpretation of LANDSAT images. Where there are no adequate interpretation controls a lot of time may be required in actually relating and recognising image features e.g. some meta-sedimentary ridges of quartzite can easily be mistaken for dykes.

(a) Geographical factors

Cloud cover and atmospheric transmission problems

limit the use of LANDSAT images in very low latitudes. The same rock type can show up as positive topographic features in some climatic regions and as negative features in another (Lloyd-Lawrence, 1977). Climatic influences on imaged features needs to be evaluated.

(b) Lithological identification

It is nearly impossible to name a rock from satellite images.

(c) Sun angle effects

The actinic brightness of an object varies with its position relative to the sun. The sun's apparent N-S movement reduces the brightness of features during winter months. It is therefore possible that the sun's elevation affects the manifestation of some features. This effect varies with latitudes.

(d) Scale

Only features over one kilometer in extent can show up on LANDSAT images. It is not useful for detailed work on any area.

(e) Stereo studies

LANDSAT image studies within lower latitudes cannot be satisfactorily studied stereoscopically because of very small overlaps of images of successive swaths.

(f) Mineral locations

Some LANDSAT users claim that minerals can be

discovered from LANDSAT images alone. This does not appear to be very true. Geological structures which may be associated with ores can be detected on images, but mineral deposits can hardly be discovered from LANDSAT images alone. LANDSAT image studies seem best used in conjunction with other conventional mineral exploration techniques.

8.7. SUGGESTIONS FOR FUTURE GEOLOGICAL WORK ON NIGERIA

The present LANDSAT studies of Central Nigeria has directed attention to many new tectonic features of the area. The most extensive data is on lineaments. Quasi-geological maps of many image frames have also been drawn. It is necessary that details be added to the quasi-geological maps.

The lineament intersection patterns may also be useful in mineral exploration. Geochemical analyses of areas of high lineament intersection frequency is advisable. Marginal fracture zones to low-grade metasediments and the Benue trough require careful geochemical examinations.

Gravity data relate well with the Nigerian lineaments. Unusual lineament shapes such as those of plate 6 need corroborative geophysical evidence. Detailed photo-geological studies of the country may be a good idea at this stage.

8.8. CONCLUSIONS

LANDSAT imagery studies of Nigeria has indicated that orbital images handled by an experienced interpreter with a reasonably good geological background can yield unique geological data. In the present study, the following information about the Nigerian Basement Complex have been suggested entirely from satellite images:

(a) Crustal evolution and some processes

LANDSAT studies of Central Nigeria indicated a widespread occurrence of extensive luniform folds. Field evidence on one such a fold (Burke et al. 1976) suggest that the folds were previously flat-lying. The gneissic basement was also involved in the horizontal folding. This style of folding has been recognised in the better studied fundamental basements of Greenland, S. Africa and Canada. This nappe-like folding episode or "horizontal tectonic regime" in Greenland is considered to date back to a 3,000 m.y. orogenic cycle. It is not clear how these flat-lying folds formed. It is now evident, however, that these flat-lying structures represent a distinct tectonic style of the Nigerian basement. Some geologists believe that the horizontal deformation style is very old and may have led to a considerable thickening of the sialic crust (Bridgewater et al., 1974).

(b) Origins of cratons and mobile belts

It is a current geological thinking that in the Proterozoic times that the earth's crust formed a mosaic of shields and mobile belts. The mobile belts enclosed the more stable massifs and that both the mobile belts and stable massifs moved as coherent entities (Sutton and Watson, 1974). LANDSAT studies of Nigeria and a few other parts of Africa suggest that the "mobile belts" and stable massifs were one landmass and that the stable massifs tend to represent strain-hardened, recrystallised rocks near circular basins while the mobile belts tend to represent sediments and metasediments probably of graben originating from meteoritic impacts. In-situ deformation appears to be more probable within Nigeria and possibly other African basements.

(c) Igneous activity within the Nigerian fractured craton

Studies of the shapes and spatial distributions of some charnockitic granulites, the "older granites" and the "younger granites" from LANDSAT images suggest that they have been controlled by the same major tectonic features. Most of the igneous activity in Nigeria is associated with the N-S lineaments. These lineaments have been active over many geological periods. The N-S lineaments extend to the Ahaggar where similar arrangements of intrusions with respect to the lineaments are also in evidence. Igneous activity in Precambrian cratons

therefore tend to follow established lines of weakness. Regional metamorphic grades appear to be related to these fundamental lines of failure, straight or concentric.

(d) Fault controlled ensialic basins in Nigerian Precambrian

Both the N-S regular fracture zones and the concentric lineaments in Nigeria appear to have been associated with strong vertical movements. Intercratonic basins therefore developed along them at various geological periods. It appears that the basins developed on well formed hardened crusts quite different from the modern oceanic crusts. The Nigerian metasedimentary troughs as suggested by LANDSAT images are ensialic and fracture controlled.

(e) Mineralisation in a fractured craton

The fundamental fractures which control igneous activity and basin formation probably acted as conduits of hot magma and as channels for the circulation and interaction of magmatic and meteoric waters. Minerals in Nigeria appear to be closely related to major disjunctive zones within the cratons. The identification of such cratonic lineaments on LANDSAT images will reduce exploration costs.

(f) A possible cause of the Nigerian thermo-tectonic basement reactivation

The discovery of concentric lineaments, their

characteristics and their similarities with structures obtained from experiments suggest a possible cause of basement reactivation. It is very likely that the earth did not undergo a different evolutionary history from the moon and other planets. It appears likely that the concentric features represent scars of ancient meteoritic impacts. Shock waves resulting from impacts of meteorites some 150-300 kilometers in diameter sweep out after impact in all directions. At a critical distance from the point of impact, the shock waves change from plastic deformation to brittle with a release of energy. Basement reactivation, especially the thermal reactivations may have resulted from large impacts. The Pan African thermo-tectonic event may have been caused by such phenomenon. Impact structures later become axes of intense igneous activity.

(g) Pre-drift structures

The possible effect of arcuate structures of possible impact origin in shaping the present coastlines have been suggested (Norman, Price and Chukwu-Ike, 1977). It seems to the writer that ancient impact structures of Archaean or older age may have been reactivated in the late Proterozoic times by similar events. Circular fractures originating from large impacting bodies involve a lot of energy and may have fissured through the crust. Mantle materials would therefore tend to upwell along such

structures where possible. In West Africa it appears that the locations of aulacogenes, rifts and coastlines were determined by the concentric fractures and that spreading axes probably resulted from mantle upwelling along peripheral fracture zones of meteoritic impact origins. Circular and concentric features probably existed on earth in much the same way as they are on the moon.

(h) Amount of crustal rotation between drifted continents and intercontinental correlation of structures based on satellite images

Studies of lineament patterns of lineaments on different continents may indicate those that were formed at the same time. Such structures may suggest the amount of relative rotations of the continents. Some lineament shapes on two different continents can form crude guidelines for intercontinental structural correlation. This type of information appears to be more readily observable on orbital images.

(i) Igneous activity along concentric fractures

LANDSAT image studies show that igneous activity along the concentric fracture are likely to be by upward protrusion of magma and mantle materials into the fractures. A positive gravity anomaly flanked by negative anomalies should be expected of such fracture zones. This is known to be characteristic of the Akwapian fracture zone as well as the Benue trough (Cratchley and Jones, 1965).

(k) Statistical analyses of fractures

The photogeological method for the analysis of thousands of fractures obtainable from air photographs is to draw rose diagrams - a histogram depicting the angular or directional frequency of fracture traces. The present study has indicated that such diagrams without the consideration of other geological features in their regional contexts may be very misleading. For example, there would be a tendency to break up curvilinear and concentric lineaments and fractures into straight segments to obtain the rays of a rose diagram.

A rose diagram by itself does not suggest possible mineral sites whereas certain features seen on LANDSAT images may be more meaningful for exploration purposes. Such LANDSAT features ought to be examined independently and not used in statistical compilations if such statistics are to be geologically significant.

(l) Regional petroleum studies from satellite images

LANDSAT imagery studies of the Benue trough shows that major shear zones exist. The shear zones showing through thousands of feet of sediments are not obvious by other means. Major folds are associated with the shear zones and this association could be exploited for regional petroleum exploration.

Peripheral graben are associated with the impact structures discussed earlier in this thesis. Where spreading

or continued subsidence is associated with the grabens, block-faulting is expected to result. Sediments draping over these blocks are important oil trapping structures as well as the basal unconformity between the foundered blocks and the overlying sediments. Foundered continental margins tend to be petroliferous.

It has also been mentioned earlier that exposed lower crustal levels can be interpreted from LANDSAT images. Where a previously lower crustal level lies adjacent to a Phanerozoic basin, the source of the sediments can be inferred. Palaeoslopes could also be inferred between the two areas based on careful imagery studies. This may lead to the discovery of channel sands and palaeo-deltas, which form important oil-bearing structures, within a basin.

TECHNICAL TERMS AND DEFINITIONS

In this thesis a number of words have been used. Some of the terms used are established although with various modifications in definition. Some terms like the 'older granite' are only significant to Nigerian geology. These and other terms are defined here to clarify their usage in the context of this thesis.

ASTRON

This is a new slang to represent the disc of plastically welded rocks resulting from shock waves generated by meteoritic impacts. The term "astron" is an elision of the two geological terms, astrobleme and craton (Norman, Price and Chukwu-Ike, 1977).

BASEMENT COMPLEX

The term is used to refer to all Precambrian rocks in Nigeria.

DENSITY (FRACTURE TRACE DENSITY, LINEAMENT DENSITY)

The total length of fracture traces or lineaments or their segments per unit area commonly expressed in meters or kilometers per square kilometer.

FRACTURE SET/LINEAMENT SET

An array of parallel or sub-parallel lineaments or fracture traces visible on images.

FRACTURE TRACE

It is an image of a natural linear feature possessing the characteristics of the surface trace of a rock fracture in an exposed or masked bed rock.

FREQUENCY (LINEAMENT FREQUENCY OR FRACTURE FREQUENCY)

The number of individual fracture traces or lineaments or their segments per unit area commonly expressed as a number per unit area.

GNEISSIC COMPLEX

A Basement Complex in which gneiss predominates.

LINEAMENT TRACE DIRECTIONAL FREQUENCY

The total number of lineaments or the percentage of the total number of lineaments occurring at a chosen aximuthal interval.

LINEAMENT ROSE DIAGRAM

A lineament rose diagram or rosette diagram is a histogram of the statistics of the directional frequency.

LINEAMENT

This is an image of a natural linear feature consisting of topographic, drainage, vegetation, soil or rock tonal alignment, of any length in an exposed or soil covered rock.

TECTONIC LINEAMENT

This is an image of a natural linear feature consisting of topographic drainage, vegetation and soil tonal alignments, which originated from tectonic disturbances.

METASEDIMENT'S

The term metasediments is used to refer to supracrustal rocks, metamorphosed to markedly various degrees. Three groups of metasediments have been recognised in Nigeria. The early Proterozoic extensive volcano-sedimentary rocks, initially flat-lying and E-W trending but now refolded and infolded into the gneissic basement, and two mid-late Proterozoic trough metasedimentary groups trending N-S, and generally fault controlled. The metasediments tend to be absent in exposed previously lower crustal rocks.

OLDER GRANITE

This is used in Nigerian geological literature to refer to a dominantly porphyritic granites of Late Proterozoic to early Palaeozoic age. Emerging radiometric dates indicate that possibly a 2000 m.y. orogeny and intrusive cycle occurred within the Nigerian basement, thus making the term 'older granite' a misnomer.

PATTERN

Pattern refers to the spatial arrangement of objects, the repetition of certain general forms and the relationship of certain characteristics which enables the image interpreter to recognise the objects.

RIFTS OR GRABEN

Elongate tectonic depressions bounded by faults.

TECTONIC DOMAIN (Hepworth 1967)

This is an extensive area, delineated from photogeological studies, because of its distinctive tectonic characteristics, such as fold styles, metamorphic grades, trend lines and tectonic sequences.

YOUNGER GRANITES

This term is used in Nigerian literature to refer to a suite of high level anorogenic ring intrusions of Jurassic age. The younger granites occupy a belt about 120 kilometers wide and over 400 kilometers long. They are associated with tin mineralisation.

A P P E N D I X



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APPENDIX 1

A LANDSAT 1 false colour composite generated from bands 4, 5 and 7. Scene number E-1484-09182 covering NW Nigerian metasedimentary belt (same area as Plate 2).

Note the tonal contrasts between the low grade rocks (red) and the adjacent migmatitic terrain (whitish). The degree of redness is related to the vegetation vigour and amount, which in this case reflects the underlying geology.

APPENDIX TWO

Many Central Nigerian lineaments, hitherto unrecognised have been revealed by LANDSAT images. Those lineaments that appear prominently on images have been named as follows:- (see figure 26a)

A. Koriga lineament. This is a major N-S lineament controlling elongate intrusions bordering the eastern margin of the Nigerian low-grade metasedimentary rocks. It passes through Koriga village, and controls a river of the same name. It is a broad topographic depression some 10 kilometers across. About 6 kilometers east of Alawa (N.10° 26', E.6° 40') the lineament bifurcates and gives rise to Minna lineament.

B. Minna lineament. This lineament passes through the vicinity of the town of Minna (N 9° 37', E 6° 31'), where it passes through a major intrusion of batholithic proportions. A trough metasediment that wrapped round the batholith is abruptly terminated by this lineament. The lineament appears to have been deflected eastwards and can be traced into the Niger River - Benue confluence, where it merges with the Lokoja lineament.

C. Lokoja lineament. The location of Lokoja lineament is marked by a sudden N-S swing along River Kaduna, near the village of Galadima Kogo (N 10° 04', E 6° 52').

It continues nearly N-S into the Niger-Benue confluence at Lokoja.

D. & E. The Tubo River and Kaduna lineaments. The Tubo River lineament, D, runs along a river of the same name. Evidence of strong shearing and faulting can be seen along this river beneath the bridge along the old Kaduna-Lagos Road. The Tubo River lineament bifurcates at a point about 20 kilometers east of Funtua to give rise to Kaduna lineament. This latter lineament passes through Kaduna town and right beneath the Geological Surveys Headquarters in Kaduna. Silicified mylonites associated with this fracture zone are in evidence about 100 meters east of the Geological Surveys office along Aliyu Makama Road. It continues faintly along a near meridional trend further south.

F. Tagbari lineament. The Tagbari lineament is a NE trending fracture zone. It also passes close to the town of Minna. The Nigerian railway line runs along this lineament between Minna and Sarkin Pawa.

G. Kafui lineament. This is another NE trending lineament, defined mainly by drainage alignments. It passes through the village of Kafui ($N 9^{\circ} 31'$, $E 7^{\circ} 05'$).

H. The Izom lineament. The Izom lineament trends in

the same direction as the Tagbari and Kafui lineaments and appears to be related to them. The Izom lineament can be traced to the vicinity of Offa and Iwo areas in Western Nigeria. It is also gently curved.

I. Katchia lineament. This is a well defined lineament. It appears to be a major block fault. The lineament passes through and continues north westwards into Kaduna and south eastwards into Kajanchan area where it appears to terminate against a N-S lineament. The Katchia lineament is also parallel to another major structure passing through Kagarko (N $9^{\circ} 22'$, E $8^{\circ} 43'$). Both of them locally show prominent scarps associated with level erosion surfaces. The Kagarko lineament trends north westwards through a point about 30 kilometers south-west of Kaduna. It has some evidence of sinistral displacements of 10-15 kilometers.

J. The Karaye lineament. This lineament trends N-S and has about 15 kilometers east of Zaria (N $11^{\circ} 07'$ and E $7^{\circ} 45'$). It passes through the vicinity of the village of Gimi. The Karaye lineament is clearly expressed on LANDSAT images and continues northwards through the village of Kankiya (N $12^{\circ} 33'$, E $7^{\circ} 50'$). It is expressed on the ground by a linear shatter belt.

K. The Funtua - Mardi lineament. This is a prominent

drainage lineament also expressed as a shatter zone.

It trends north westwards. It also has a strong imagery expression (Plate 5). This lineament appears to continue through River Galma into Jos Plateau.

L. Zurmi lineament, is expressed by drainage and tonal contrast. It intersects the Funtua Mardi in the vicinity of Kankara, N $11^{\circ} 55'$, E $7^{\circ} 25'$ and controls River Bunsuru, a tributary of the Sokoto River.

M. Dan Gulbi lineament is a major E-W trending topographic lineament. It extends for over 500 kilometers from Soko to Jos. It is also a major drainage divide. LANDSAT images suggest that this lineament separates areas where rocks belonging to different crustal levels are exposed.

N. Jemaa lineament passes through a town of the same name. It has been previously recognised from the overlapping nature of ring intrusions along it for about 100 kilometers (Wright, 1970). Plate 3 illustrates this lineament.

O. Kontagora lineament is expressed as a distinct tonal lineament separating the Mesozoic sedimentary cover from the fundamental basement rocks, of NW Nigeria. It passes near Kontagora.

P. The Oshogbo lineament (Plate 6) is a peculiar U-shaped structure. It appears to outline a palaeo trough that petered out at the northern end. A geophysical examination of this lineament may resolve the unusual shape.

Q. Bakundi - Ogoja. This lineament is a gently curved N 45° E lineament, with some sectors of it broken into en-echelon fractures. It is considered to be the marginal fracture system of the Benue trough's southern boundary.

R. Tchamba lineament passes through a village of the same name. It is a well defined lineament, at least 200km in length, and appears to be related to the Bakundi Ogoja fracture system.

S. Zurak lineament is curved and trends N 50° E close to the town of Zurak in the Upper Benue trough regions. This lineament appears to disturb an anticlinal structure within the Benue trough (Plate 15a). It is a wide fracture zone and passes through the vicinity of Biu. A branch of this lineament runs along River Hawal.

T. Tafawa Balewa lineament is over 900 kilometers long. It extends from the Cameroon Volcanic area north-westwards (N 45° W) through River Taraba, across the Benue trough and Jos ring complexes to N.W. Nigeria.

U. Upper Wase lineament trends N 8° E and lies east of Bauchi. It marks the contact between the Jos Basement block and the Benue trough, in this region. It is also clearly defined as a complexly fractured zone.

V. Beli lineament is also a well defined N-S fracture zone, linking the Ka Boragap mylonite (the Cameroon volcanic line) and the Benue trough. This lineament is also bifurcated. One notable characteristic of this lineament is that it appears to control the configuration of the Benue trough in some places. It is also associated with sharp deflection of the Bouguer gravity anomaly of the Benue trough (figure 21).

W. Bida lineament trends N 30° W through Bida - NW Nigeria. It is also curved and could be traced across the Niger River Valley towards Kabba province. It passes through Gulbiu Boka to Zuru. The Bida lineament is locally defined by drainage alignments.

X and Y. Bukuru-Jos and Pankshin lineaments have been previously suggested (Wright, 1970) based on the alignment of ring intrusions and volcanoes. The N-S alignment of these intrusions are also obvious on satellite images.

Z. Iwo lineament is a N-S lineament locally marked

by a N-S alignment of elongate intrusions. It can be traced into the River Niger in Kaniji and northwards.

Ka. Kalangani fault was first mapped by Trusswell and Cope (1963) and is clearly visible on LANDSAT images as a dexteral wrench fault.

BIBLIOGRAPHY

- ANHAEUSSER, C.R., MASON, R., VILJOEN M.I., and VILJOEN R.P.
(1969) A reappraisal of some aspects of
Precambrian shield geology. Bull. Geol. Soc.
of Am. 80 pp.2175 - 2200
- ALLUM, J.A.E., (1966). Photogeology and regional mapping;
Pergamon Press, London, 107 pages.
- ALLUM, J.A.E., (1961). Photogeological interpretation of
areas of regional metamorphism. Trans. Inst.
of Min. and Met. (Lond). 70 (9) pp.521 - 543
- ALLUM, J.A.E. (1960). Photogeological interpretation of
areas of regional metamorphism. Unpub. Ph.D.
Thesis, University of London.
- AJAKAIYE, D.E. (1970). Gravity measurements over Nigerian
Younger Granites Province. Nature 225 pp.50-52.
- AJAKAIYE, D.E. and BURKE, K., (1972). A bouguer gravity
map of Nigeria. Tectonophysics 24 (4)
pp. 331 - 341.
- ANDERSON, E.M., (1951). The dynamics of faulting; Oliver
and Boyd, Edinburgh, 206p.
- BADGLEY, P.C., (1965). Structural and tectonic principles.
Harper and Row, New York, 521 pp.
- BALDWIN, R.B. (1968). Lunar mascons; Science 162, pp.1407-8
- BERTRAND, J.M. and LASSERRE, M. (1976). Pan African and
Pre-Pan African history of the Hoggar (Algerian
Sahara) in the light of new geochronological
data from the Aleksod area. Precambrian Research
3 pp.343-362.
- BLACK, R. and GIROD, M. (1970). Late Palaeozoic to Recent
igneous activity in West Africa and its relation-
ship to basement structure
in African magmatism and tectonics pp. 185-210.
Eds. Clifford, T.N. and Gass, I.G.; Oliver and
Boyd, Edinburgh.
- BLANCHET, P.H. (1957). Development of fracture analysis
as an exploration method. Bull. Am. Ass.
Pet. Geol. 41 (8) pp. 1748-1759.

- BLUNDELL, D.J. (1976) Active faults in West Africa;
Earth and Planetary Science Letters 31 pp.287-290
- BOISSONNAS, J., S. BORSI, J. FABRE and M. GRAVELLE (1969)
On the early Cambrian age of two late orogenic
granites from West-Central Ahaggar (Algerian
Sahara). Canadian Journal of Earth Sciences
6 (25) pp.25-37.
- BONATTI, E. and HONNOREZ, J. (1971) Nonspreading crustal
blocks at the Mid-Atlantic Ridge. Science
(174) pp.1329-1331
- BOWES, D.R. and A.M. HOPGOOD (1976) The significance of
Basement trends. Acta geologica polonica
26 (1) 76-82.
- BRIDGEWATER, D., V. MCGREGOR and J. MYERS (1974).
A horizontal tectonic regime in the Archaean
of Greenland and its implications for early
crustal thickening.
Precambrian Research 1 (3) pp.179-197.
- BROCK, B.B. (1957). World patterns and lineaments.
Trans. Geol. Soc. S. Africa 60 pp.149-197
- BURKE, K. and DEWEY J. (1973) Plume generated triple
junctions. Key indicators in applying plate
tectonics to old rocks. Journal of Geology
81 (4) p.381.
- BURKE, K. and DEWEY, J. (1974) Two plates in Africa
during the Cretaceous Nature 249 pp.313-315
- BURKE, K., T. DESSAUVAGIE and A. WHITEMAN (1970).
Geological History of the Benue Valley and
adjacent areas. In African Geology. Eds.
Dessauvague T. and A. Whiteman. University
of Ibadan Press pp.187-205.
- BURKE, K. and DEWEY J. (1970) Orogeny in Africa.
In African Geology, Eds. T. Dessauvague and
A. Whiteman, University of Ibadan Press
pp. 583-634.
- CHOURBERT, G. (General Co-ordinator) and A. FAURE-MURET (1971)
Tectonics of Africa, UNESCO, Paris.
- CHUKWU-IKE, I.M. (1977). A crustal suture and lineament
in north Africa: A Discussion.
Tectonophysics (in press)

- CHUKWU-IKE I.M. and J.W. NORMAN (1977) Mineralised crustal failures shown on satellite imagery of Nigeria. Trans. Inst. Min. Met. (Lond). 86 B55-B57.
- CLIFFORD T.N. (1968) Radiometric dating and the pre-Silurian geology of Africa. In Radiometric dating for geologists. Eds. E. Hamilton and R. Farquhar. John Wiley, London, pp.299-415
- CLIFFORD T.N. (1966) Tectono metallogenic units and metallogenic provinces of Africa. Earth and Planetary Science Letters, 1 pp.421-434.
- CLIFFORD T.N. (1973) African granulites and related rocks: A preliminary note. Spec. Pub. Geol. Soc. S. Africa 3 pp.17-23
- COLEWELL R.N. (1954) A systematic analysis of some factors affecting photographic interpretation. Photogramm. Eng. 20 (2) pp.433-462
- COWARD, MP. and JAMES, P. (1974) The deformation patterns of two Archaean greenstone belts in Rhodesia and Botswana. Precamb. Research 1 pp.235-258
- CRATCHLEY, C.R. and JONES, G.P. (1965) An interpretation of the geology and gravity anomalies of the Bene Valley, Nigeria. British Overseas Geol. Surv. Geophysical Paper 1
- CROSBY (1971) Aeromagnetism and photogeology, Western Miner, June 1971 p.31.
- DOWLING J.W.F. (1965) The mode of occurrence of laterites in Northern Nigeria and their appearance in aerial photography. Eng. Geol. 1 (3) pp.221-233
- Du PREEZ, J.W., 1949. The hydrology of Gumel Emirate Rep. Geol. Surv. of Nigeria, 1949.
- EILBERS, J. (1976) Calcalkaline Plutonism, Volcanism and related mineralisation CIM, 69 (771) pp.83-95
- FARRINGTON, J.L. (1952) A preliminary description of the Nigerian lead-zinc field Econ. Geol. 47 pp. 583-608
- FYFE, W.S., (1974) Archean tectonics. Nature 249 p.338
- GEE, R. and WILLIAMS I.R. (1974) The application of ERTS imagery to geological mapping in the Kalgoorlie area. Geol. Surv. of Australia Annual Rept. 1974 pp.54-57

- GIRDLER, R.W. (1975) The great negative bouguer gravity anomaly over Africa. EOS (American Geophysical Union) 56 (8) pp. 516-519.
- GOETZ, A.F. and BILLINGSLEY, F.C. (1973) Geologic applications of ERTS images on the Colorado plateau. Third Earth resources technology satellite - 1 Symposium Volume 1, Section A, paper G.9 pp.719-744
- GOETZ, A.F., BILLINGSLEY, F. A. GILLESPIE et al. (1975) Application of ERTS images and image processing to regional geologic problems and geologic mapping in Northern Arizona NASA Tech. Rept. no. 32 - 1597 188pp.
- GRANT N.K. (1969a) The Late Precambrian to early Palaeozoic Pan African orogeny in Ghana, Togo, Dahomey and Nigeria. Bull. Geol. Soc. Am. 80 pp.45-55
- GRANT N.K. (1969b) The nature of the Pan-African orogeny in Nigeria. 13th Ann. Rept. Inst. Afr. Geol. 1967-68, University of Leeds, pp.20-21.
- GRANT N.K. (1970) Geochronology of the Precambrian basement rocks from Ibadan, South-western Nigeria. Earth and Planet Sci. Letters 10 pp.29-38
- GRANT N.K. (1972) Kibaran metamorphic Belt in Pan African domain of West Africa. Nature Phys. Science 238 p.90.
- GREGORY, A.F. and MOORE H.D. (1975) The role of remote sensing in mineral exploration with special reference to ERTS-1, CIM Bulletin pp.67-72
- GRIGGS, D. (1951) Deformation of Yule marble Bull. Geol. Soc. Amer. 62 pp.853-862
- HAMAN P.J. (1961) Lineament analysis on aerial photographs; West Canadian Res. Pub. No. 1 series 2, 22pp.
- HENDERSON, G. (1960) Airphoto lineaments in Mpanda area, Western Tanzania; American Assoc. Petroleum Geologists 58 (1) pp.53-71
- HEPWORTH J.V. (1967) The photogeological recognition of ancient orogenic belts in Africa. Quarterly Journ. Geol. Soc. 123 p.253.

- HESS, H.H. (1960) History of Ocean basins. In Petrologic Studies, A volume in honour of A.F. Buddington. Geol. Soc. Am. pp.599-620
- HILLS, E.S. (1963) Elements of Structural Geology; Methuen and Co., London, 483 pp.
- HOPGOOD, A.M. (1971) Correlation by tectonic sequence in Precambrian gneissic terrains; Geol. Surv. Austr. Spec. pub. No. 3 pp.367-376
- HOBBS, W.H. (1911) Repeating patterns in the relief and the structure of the land. Bull. Geol. Soc. Am. 22 pp.123-176
- HODGSON, R.A. (1961) Regional study of jointing in Comb Ridge - Navajo Mountain Area - Arizona. Am. Ass. Pet. Geol. 45 (1)
- HUBBARD F.H. , Precambrian crustal development in W. Nigeria. Indications from Iwo region. Bull. Geol. Soc. Am. 86 p.548-554
- HULLEY, J.C.L. (1963) Correlation between gravity anomalies, transcurrent faults and pole positions. Nature 198 pp.466-467
- HUNTINGTON, J. (1975) A photogeological study of fracture trace patterns using data processing techniques. Unpub. Ph.D. Thesis, Geology Dept., Imperial College.
- HURLEY, P.M., FAIRBAN, H.W. and PIRSON (1966) Massachusetts Institute of Technology Annual Progress Report no. 1381
- ISAACKS, B., OLIVER, J. and SYKES, L.R. (1968) Seismology and the new global tectonics Journ. Geophys. Res. 73 pp.5855-5900
- ISAACHSEN, Y.W., FAKUNDINY R.H., and FORSTER, S. (1973) Evaluation of ERTS imagery for spectral geological mapping in diverse terrains of New York State. Third Earth resources tech. satellite-1, Symposium Vol. 1, Sect. A p.691
- JONES G.H.S. (1966) The morphology of central uplift craters. An experimental study and review. Canadian defence research establishment, project no. D95-11-69. Suffiend rept. no. 281
- JONES. H.A. and R.D. HOCKEY (1964) The geology of part of South-western Nigeria. Geol. Surv. of Nigeria Bulletin no. 31 101p, map

- JACOBSON, R.R.E., SNELLING, N.J. and TRUSSWELL, J.F. (1964)
 Age determinations in the geology of Nigeria
 with special reference to the older and
 younger granites.
Overseas geology and mineral resources 9 pp.168-182
- JACOBSON, R.R.E., MACLEOD, W.N. and BLACK, R. (1958)
 Ring-complexes in the younger granite province
 of northern Nigeria.
Geological Soc. of London memoir no. 1, 72pp.
- KARIG, H. and PRESS, F., (1970) Ridges and basins of the
 Tonga-Kermadec island arc system.
Journ. geophys. Res. 75 (2) pp.239-254
- KATTERFIELD, G.N. (1976) Global and regional systems of
 lineaments on the Earth, Mars and the Moon.
In: Proceedings of the first International
 Conference on the new basement tectonics.
 Eds. Hodgson, R. and Gay S.P., Utah Geological
 Assoc. pp.369-378.
- KENNEDY, W.B. (1964) The structural differentiation of
 Africa in the Pan African (+ 500 m.y.) tectonic
 episode. 8th a Rept. Scient. Results. Inst.
 Afr. Geol. (University of Leeds) 1962-1963
 Session, pp.48-49.
- KING, B.C., and de SWARDT, A.M.J. (1949) The geology of
 the Osi area, Ilorin Prov.
Bull. Geol. Surv. of Nigeria, no. 20.
- KIOOSTERMAN, J.B. (1975) Roraima, Tafelberg and Uatuma
 formations of the Guiana shield: a correlation.
Geologie en Mijn bouw 54 (1) pp.55-60
- KOWALIK, W.S. and GOLD, D.P. (1976) The use of LANDSAT-1
 imagery in mapping lineaments in Pennsylvania.
In: Proceedings of the first International
 Conference on the new basement tectonics.
 Hodgson R. and Parker Gay Eds. Utah Geol.
 Assoc. pp.236-249
- LATHRAM, E.H. and AIBERT, R.N. (1976) Significance of
 space image linears in Alaska.
In: Proceedings of the first International
 Conference on the new basement tectonics.
 Eds. R. Hodgson and P. Gay. Utah Geol. Ass.
 pp.11-26.
- LATTMAN, L.H. (1958) Technique for mapping geologic
 fracture traces and lineaments on aerial
 photographs. Photogramm. Eng. 24 (4),
 pp.568-576

- LATTMAN L.H. and NICKELSEN R.P. (1958) Photogeologic fracture trace mapping of the Appalachian Plateau.
Bull. Am. Ass. Pet. Geol. 42 pp.2238-2245
- LLOYD-LAWRENCE A.H. (1977) The characteristics of plutonic rocks in various climatic zones as shown on multiband satellite imagery.
Unpub. Ph.D. Thesis, Dept. of Geology, Imperial College of Sc. & Tech. London, 269pp.
- LOWE. R.G. (1971) Forestry in the different vegetation zones of Nigeria.
Annual Rept. of the Nigerian Federal Dept. of Forest Research, Ibadan.
- LOWMAN, P. (1972) Lunar craters.
Journal of Geology 80 pp.125-166
- MALAHOFF, A. (1971) The Murray fracture zone, history, structure geology and comparison to other Pacific fracture zones.
Rec. Proc. 12th Pacif. Sci. Congr. Canberra, 1 pp. 355
- MAYO, E.B. (1958) Lineament tectonics and some ore districts of the south west.
Trans AIME pp.1169-1175
- McCONNEL, R.B. (1974) Evolution of taphrogenic lineaments in continental platforms.
Geol. Rund. 63 pp.389-430
- McCURRY, P. (1973) Geology of degree sheet 21, Zaria, Nigeria.
Overseas geology and mineral resources no. 45 45pp.
- McCURRY, P. (1971) Pan African orogeny in northern Nigeria.
Geol. Soc. Am. Bull. 82 pp.3251-3262
- McCURRY, P. (1976) The geology of the Precambrian to Lower Palaeozoic rocks in northern Nigeria - A Review.
In Geology of Nigeria, ed. A. Kogbe., Elizabeth Press, Lagos, pp.15-39.
- McDONALD, D.E. (1957) Resolution as a measure of interpretability.
Photogramm. Engng. XIX pp.58-62.
- McKENZIE, D.P. (1967) Speculations on the consequence and causes of plate motions.
Geophys. Journ. Roy. Astr. Soc. 18 pp.1-32

- MELSON, W.G., S. HART and G. THOMPSON (1972) St. Paul's rock, equatorial Atlantic; Petrogenesis, radiometric ages and implications on sea-floor spreading.
Geol. Soc. Am. Memoir no. 132 pp.241-272
- MILANOVSKY, Ye, Ye (1976) Rift zones of the geologic past and their associated formations. Rept. 1
Int. Geol. Review 18 (5) pp.515-531.
- MOLLARD, J.D. (1959) Photogeophysics - its application in petroleum exploration over glaciated plains of Western Canada.
2nd Williston Basin Conf. Sask. Soc. Petr. Geol.
- NAGY, R., GHUMA, M. AND J. ROGERS (1976) A crustal suture and lineament in N. Africa.
Tectonophysics 31 T67-T72.
- NASA (1971) Data users handbook - NASA earth resources technology satellite, Goddard Space Flight Centre, Greenbelt, Maryland, Document no. 71SD4249.
- NASA (1973) (1974) Symposium on significant results obtained from the Earth Resources Tech. Satellite-1 Vol. 1 Technical Presentation Sect. A 877 pages.
NASA Special Publications SP. 327 and 351.
- NORMAN J.W. (1968) Airphoto requirements of geologists
Photogramm. Record 6 p.133
- NORMAN J.W. (1968) The geological significance of natural linear features occurring in areas of superficial deposits as revealed by air photographs
Unpub. Ph.D. Thesis. Dept. of Geol. Imperial College, London.
- NORMAN J.W. (1976) Photogeological fracture trace analysis as a subsurface exploration technique.
Trans. Inst. of Min. and Met. 85, B52-62.
- NORMAN J.W. and CHUKWU-IKE I.M. (1977) The world is a bit cracked!
New Scientist 73 (1038) pp.320-322.
- NORMAN, J.W. PRICE J. and CHUKWU-IKE I.M. (1977) Astrons - The Earth's oldest scars?
New Scientist 73 (1044) pp.689-692.
- OGEZI, E. (1976) University of Leeds (Personal Communication).

- OLADE, M.A. (1975) Evolution of Nigerian Benue Trough (aulacogen) - a tectonic model.
Geol. Mag. 112 (6) pp.575-583
- O'LEARY D.W., J.D. FRIEDMAN and H.A. POHN (1967)
Lineament, linear, lineation - some proposed new standards for old terms.
Remote Sensing and Mineral Exploration; IGCP Project no. 143
- ORAJAKA S.O. (1964) The geology of the Obudu area.
Naturaliste Canadien 41 pp.73-100
- ORAJAKA S.O. (1972) Salt water resources of E. Nigeria.
Jnl. of Min. and Geol. (Nigerian) 7 (1 & 2) pp.35-41
- OVERSBY, V.M. (1975) Pb isotopic study of aplites from the Precambrian basement rocks near Ibadan, S.W. Nigeria.
Earth Planet. Sci. Lett. 27 p.177
- OYAWOYE, M.O. (1964) The geology of the Nigerian basement complex.
Jnl. Min. Geol. (Nigeria) 1 pp.87-102
- PARK, R.G. (1969) Structural Correlation in metamorphic belts.
Tectonophysics 7 (4) pp.323-338
- PARKKINEN J. (1975) Deformation analyses of a Precambrian mafic intrusive Haukivesi area, Finland.
Geol. Surv. of Finland Bull. 278
- PERMYAKOV, Y.E. (1949) Tectonic jointing of the Russian platform.
MOIP Publications, Series no. 12 16pp.
- PETTIJOHN, F.J. (1970) The Canadian Shield - A status report:
Canadian Geol. Surv. paper 70-40 pp.239-265
- FRETORIUS, J. and PARTRIDGE, T.C. (1974) The analysis of angular atypicality of lineaments as an aid to mineral exploration.
Jnl. S. Afr. Inst. of Min. and Met., May 1974 pp.367-69
- PRICE, N.J. (1966) Fault and joint development in brittle and semi-brittle rock.
Pergamon Press, London.
- PRICE, N.J., (1975) Rates of deformation.
Jnl. Geol. Soc. London, 131 pp.553-575

- PIPER, J.D.A. (1974) Proterozoic crustal distribution mobile belts and apparent polar movements. Nature 251 (5474) pp.381-384.
- PULVERTAFT, T.C. (1973) Recumbent folding and flat-lying structure in the Precambrian of W. Greenland. Phil. Trans. R. Soc. London. 273 pp.535-545
- PUGH J.C. and KING L.C. (1952) Outline of the geomorphology of Nigeria. S. Afr. Geogr. Jnl. 34 pp.30-37
- RICHARDS D.J. and WALRAVEN F. (1974) Airborne geophysics and ERTS imagery. Minerals and Sc. Engineering 7 (3) pp.234-278
- ROWAN L.C., WETLAUFER, P., GOETZ A.F. et al. (1976) Discrimination of rock types and altered areas in Nevada by the use of ERTS images. U.S. Geol. Surv. Prof. paper no. 883 31pp.
- RUMSEY, N.J. (1971) Relationship of fractures in unconsolidated superficial deposits to underlying bedrock. Modern Geology 3 (1) pp.25-41
- RUSS, W. (1957) The geology of parts of Niger, Zaria and Sokoto provinces. Geol. Surv. of Nigeria bulletin no. 27, 42p. map
- SACCHI, R. (1968) The geology of the region around Bena in N. Nigeria. Memorie 1st geol. miner. Univ. Padova Vol. 24 41pp.
- SALES, J.K. (1968) Crustal mechanics of Cordilleran foreland deformation: a regional and scale model approach. Am. Ass. Petr. Geol. Bull. 52 (10) pp.2016-2044
- SAUNDERS, D.F., THOMAS G.E., KINSMAN et al. (1973) ERTS-1 imagery use in reconnaissance prospecting. NASA Rept. prepared for Goddard Space Flight Centre, Greenbelt, Maryland no. U1-70Z700F
- SHACKLETON, R.M. Problems of the evolution of the continental crust. Phil. Trans. R. Soc. London. A273 pp.318-320
- SHACKLETON, R.M. (1973) Correlation of structures across Precambrian orogenic belts in Africa. In: Implications of Continental Drift to the Earth Sciences Vol. 2 Eds. D.H. Tarling and S.K. Runcorn pp.1091-1095.

- SISSELMAN, R. (1975) Looking for minerals via satellite a far-out approach to exploration.
E/MJ May 1975, pp.87-94.
- SMITH, G.A. (1976) Plate tectonics: a review.
Tectonophysics, 33 pp.215-285
- SONDER, R.A. (1947) Discussion of shear patterns of the earth's crust, by F.A. Vening Meinesz
Am. Geophys. Union Trans. 28 pp.939-945.
- SPENCER, W.E. (1959) Evolution of the Beartooth mountains, Montana and Wyoming.
Geol. Soc. Am. Bull. 70 pp.467-508
- SUTTON, J. and WATSON, J.V. (1974)
Tectonic evolution of continents in early Proterozoic times.
Nature 247 (5441) pp.433-435
- SUTTON, J. (1963) Long term cycles in the evolution of continents.
Nature 198 (4882) pp.731-735.
- SUTTON, J. (1973) Some changes in continental structure since early Precambrian time. In: Implications of Continental drift to the earth Sciences.
Eds. D. Tarling and S. Runcorn. Academy Press p.1071.
- SYKES, L. and SBAR, M. (1973) Intraplate earthquakes, lithospheric stresses and the driving mechanism of plate tectonics.
Nature 245 pp.298-302
- THOMAS, F.M. (1974) Tropical Geomorphology; Macmillan Press, London, 332pp.
- THOMAS, G.E. (1976) The crustal fracture system of N. America and its possible origin.
In: Proceedings of the 1st Int. Conf. on the New Basement Tectonics, Eds. R. Hodgson and S.P. Gay. Utah Geol. Ass. pp.537-549
- TOUMINEN, H.V., AARNISALO, J. and SÖDERHOLM, B. (1973)
Tectonic patterns in the Central Baltic shield.
Bull. Geol. Soc. Finland 45 pp.205-207.
- TRUSWELL, J.F. and COPE, R.N. (1963) The geology of parts of Niger, and Zaria Provinces, N. Nigeria.
Geol. Surv. of Nigeria Bull. no. 29, 48pp. map
- TURNER D.C. (1971) The Precambrian and Lower Palaeozoic Basement of Nigeria.
In: Tectonics of Africa, UNESCO pub. pp.255-260.

- UZUAKPUNWA, A.B. (1974) The Abakaliki pyroclastics - Eastern Nigeria: new age and tectonic implications.
Geol. mag. 111 (1) pp.65-70
- VILJOEN, R.P. and VILJOEN, M.J. (1975) ERTS-1 imagery: an appraisal of applications in geology and mineral exploration.
Minerals Sci. Engng. 7 (2) pp.132-167
- VILJOEN R.P. (1973) ERTS-1 imagery as an aid to the understanding of the regional setting of base metal deposits in the North-west Cape Province, South Africa.
In: Third Earth Resources Tech. Satellite 1 Symposium Vol. 1: Tech. Presentations, Sect. A NASA pp.797-807
- WATSON J. (1973) Effects of reworking on high grade gneiss complexes.
Phil. Trans. R. Soc. London A273 pp.443-455
- WATSON, J. (1973) Influence of crustal evolution on ore deposition.
Trans. Inst. of Min. and Met. August 1973
pp.B107-B113
- WERTZ, J.B. (1970) The Texas lineament and its economic significance in SE Arizona.
Econ. Geology 65 pp.166-181
- WHITE, D.E. (1974) Diverse origins of hydrothermal ore fluids (Econ. Geol. 69 pp.954-973.
- WILCOX, R.E., HARDING, T.P. and SEELY, D.R. The Basic Wrench tectonics, AAPG 57 (1) pp.74-96
- WILSON J.T., (1972) New insights into old shields.
Tectonophysics 13 (1) pp.73-94
- WINDLEY, B.F. (1973) Crustal development in the Precambrian
Phil. Trans. Roy. Soc. London. A.273 pp.321-41
- WISE, D.U. (1968) Regional and subcontinental sized fracture systems detectable by topographic shadow technique.
In: Proc. Conf. on research in tectonics Geol. Surv. Canada paper no. 68-52 p.175
- WRIGHT, J.B. (1970) Origin of the Younger Granites of N. Nigeria.
Contr. Mineral and Petrol. 29 pp.89-90

- WRIGHT, J.B. (1969) High pressure phases in Nigerian Cenozoic lavas, distribution and geotectonic setting.
Paper printed at the IAVCEI Symposium, Oxford, Sept. 1969
- WRIGHT, J.B. (1972) Tholeiite from Cenozoic alkaline volcanic province of Nigeria.
Geol. mag. 109 (3) pp.243-246
- WRIGHT, J.B. (1970) Controls of mineralisation in the older and younger tin fields of Nigeria.
Econ. Geol. 65 pp.945-951.
- WRIGHT, J.B. (1976) Fracture systems in Nigeria and initiation of fracture zones in the S. Atlantic.
Tectonophysics 34 pp.T43-T47.
- WRIGHT, J.B. (1968) South Atlantic continental drift and the Benue trough.
Tectonophysics 6 (4) pp.301-310
- WRIGHT, J.B. and P. McCURRY (1971) Note on Atlantic fracture zone and the Guinea Coast.
Nig. Jnl. of Min. and Geol. 6 (1-2) 1972 (for 1969) p.65.
- WRIGHT, J.B. (1976) Volcanic rocks in Nigeria.
In: Kogbe ed. Geology of Nigeria, Elizabeth Press, Lagos, pp.93-141
- WRIGHT, J.B. and McCURRY P. (1970) A reappraisal of some aspects of Precambrian shield Geology: Discussion.
Bull. Geol. Soc. of Am. 81 pp.3491-3492
- WRIGHT, J.B. (1976) Origins of the Benue trough - a critical review.
In: Geology of Nigeria, C. Kogbe Ed. Elizabeth Press, Lagos, p. 309-317.
- YAIRI, K. (1975) Geometry and mechanics of en-echelon faulting with applications to the East African rift system.
1st Prelim. Rept. of Afr. Studies. Ass. for Afr. Studies, Nagoya Unit, Japan, pp.29-38.
- ZWAIN, J.A. (1976) Analysis from air photographs of fracture traces in N. Iraq. A structural geological study with reference to oil exploration
An unpub. thesis, Dept. of Geology, Imperial College of Sc. & Tech., London.

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Technical note

**Mineralized crustal failures showing on
satellite imagery of Nigeria**

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Mineralized crustal failures shown on satellite imagery of Nigeria

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The extensive current studies of imagery from LANDSAT (formerly named Earth Resources Technology Satellite) are proving their value for the detection of long fractures in shield areas. The scale and resolution of the imagery limits practical detection to a minimum length of the order of 1 km; but with several bands and 'scenes' from

different seasons, a profusion of faults of greater length can often be detected. Concealed in this apparently chaotic random pattern may be important block faults or 'disjunctive zones', which coincide with zones of mineralization, areas of intrusives and extrusives, and major geophysical anomalies.¹ In regions that are not geologically mapped it is often a problem to pick out these significant features. Length is not a satisfactory basis on its own, for the imagery may show a discontinuous trace (or even no surface trace) of some of these important features.

One useful approach is to search for systems of parallel fractures of long and medium lengths, regularly spaced at intervals of the order of 25–75 km, exemplified by those seen in central Nigeria. There, a near-meridional set is one of the oldest and most pervasive, with members that measure hundreds of kilometres in length (Fig. 1) and display some of the characteristics of taphrogenic lineaments.² One of these lines of failure has been traced as far as the Hoggar in central Sahara — the limit of our imagery. Parts of four of the lineaments confirm features inferred by Wright³ from the orientation of igneous bodies.

The trend of these lineaments corresponds to the dominant grain of the Nigerian Basement Complex. Although other lineament trends exist,

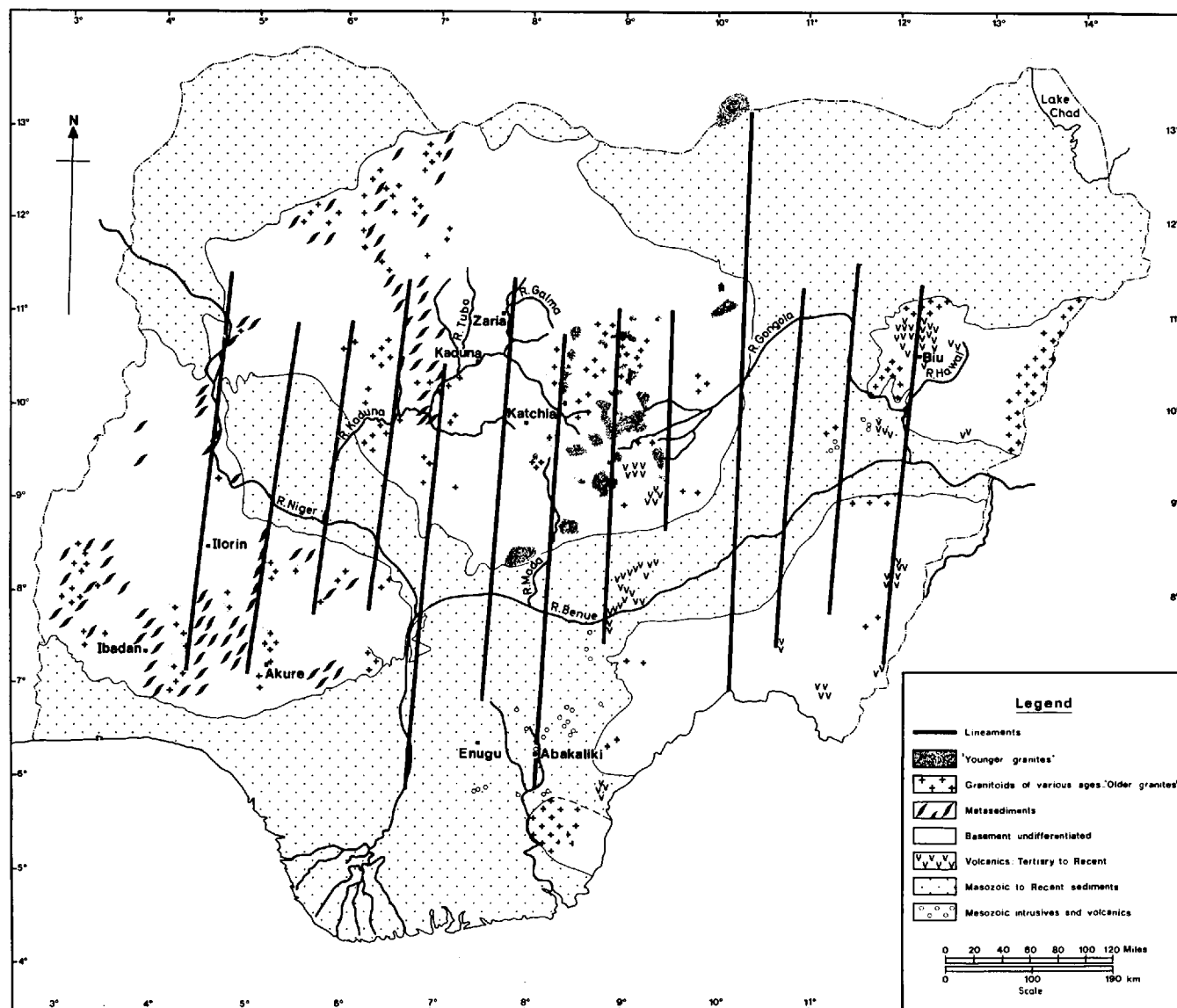


Fig. 1 Generalized geological map of Nigeria, showing positions of north-south lineaments

the north–south direction appears to be very extensive. These meridional lineaments seem to exercise sharp control of the shapes and positions of the pear-shaped intrusions in Nigeria; according to an interpretation of the tones and patterns seen on the imagery, the distribution and grades of metamorphism also appear to be directly related to the lineaments.

The north–south lineaments are fairly regularly spaced across the country at intervals of 40–50 km, and seem to have exerted a dominant influence on structures referable to different tectonic episodes or origins. The meridional lineaments tend to realign pre-existing structures that had distinctly different trends.

The ages of these meridional lineaments cannot be readily ascertained; but they appear to be very ancient, and to have predated the northeast–southwest and northwest–southeast sets, which tend to displace them. The amounts of displacement are insignificant at the scale of Fig. 1, but are actually up to several kilometres in length; similarly there are relatively small local deflections (in terms of the diagram scale), but the lineaments resume their near-meridional trend on each side of the deflections.

Field checks on the surface expression of some of these features indicate that most of them are negative features, sometimes 10–15 km wide, although the lineament image appears to be a much narrower sharp central line. A few are positive topographic features. They generally extend for over 500 km, and where outcrops occur they contain locally parallel silicified mylonites and blastomylonites. The sense of movements on these zones is difficult to decipher, but, judging from present-day levels and landforms, vertical movement seems to have been dominant. The lineaments apparently coincide with areas of pegmatite tin–columbite mineralization and lead–zinc mineralization, but further work is necessary to establish this relationship more closely.

An example of one lineament which connects mining areas is shown in Fig. 2. In the north of the diagram, in the tin-mining area, there is a series of Jurassic igneous intrusive bodies ‘younging’ to the south. This gives the impression that it may be due to a progressive opening of a line of failure rather than to a migrating mantle plume, and it could have been fissured to the base of the crust. For several hundred kilometres of its length, the lineament can be traced southwards, where the

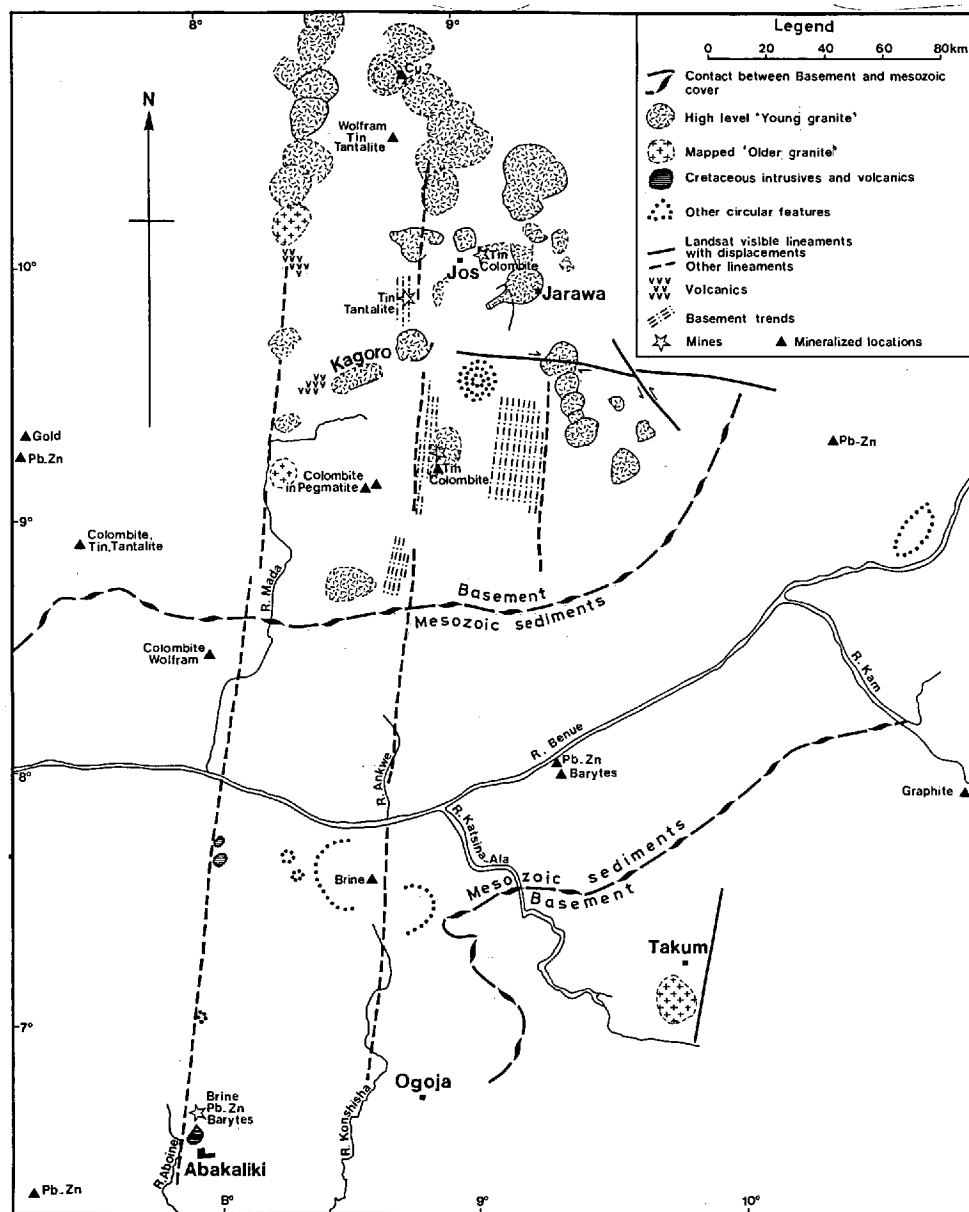


Fig. 2 Connexion of Jos ring complexes to Abakaliki volcanics by one lineament

basement is concealed under Phanerozoic sediments, to the Abakaliki lead—zinc mining area.

The nature and origin of these meridional lineaments is still being investigated. One speculative hypothesis is illustrated in Fig. 3. This shows some stages in the history of the basement rocks as set out below.

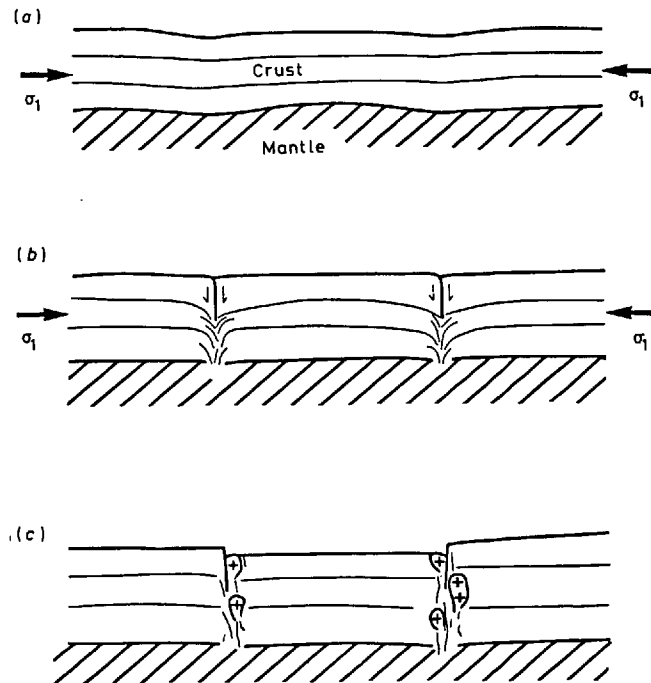


Fig. 3 Possible sequence of events that cause lineaments

(a) A horizontal east—west compression tended to cause gentle symmetric buckling with a spacing of the order of the crustal thickness.

(b) The roots of the potential synformal features, on being forced down, started to become plastic; thus they helped to increase horizontal shortening along these zones, and caused brittle failure nearer to the surface (the lineaments). Where the deeper part of the original synformal—failure zone is now exposed at the surface, there is a diffuse zone of minor failures and lineation instead of a clear sharp boundary to the structure.

(c) Continued compression caused uplift between the lineaments and further down-forcing of the old potentially synformal roots, which then became partly mobile, caused intrusion upwards through lines of weakness, and possibly brought up some material from the mantle.

A possible crustal doming in the tin mining area around Jos (as suggested by Wright³) could have caused the opening of the lines of brittle failure and extra igneous activity in this area. An unusual feature of these lineaments is their straightness and parallelism over such great lengths. The lineament system seems to require a very large force applied uniformly over a large area. Some possible causes might be related to the earth's rotation. For example, if large bodies were to impact or pass near to the earth, they might cause changes in rotation speed, which could generate enormous inertial forces.

Parallel systems of lineaments may be more widespread than was realised prior to the availability of LANDSAT imagery. A LANDSAT MSS band 5 of southwest England, on a quick

examination, shows a northeast-trending set aligned along the granites and zones of tin mineralization. It parallels linear variation in geochemical levels of metals and some offshore geophysical trends. The faint lineaments presumably are surface expressions of basement failures under the Devonian, Carboniferous and Permian cover.

Acknowledgement

The authors wish to express their gratitude for the generous manner in which the U.S. Government has made cheap satellite imagery internationally available.

References

1. Aarnisalo J. and Mikkola A. K. Fracture patterns of Finnish Lapland and their relation to ore deposits. Paper presented to Meeting of European Geological Societies, Reading, UK, September, 1975, in press.
2. McConnel R. B. Evolution of Taphrogenic lineaments in continental platforms. *Geol. Rdsch.*, **63**, 1974, 389–430.
3. Wright J. B. Controls of mineralization in the Older and Younger tin fields of Nigeria. *Econ. Geol.*, **65**, 1970, 945–51.

Discussions and contributions

Photogeological fracture trace analysis as a subsurface exploration technique

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Report of discussion at October, 1976, general meeting (Chairman: Professor G. R. Davis, Vice-President), contributed remarks and author's reply. Paper published in *Transactions/Section B (Applied earth science)*, vol. 85, February, 1976, pp. B52-62

Dr. J. W. Norman introduced his paper with examples of fracture traces on air photographs of London Clay and recent river deposits. He showed examples of crustal failures on satellite images, and explained that the work described in the paper dealt with smaller, second-order, fractures detected on air photographs. He then showed illustrations from petroleum and mineral exploration projects where fracture traces had been used to detect folds and intrusive features several thousand feet below the surface, by use of both visual and computer-based interpretations. Those features were detected after the regional stress pattern of the surface rocks had been solved from the fracture patterns; where possible, several different approaches had been used.

Dr. C. H. James thought that the paper was fascinating. The author had referred to the difference between an art and a science: the paper was perhaps the beginning of the science of photogeology.

It appeared that in the sort of field referred to, people were attempting to apply statistics to sampled data. Should they ask themselves whether the criteria by which sampling was judged had been met? That could be seen through quite thick materials, such as dolomites. To what extent could one assume continuity through it? How much would the linear pattern shown on the surface be related to the structure? Would the fractures related to *one* system show through, but not those of another system? Again, there were the effects of overburden, which could vary. All that could quite destroy the general idea of sampling: what was found on the surface was representative of what was underneath. If so, what would be the effect on the work? Another point was: did the author just measure the length he could see, or did he assume that there was continuity between them?

In the paper, Dr. Norman had drawn attention to the problems if glacial overburden gave rise to false linears. In the example shown, the last ice movement was probably east-west. Could that be glacial-orientated rather than structure-orientated?

P. R. Harnett* asked about the extent to which the subjective bias of the interpreter could affect the compilation of fracture trace arrays. He wished to point out that it was a subject of considerable concern among photogeologists, upon which research was being undertaken.

In addition to the increasing application of digital computing methods, the development of optical Fourier

transform processors, as mentioned in Dr. Norman's paper, might constitute a suitably objective aid or monitor for photo-interpretation. Barnett* and he had recently submitted a joint technical note that touched on that theme.

They also hoped to maintain contact with Dr. Norman and other colleagues in the earth sciences, to continue examination of the topic.

Dr. G. W. Richards said that he had read the paper with interest. He thought that it tended to say that one must be pragmatic and that what people saw might not be what they thought they saw. He did not know of any means of looking 4000-6000 ft below the surface, other than photogeology, and felt that the author should be congratulated. In oil and metals, aerial photography interpretations were now very actively used. Recently, in the U.S.A., a thermocouple had been discovered, at a depth of 2000 ft, by use of aerial photographs: although he could not see what use that would be, it gave an indication of the potential of the method.

The Chairman pointed out that the Orange Free State goldfield had been discovered at a similar depth, and the technique might have been useful in that case, if it had been available.

J. McM. Moore pointed out that Dr. Norman's interesting paper illustrated some of the difficulties attached to the dynamic interpretation of photo-lineament rose diagrams in

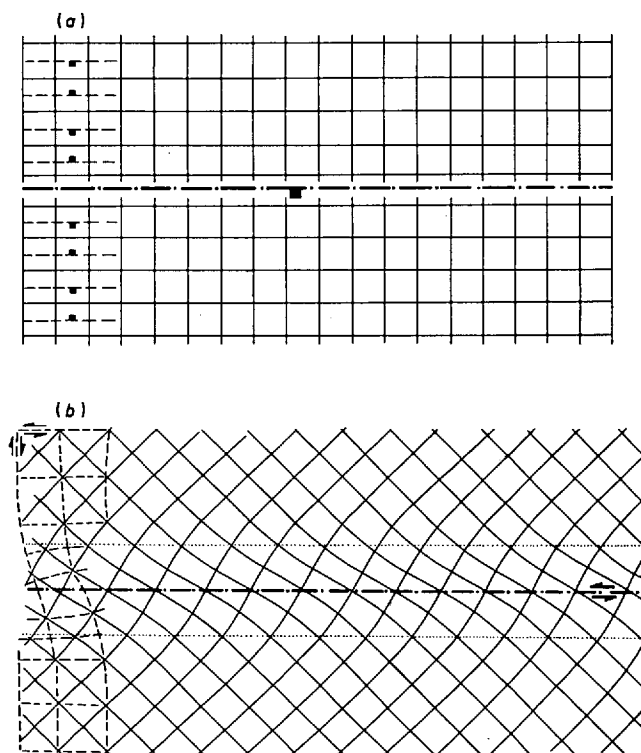


Fig. 1 Generalized plans of joint trace orientations associated with (a) normal fault movement and (b) strike-slip fault movement

terms of stress systems. The surface traces of joint fractures, particularly in the vicinity of a major fault that had undergone strike-slip (wrench) movement, were commonly curved (Fig. 1(b)).¹ It was important not to presume that a partially obscured fracture system associated with such a fault was necessarily orthogonal, or that hidden extensions

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*Harnett P. R. and Barnett M. E. Optical rose diagram for lineament analysis. *Trans. Instn Min. Metall. (Sect. B: Appl. earth sci.)*, in press.

Astrons - the Earth's oldest scars?

In this speculative article three geologists advance the idea that large-scale cosmic impact features—the *astrons*—can be detected on the Earth's surface, and that the shapes of our continents are still controlled by these results of major meteoritic events that happened billions of years ago

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Our understanding of the geological evolution of the world has greatly benefited from the concept that the crust consists of a series of plates, sometimes slowly separating or colliding (the theory of plate tectonics). Nevertheless, there remains a number of puzzling observations and relationships which cannot be

readily interpreted by this concept. For example, in a recent article ("The world is a bit cracked", *New Scientist*, vol 73, p 320) two of us (J.W.N. and I.M.C-I.) showed that there is an old major fracture system of the Earth's crust in West Africa, and a corresponding system in Brazil, that was established well before the separation of South America from Africa by the process of plate tectonics. It is reasonable to expect that the two continents would have separated along some of these old straight fractures and that the coastline would show a relationship to this failure system. A casual examination of any school atlas will show the futility of trying to test this relationship, for West Africa's external shape is nearer that of part of a large circle.

Why should this huge arcuate coast have formed in preference to a series of breaks along the old straight lines of weakness? Photogeologists working on regional fracture patterns with air photographs frequently find small arcuate fractures formed during subsidence collapse over voids, or where low-density materials such as granites or salt domes

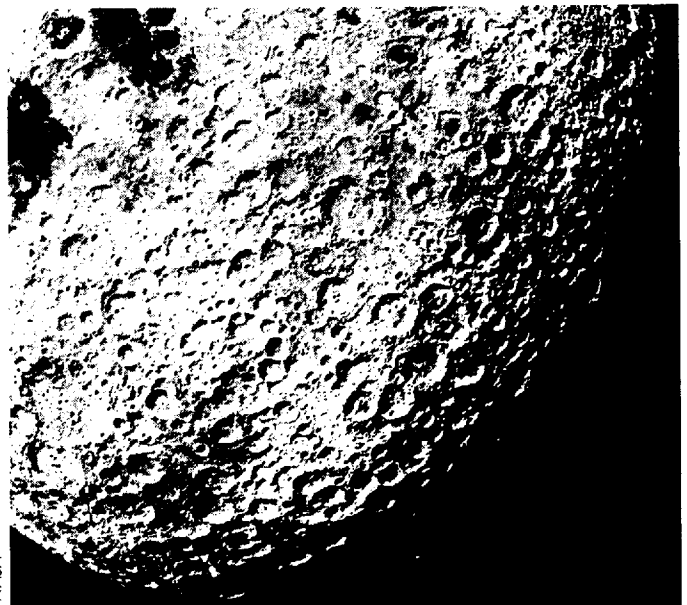
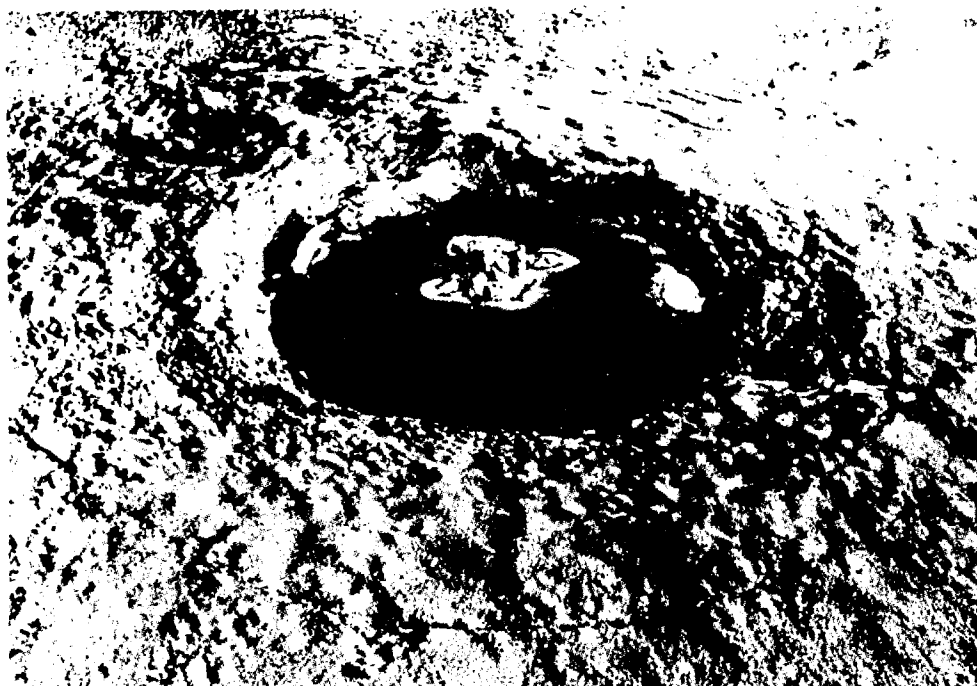


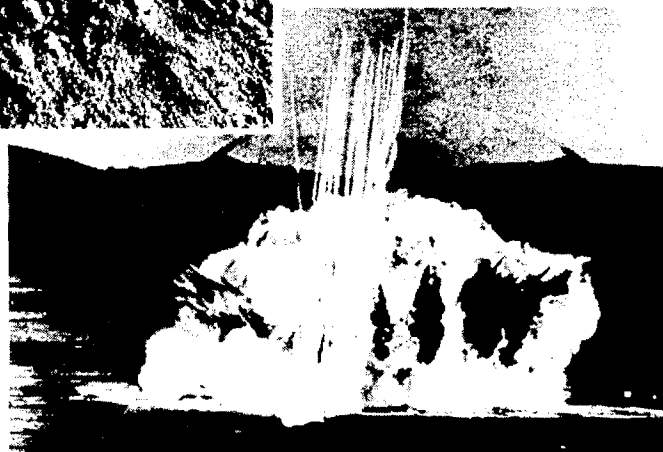
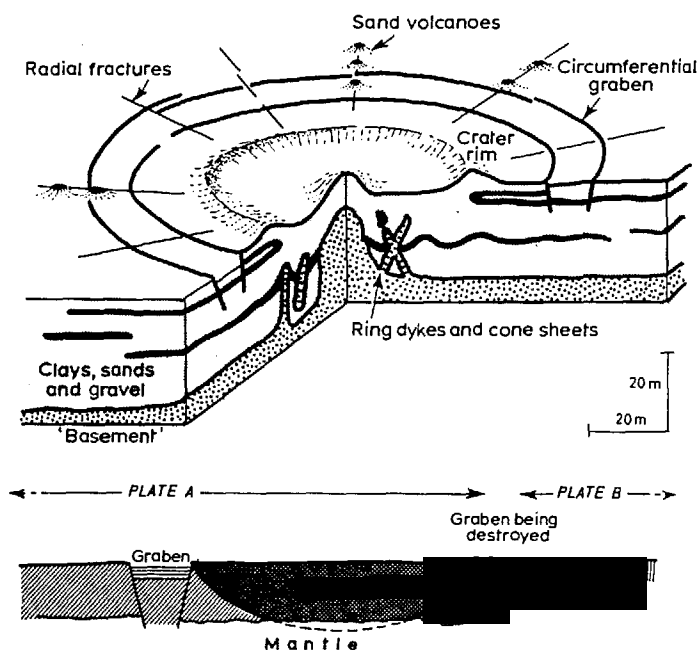
Figure 1 The pock-marked surface of the Moon provides evidence of ancient bombardment. The Earth experienced a similar series of events but the relatively rapid erosion of surface features on our planet has concealed the effects



The explosion below, of 500 tons of TNT, created the 70-m-diameter crater (shown in Figure 2 at top left) on the bed of a dried-out lake. Note the small central rebound uplift and crater rim. (Courtesy Dr G. H. S. Jones and the Defense Board of Canada)

Figure 3 (Centre left) Diagrammatic representation of main structural features revealed by sub-surface exploration of the crater shown in Figure 2. (After Neville Price)

Figure 4 (Below left) Plate collision may result in an astron deflecting crustal material downward as indicated



shown in Figure 2. This was formed by exploding 500 tons of TNT in a series of experiments (reported by G. H. S. Jones of the Canadian Defense Research Board) conducted on flat-lying sediments forming the bed of a dried-up former lake at the Suffield Experimental Station, Alberta, Canada.

The Earth, being larger than the Moon, Mars and Venus, must inevitably have suffered the same bombardment of meteorites but, because of its atmosphere, ancient surface features have disappeared as the result of erosion by wind, rain, rivers, etc. Some craters and events on Earth have already been attributed to meteoritic impact. For example, the Diablo Canyon in America is a geologically recent crater measuring 1.5 km in diameter. Somewhat larger, more ancient, structures have been detected (eg that at Sudbury, Canada) although their origin is still debated. Nothing approaching the size of the Moon's maria has been reported. But we cannot escape the conclusion that, in the past, the Earth must have endured many tens of thousands of impacts from meteorites, and that nearly all of these events involved high expenditure of energy.

What is the maximum impact shock that the Earth can absorb without disintegration? Obviously the Moon has been able to absorb the energy which has resulted in the larger maria. If we take Mare Imbrium and scale it up to the Earth's dimension, we obtain a comparative diameter for a terrestrial feature of the order of 3500 km. One should not, of course, take simple linear relationships between the size of Moon and Earth structures. But, we may certainly anticipate Earth structures resulting from impacts which could approach diameters of 3000 km. By scaling up the dimensions of Jones' experimental results, it follows that a structure of 3000 km diameter would require an

have forced their way up towards the Earth's surface. We have recently also noted, on the much smaller-scale satellite images of the Earth, concentric arcuate fractures in geologically old areas having much larger diameters of tens or a few hundreds of kilometres and at first we could not explain their origin. One cannot conceivably justify scaling up such events as granite or salt intrusion to the required huge size, and we need to look for another explanation. However, it is possible to see apparently similar fractures around some Moon craters and herein lies the clue.

It has been reported that there are more than 300 000 craters of over 1 km diameter on the Moon. Mars and Venus have been bombarded also by a host of meteorites. The kinetic energy of such meteorites is so huge that it generates a shock wave which, in turn, produces the circular crater (see Figure 1). The cross-sectional profile of the smaller craters is identical with the man-made crater

energy of 10^{35} ergs (equivalent to the detonation of a billion-megaton nuclear device). Such energy would be generated by the Earth, moving at its normal speed (approximately 30 km/s) around the Sun colliding with a "stationary" stony meteorite of the size of some of the larger asteroids (diameter 300 km).

The magnitude of the shock wave generated by such an impact would be enormous with a maximum measurable in megabars—ie a pressure only normally encountered in the Earth's core at depths greater than some 3000 km. A pressure wave with such intensity would sweep out from the impact point, deforming and welding the rock particles together and inducing phase changes in minerals. As the shock wave spread out from its impact point it would progressively lose energy until it reached a point where it was no longer able to produce plastic deformation within the rock, but would still have the energy to produce "brittle" fracturing. During the initial compression phase these brittle fractures would form radially to the structure so that if projected inwards they would intersect at or near the impact point. During the elastic rebound that followed the passing of the shock wave an even more significant series of circumferential fractures would be expected to develop. The traces of similar fractures of this type can be seen in Figure 2. They resemble the fractures seen outside craters on the Moon. A most significant aspect of Jones' experimental work is that the craters produced by the explosions were subsequently drilled and excavated to establish the sub-surface structures. (Figure 3). The research demonstrated that the circumferential fractures define a complex trench—a *graben* in geological terminology.

If you take these concepts, coupled with the data obtained by Jones, you would conclude that an event producing an energy at impact of 10^{35} ergs would cause a depression in the crust of between 10 and 20 km beneath which would be a thick unit of plastically welded rock. The thickness of this plastically strengthened rock would be thinnest at the peripheral graben which demarks the zone of brittle fracturing. The graben might be over 200 km wide. The major peripheral faults would cut completely through the crust and the magnitude of down-throw would be several kilometres. Thus, we would have a strong, resistant "disc" of plastically welded rock bounded by a well defined circumferential fracture zone. We are naming such a "disc" an *astron* (an elision of the geological terms *astrobleme* and *craton*, signifying, respectively, an impact crater, and a region of old, consolidated and recrystallised crustal rocks). Taking the Moon as a good indication of the Earth's past history of impacts, we should now search the world for astrons but, first, let us consider their possible appearance.

The fragmentary record

With our climate and present rates of erosion, the crater rim will have disappeared in a fraction of the time since the period when the Moon apparently developed its main craters. The eroded material will have been transported by water or ice, partly back into the craters, and partly into the graben. Later, perhaps smaller meteoritic impacts will have tended to obliterate or obscure the outlines of earlier major impacts, and other well documented causes of geological structural change will have interfered with the simple circular patterns we might expect. New and different types of geological features may have been created above these old stable foundations; sections may have been broken off; and, in other cases, more recent impacts may have welded newer astrons on to parts of older.

The fractures of the graben bordering the astron in some instances must dominate the development of subsequent geography. For example, we suggest that the almost circular bulge of the West African coast marks the graben-defined boundary of one of the Earth's major

astrons. Work with satellite images has shown us that a large arcuate graben full of sediments continues this circle along the line of the Benue River, and that further sedimentary basins align themselves with the circle through Chad, Libya, Mauretania and Morocco. There are interruptions in this circle, but that is not surprising when you bear in mind the complex pattern of overlapping craters seen on the Moon. We suggest that when the processes of plate tectonics opened up the Atlantic Ocean the fractures of the graben, which formed a curved zone of existing weakness, were exploited and so determined the present coast line of the West African bulge. Furthermore, movements inherent in plate tectonics would have reactivated movement elsewhere on the peripheral graben, thereby making possible the development of the Benue, and other, sedimentary troughs.

In some instances portions of such a reactivated astron graben may not be completely filled with sediments but remain as a major depression—as in the westward curving sweep of that part of the Great Rift Valley system occupied by Lakes Tanganyika and Albert. It is interesting to note that this curve centres on the volcano Kilimanjaro, so that the central uplift may also be rejuvenated.

If an astron forms part of a larger migrating continental plate it may greatly modify the trend of major mountain chains which result from this migration. The sediments in the graben at the leading edge of the migrating astron would eventually become deformed and contribute to the development of mountains. It is suggested that an astron showing this effect is the curve of the Peruvian part of the Andes, where South America has a coastal outline reminiscent of West Africa. In eastern Brazil a curved zone of geological features lies on the circle which is defined by the arcuate portion of the Andes. The downward inclination of

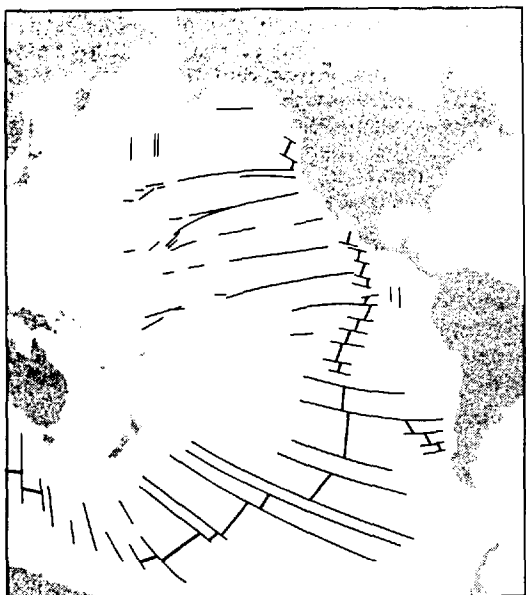


Figure 5 (Left) Note the tendency of transform faults in the Pacific to converge on an area NE of Australia—an area of high gravity anomaly. Figure 6 (Above) Some possible astrons inferred mainly from topographic maps. Those indicated with dashed lines are extremely tentative

the over-riden ocean-floor crustal material (Plate B in Figure 4) beneath this curved portion of the Andes may have been initially influenced by the eastward-dipping fractures of the outer part of the astron's graben; or it may be controlled by the downward curving rim of the astron (Figure 4). In either case, the surface curvature of this inclined zone immediately leads one to suggest that island arcs such as the Aleutians now need examination in the light of their being the outer expression of an astron.

We have noted horizontal displacements along some of the arcuate failures, indicating that astrons may be able to rotate in certain situations (eg during oblique impact with a plate). Nor is it only the faults of the circumferential graben which may undergo renewed movement, for the radiating faults provide extensive planes of weakness which may subsequently be utilised. In this context the Pacific is of interest. For example "transform faults" (see Figure 5) mapped on the Pacific Ocean floor, tend to radiate from an area north-east of Australia, where the world's largest positive gravity anomaly has been recorded. Correlation of this phenomenon with the "mascons" (mass-concentrations), which occur in several of the maria of the Moon, is tempting.

Slow-moving meteorites

A relatively small, but very fast moving, meteorite could completely vaporise on contact. However, slower moving high-density (eg iron) meteorites may penetrate into the mantle (below the crust) and so form a gravity anomaly. Very large and relatively slow moving stony meteorites may penetrate deep into the mantle. Moreover, subsequently, because of their low density, these could slowly rise to form features of the type obtained by the Swedish geologist Hans Ramberg in his classical centrifuge experiments. If the upward migration path of such an embedded body is sufficiently long, the associated flow of mantle material could result in crustal movements comparable with those normally explained by plate tectonics.

There appears to be a fascinating geological task ahead in trying to solve a mainly concealed jig-saw puzzle consisting of incomplete pieces of different ages. However, we suggest that any large-scale crustal feature which exhibits an arcuate outline is deserving of special scrutiny—for example, the curve of the coast of China, the curved mountainous coast of eastern Australia, and the magnificent sweep of the Himalayas bordering northern India. Smaller-scale versions exist bordering the southern parts of the Caspian and Black Seas, and eastern Korea. We must also

think of examining concave arcuate coasts such as the Gulf of Mexico or the Great Australian Bight. These and other possible astrons are indicated in Figure 6.

For geologists the concept outlined above has implications of a more specialised nature. These include the development of the still enigmatic mantled gneiss domes. We have noted the relationship between astrons and mineral deposits (particularly uranium), and oil fields in areas where astron-grabens have been rejuvenated and filled with post-Carboniferous sediments (younger than 300 million years). Thus the astrons could provide a strategic guide to prospecting.

It is possible that most major impacts occurred in Early Pre-Cambrian times more than 3000 million years ago. However, lunar scientists now believe that quite large impacts have left their mark on the Moon more recently. For example, they have suggested that the craters Copernicus and Tycho formed 900 and 100 million years ago, respectively. One must anticipate that the Earth has also received its quota of high-energy impacts since Pre-Cambrian times (in the last 600 million years) and although these events need not have been sufficiently energetic to induce the development of astrons, they could nevertheless be of vital importance. Oceans and seas cover two-thirds of the Earth's surface so that, in all probability, some of the larger meteorites to reach the Earth since Pre-Cambrian times have fallen in deep water. The resulting shock wave would have destroyed marine life forms over a wide area; while the resulting "king-size" tsunami, or tidal-wave (possibly as high as 3 km), would have caused widespread havoc among terrestrial life forms in adjacent low-lying coastal areas. The steam, water vapour and dust generated by the impact would have risen into the upper atmosphere and influenced the world's weather for a considerable period. Indeed, it is not inconceivable that a sufficiently large impact could have induced the onset of an ice age. Furthermore, the impact may have severely modified the Earth's magnetic field—even causing a change in position of the magnetic pole.

The combined effect of such an event: instant destruction of life over a wide area, the possible modification of climate and of terrestrial magnetism (and therefore of the radiation-trapping Van Allen Belts) have obvious implications regarding the subsequent evolution of life forms on Earth. One is tempted to suggest that the demise of the dinosaurs could have been decided by a relatively small cosmic "catastrophe"—and even that mankind could suffer the same fate! □

The world is a bit cracked!

Satellite pictures of the world are now revealing huge crustal fractures showing evidence of its past history and possible locations of sources of minerals and thermal energy

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Muo Chukwu-Ike is doing postgraduate research at Imperial College, London

For several decades geologists have been looking down on the world with the aid of air photographs. One of the major advantages of this high viewpoint is the ease of detecting steeply inclined rock fractures, sometimes even where glaciers have moved material to cover them. Specialised studies of the fracture patterns are helping some photogeologists to detect concealed structures that might

contain oil, water, or intrusive rocks related to economic minerals. A lesson from these studies has been that the scale of the photography used is closely related to the size of the features detected. Doubling the flying height of an aircraft halves the scale of photography, and each photograph then covers four times the area. In this greater area large features can be better sensed in their setting, so we began to look forward to the results of reducing the scale by two orders when US generosity made available the products of imaging devices scanning the Earth from satellites.

Literature on the new, bigger and better fractures (showing as lineaments) has grown into a torrent, but although many accompanying diagrams show patterns that cry out for interpretation, there are surprisingly few explanations that extend beyond local interest. We report here an interesting pattern from one area with our own very speculative interpretation. We hope unconvinced readers will produce practical alternatives for *New Scientist's* correspondence columns.

Figure 1 shows one of a number of sets of parallel lineaments in Nigeria revealed by the multispectral scanner carried by NASA's LANDSAT spacecraft. Most geologists will be surprised that there should be such a long, parallel, closely and regularly spaced system, and that all the lineaments should be so uniformly straight over such lengths. The spacing is of the order of the thickness of the Earth's crust. In the field only vertical movements are detectable along these lineaments (fuller details will be published by us in the February 1977 issue of the *Transactions of the Institute of Mining and Metallurgy*). Two other less continuous sets cross these meridional lineaments at 45°. Unlike the first set these show horizontal shearing, displacing the first set by up to several kilometres in places. These directions show the type of failure pattern that would be caused by a horizontal principle compressive stress in an east-west direction (σ_1 in Figure 2).

But what huge stress could cause such a regular pattern of straight failures, each hundreds of kilometres long? Perhaps the near-meridional orientation is a clue and the force may have been related to the Earth's spin.

A cosmic near-miss?

As a tentative explanation we suggest the cause as a change of the Earth's speed of rotation due to a near miss by, or an oblique impact with, another large cosmic body, with consequent inertial effects tending to wrinkle the crust. It must be remembered that the Earth's crust is relatively thin—of the order of one hundredth of the radius. The crust instead of bending failed along the lines of the incipient wrinkles. It now shows zones of brittle and ductile failure along the meridional lineaments. The ductile zones, produced where the constraining pressure was

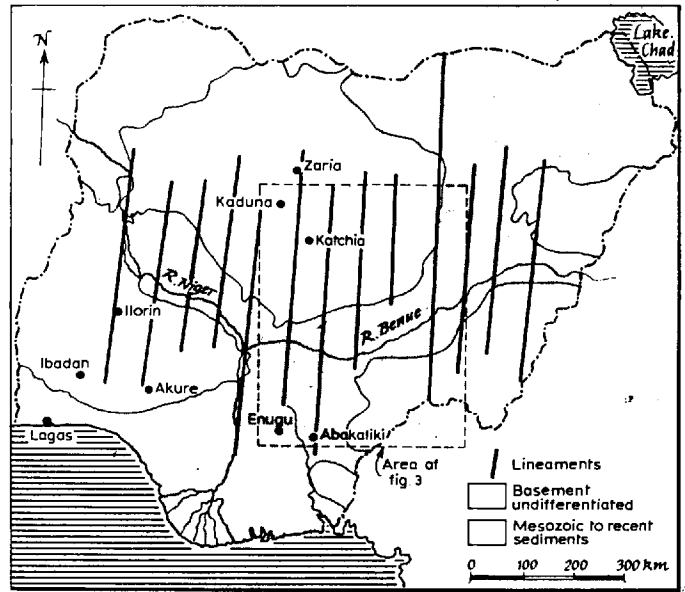
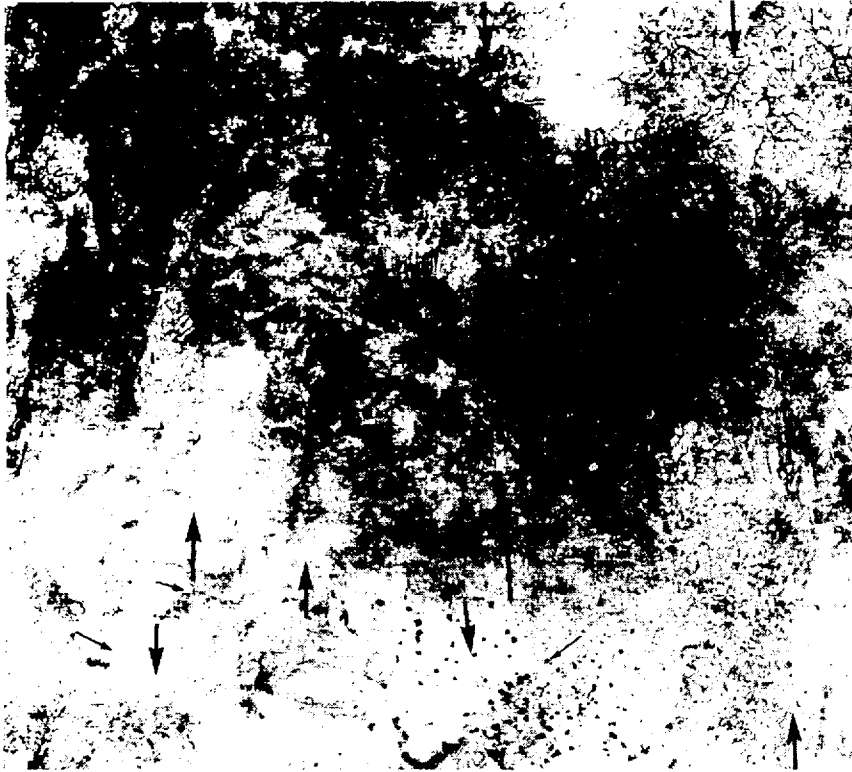


Figure 1 One of a number of sets of long lineaments in Nigeria believed to have been caused by crustal failures over 500 million years ago

greater, were presumably originally deeper in the crust beneath the zone of brittle failure, and have been exhumed by erosion. We suspect that the formation of the meridional system represents one geological episode, and that the shearing may have occurred contemporaneously in terms of geological time.

Dating the dramatic episode that caused it all is difficult. Although the failures show through a surface layer of Mesozoic rocks, and would therefore at first sight appear younger, these formations seem less disturbed along the lineaments than rocks of the old underlying Pre-Cambrian basement which is exposed in other parts of Nigeria. It is likely that the fractures were formed in the basement rocks and were later propagated up through the younger sediments by seismic events, earth tides, or some other phenomenon. The failure zones have provided easy paths for upward movement of bodies of igneous rock, and the lineaments now show as connecting lines of intruded granitic rocks associated with tin deposits, volcanic rocks, hot brine springs, and base metal deposits (Figure 3). Granites, rising in molten form from depth through other rocks because of their relatively low density, can contain valuable metals. In a late stage of cooling, these may stream out in a transport system of volatile fluids, settling in fractures to form veins, or reacting with the invaded rock, to form ore deposits in the vicinity. The hot granite, a potential source of thermal energy, can also act as a heat pump, convecting water and brines from marine sediments (see arrows in Figure 4). These can scavenge base metals from the sediments and concentrate them in zones above or adjacent to the intrusion. Thus the lineaments seem to make good strategic prospecting targets for a variety of minerals and thermal energy. They can also play an intimate role in the formation of sedimentary basins with "drape folds" and arched up folds arranged *en echelon* that are of considerable interest to oil exploration teams as potential oil traps.



You need sharp eyes to spot the Nigerian lineaments (arrowed) on this LANDSAT picture. They are part of the set shown in Figure 1

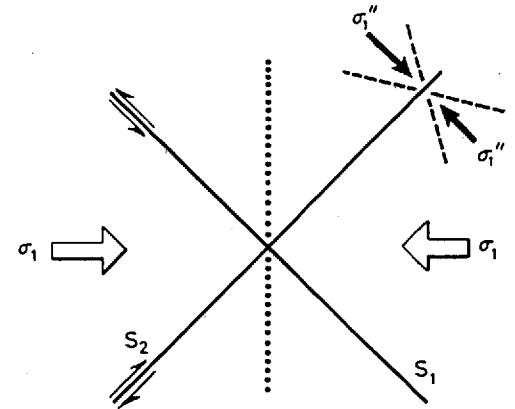


Figure 2 Diagram of the angular pattern of the old fractures in Nigeria. Dotted line represents features shown in Figure 1, and σ_1 the principle compressive force likely to have caused them. After first-order shearing (eg S_2) there will be a component of σ_1 across the failure (σ_1'') which may generate a system of secondary fractures

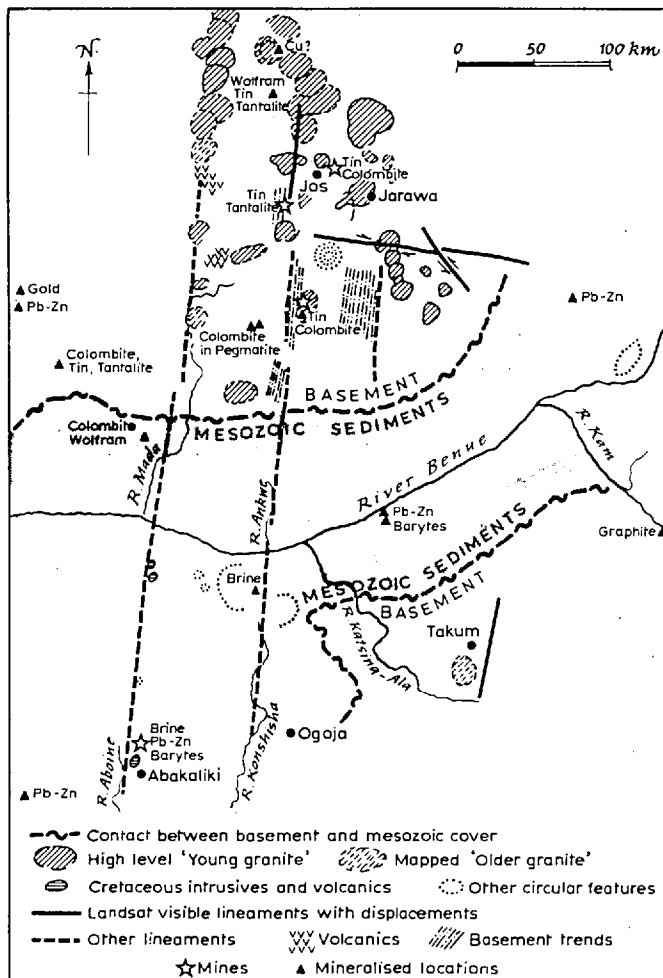


Figure 3 Enlargement of the boxed area of Figure 1, showing how the old crustal failures were penetrated by rising granites. A portion of only one shear failure is shown. Readers may like to guess where others are from the pattern of intrusives. Dotted circular features may be subsurface intrusive rocks

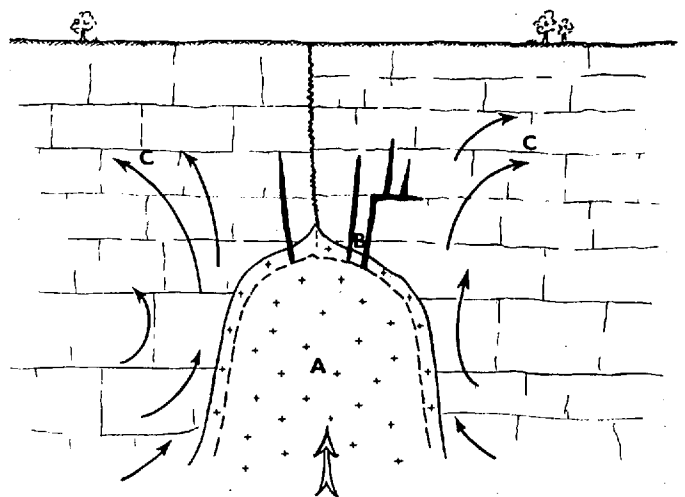


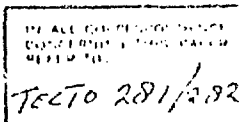
Figure 4 How a hot granite (A) intrudes other rocks, forming a hard outer shell that bottles up volatiles. These later stream out through fractures (B) filling them with veins of tin, tungsten, copper etc. The hot granite also convects water and brines in sediment fracture systems, which scavenge dispersed base metals and deposit them in the vicinity (C)

For some 15 years the photogeology group at Imperial College has been investigating smaller fracture traces showing on air photographs, and using them to resolve regional and local anomalous stress patterns to help detect these types of mineral deposits and potential petroleum reservoir structures. It is now fascinating to find that at least in some areas we can see the larger overall framework into which they fit. Consider the situation of a crustal shear such as S_2 in Figure 2. After failure there may be movement along the failure surface, but there will now be a component of the σ_1 force normal to the surface (σ_1 on Figure 2). This stress may generate a second order of failures which, in turn, may cause a third order of smaller failures, and so on. However, the fractures belonging to the lesser orders may be small enough to exist in individual rock types, and the angle between the shear failures now differs in various situations. There are other forms of secondary failures but we have been able to cope with these using a combination of human interpretation, computer, and optical image analyses. Deflections in regional stress trajectories deduced from air photographs are now seen to coincide with these visible traces of deep horizontal shear failure showing on pictures from satellites. Within the overall pattern we have used statistical treatment to detect the local mechanical effects of intrusive rocks, local folding, and settlement of rocks over resistant features—but one always feels that there is more that could be inferred from the chaos of data. The satellite pictures will

now give us vital parts of the jigsaw puzzles.

From experience with such types of studies we are surprised to find that the major meridional lineaments in Nigeria remain parallel and straight in the south where they approach the African coast. It seems that they could predate the break when South America separated from Africa and drifted westward. Reported dating studies of intrusive bodies of igneous rock now seen to be along the lineaments show that they reach back to 540 ± 20 million years ago, compared with the approximately 180-million-year age of the break-up of the former supercontinent. There are also some intrusive bodies along the lineaments which show this latter date, indicating disturbance of these old fractures at the time of break-up. We have examined some images of the eastern part of Brazil, believed to have previously fitted alongside Africa, and find a similar style of major fracturing including some unusual arcuate major fractures which we are still studying. These parallel systems of old crustal failures may be more widespread than has been realised—there are subtle but definite indications that the tin-bearing granites in Cornwall are associated with a north-west trending set showing through the surface cover of sedimentary rocks.

If our guess is correct, we now have a measure of orientation change of some old shield rocks. Thus Nigeria is only 8° from its position relative to north 520 million or more years ago, but the orientation of Brazil has changed about 52° . □



AUTHOR

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Discussion

A CRUSTAL SUTURE AND LINEAMENT IN NORTH AFRICA --- DISCUSSION

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(Received October 6, 1976)

Nagy, Ghuma and Rogers in a recent publication in *Tectonophysics* (1976, vol. 31) suggested the presence of a crustal suture and lineament spanning Africa from the Niger delta to the Nile delta. They based their evidence on the chemical analyses of the Pan African (600 ± 100 m.y.), Ben Ghnema batholith and on topographic configurations of sedimentary basins. They also suggested a direction of growth of some African cratons and that the "trans African" lineament had been topographically negative since the Phanerozoic. It is felt that the text contains basic errors of facts at least within the Nigerian portion of the proposed lineament and suture.

DEFINITIONS

Sutures, according to the plate-tectonics model, are lines along which two previously distant continental crustal plates have been welded together. Sutures are recognized by ophiolites, structural mismatches on the previously distant plates, suboceanic crusts and deep-sea sediments.

mismatches

Lineaments are significant lines on the earth's surface of "a precision which rules out fortuity" (Broek, 1957). Though lineaments manifest themselves as linear alignments of vegetation, topographic changes, streams and fractures, their causes are in doubt. Except where geophysical evidence indicates deep tectonic origin, it is often difficult to differentiate lineaments resulting from deep seated tectonic causes from those of a more extrinsic nature.

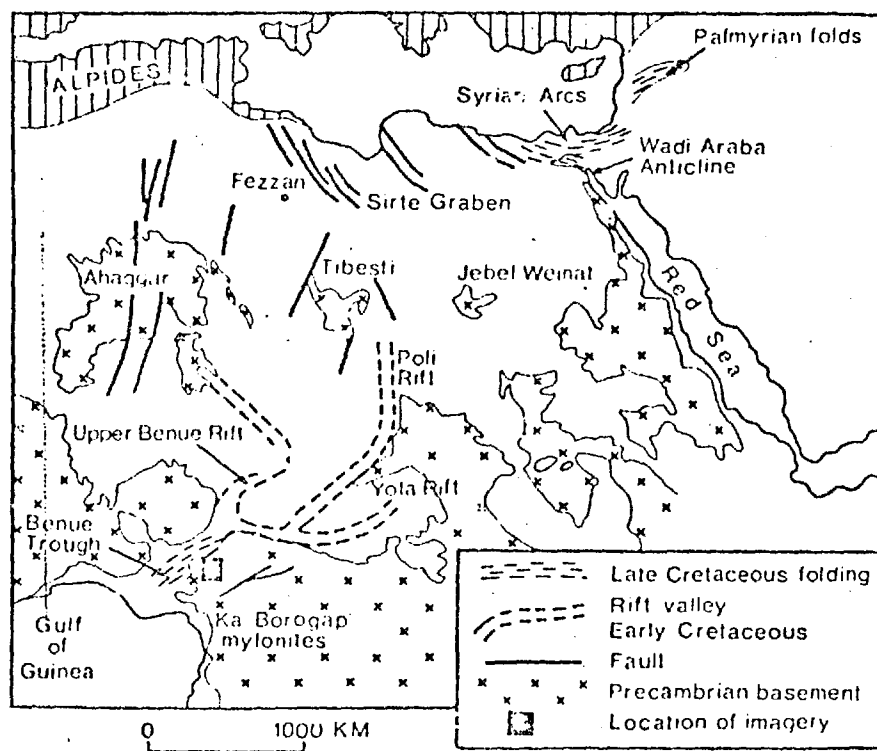
SOME SERIOUS ERRORS OF FACTS

(1) Within Nigeria, metasediments having similar structures and metamorphic grade occur on both sides of the Benue trough though rarer in the south-eastern side of the trough. The belts of tin mineralization generally considered Jurassic in age are known on both sides of the trough. Lineaments can be traced from one side on to the other while basement trends are nowhere different both within and outside the trough (Wright, 1976).

There is no evidence of structural mismatches on both sides of the trough.

(2) Nagy et al. (1976) also stated that their proposed "trans African" lineament has been topographically negative since the Phanerozoic. It is clear that Palaeozoic sediments, known to occur in Northern Africa do not exist in Nigeria and the Cameroons. Black and Girod (1970) suggested that the absence of Palaeozoic sediments in Nigeria and the Cameroons might mean that they formed an emerged landmass in the Palaeozoic and early Mesozoic times. It is not clear where they based their argument for the negative topographic expression of the suggested line since the Phanerozoic.

(3) It was also argued by Nagy and others that the proposed lineament is one of the few sections in the African continent that does not encounter any Precambrian outcrop. There is hardly any truth in that statement. Geological mapping within the Benue trough (Carter et al., 1963), has indicated some Precambrian inliers (e.g., the well known Kaltungo inlier N 9° 10', E 11° 20'). It is also known that the Benue trough is floored by continental crust, and that the trough strictly speaking, peters off in a NE direction (Olade, 1975).



After Burk and Dewey, 1974

Fig. 1. Major structure and distribution of Precambrian rocks over North and West Africa.

Not in Reference Structures

THE DIRECTIONS OF CRUSTAL GROWTH IN AFRICA

The direction of crustal growths as suggested by Nagy and others during the Precambrian times is open to argument. They admitted that the nature of the Pan African 600 ± m.y. is in doubt. They also admitted that there are widespread 1600 m.y. ages in the Ahaggar and ages from 1300 m.y. to 500

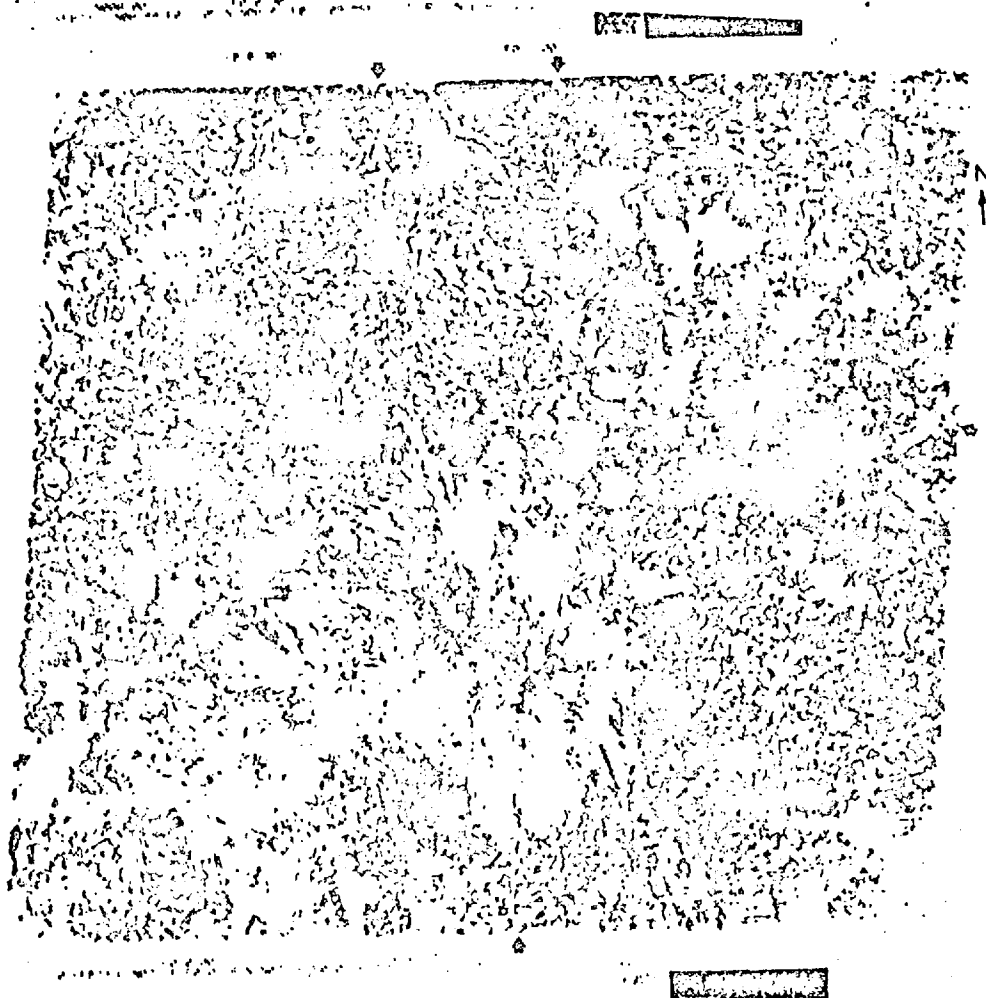
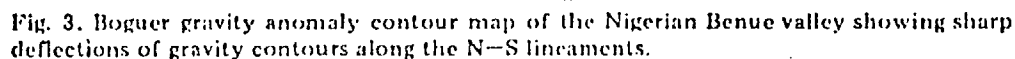


Fig. 2. A Landsat image of lineaments within the Basement and Southern part of the Benue Trough (location shown in Fig. 1). Legend: *e* = en-echelon marginal fractures of the Benue trough, *c* = Cretaceous sedimentary cover, *B* = Precambrian rocks, *v* = volcanics, *f* = foliation, *h* = NW-trending lineament.

BENUE VALLEY



SOME RELEVANT INFORMATION

The proposition of major lineaments of that nature based on limited information and hardly any geophysical evidence tends to be too subjective and should be discouraged. Geophysical work over the Benue trough indicates some crustal attenuation (Cratchley and Jones, 1965). Nearby Nigerian "Younger Granite" suites are controlled by major N-S fracture zones (Wright, 1970). There has been serious objections to the "open and close" hypothesis associated with the plate-tectonics model of the Benue trough (Olade, 1975; Wright, 1976). Salient geological evidence does not support the existence of suture (Carter et al., 1963). Major regional geological features known do not support the existence of this suture and lineament (Fig. 1). The major regional features known are curved lineaments and rifts.

LANDSAT imagery interpretation indicates the presence of major near-midridional lineaments on both sides of the trough. One such lineament, *L*, is seen in Fig. 2 covering parts of the Benue trough and the southern basement. ~~Though~~ marginal left-handed en-echelon tectonic lineaments, *e*, are seen close the Cretaceous cover contact with the basement *CB*. These lineaments have been field checked and confirmed as major fractures and shatter belts. The en-echelon fractures are interpreted as resulting from stress and strains re-orientations along the major N-S shatter belts. One other lineament, *h*, which has been traced to the "Younger Granite" province some 500 km to the NW is also shown, as well as foliation trends, *f*, and volcanics *V*. This satellite image represents about 180 km on each side.

The intersection of the N-S lineaments with the Benue trough is marked by strong deflections of the Bouguer gravity contours (Fig. 3). The Benue trough and the Cameroon volcanic line appear to be connected by N-S lineaments and not by NE-SW structures, on satellite photographs. These connecting lineaments parallel the lineaments controlling the "Younger Granites" of Nigeria.

REFERENCES

- Black, R. and Girod, M., 1970. Late Palaeozoic to Recent igneous activity in West Africa and its relationship to the basement structure. In: T.N. Clifford and I.G. Gass (Editors), African Magmatism and Tectonics. Oliver and Boyd, Edinburgh, pp. 185-210.
- Brock, B.B., 1957. World patterns and lineaments. Trans. Geol. Soc. S. Africa, 60: 149-197.
- Carter, J.D., Barber, W. and Tail, E.A., 1963. The geology of parts of Adamawa, Bauchi and Bornu Provinces in northeastern Nigeria. Geol. Surv. Nigeria Bull. No. 30.
- Clifford, T.N., 1970. The structural framework of Africa. In: T.N. Clifford and I.G. Gass (Editors), African Magmatism and Tectonics. Oliver and Boyd, Edinburgh, pp. 1-2.
- Cratchley, C.R. and Jones, G.P., 1965. An interpretation of the geology and gravity anomalies of the Benue Valley, Nigeria. Overseas (Britain) Geol. Surv. Geophys. Paper No. 1.
- Hubbard, F.H., 1975. Precambrian crustal development in Western Nigeria: Indications from the Iwo region. Geol. Soc. Am. Bull., 86: 548-554.

Burk, K. and Dewey, J. F., 1974, Evolution of the Benue Trough, Nature, 249: 313-315

- McCurry, P., 1973. Geology of Degree sheet 21, Zaria, Nigeria. Overseas Geology and Mineral Resources No. 45, 45 pp.
- Nagy, R.N., Ghuma, M.A. and Rogers, J.W., 1976. A crustal suture and lineament in North Africa. *Tectonophysics*, 31: T67-T72.
- Olade, M.A., 1975. Evolution of Nigerian Benue Trough (Aulacogen) — a tectonic model. *Geol. Mag.*, 112(6): 575-583.
- Oyawoye, M.O., 1965. The Geology of the Nigerian Basement Complex — A survey of our present knowledge of them. *J. Min. Geol. (Nigeria)*, 1: 87-102.
- Wright, J.B., 1970. Controls of mineralization in the Older and Younger tin fields of Nigeria. *Econ. Geol.* 65: 945-951.
- Wright, J.B., 1976. Origins of the Benue trough. In: C.A. Kogbe (editor), *Geology of Nigeria*. Elizabeth Publ. Co., Lagos, Nigeria, pp. 309-317.

A CRUSTAL SUTURE AND LINEAMENT IN NORTH AFRICA — REPLY

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We would like to thank Dr. Chukwu-Ike for contributing his ideas concerning the Nigerian area of our proposed lineament (Nagy et al., 1976). Our comments listed below essentially follow the sequence of statements in his discussion.

(1) Although we recognize that the occurrence of ophiolites and deep-sea sediments is strong, but not entirely diagnostic, evidence of former oceanic crust, we do not feel that their absence among present surface exposures is proof that a continent-ocean plate margin could not have existed at some time along the Benue trough.

(2) The paper by Wright (1976) referenced by Dr. Chukwu-Ike is not available to us at present, but we have consulted his earlier papers concerning the history of the area around the Benue trough (Wright, 1968, 1970). One of the most significant problems with respect to the Pan African orogeny in general is the question of whether or not an immobile continental crust existed across the belt during the orogeny. The best evidence for the existence of such a crust is the ability to correlate lithologies, structures, paleomagnetic orientations, etc. across the belt. Obviously, the features correlated must have formed prior to Pan African time, and in general, the nature of these correlations is in doubt. In regard to the Benue trough, the existence of such a correlation would not only weaken the argument for a Pan African suture but would also cast great doubt on the argument for a Mesozoic opening and closing of the rift proposed by Burke et al. (1971). We have not