TECTONIC SETTING AND STRUCTURAL ANALYSIS IN SOUTHEASTERN PART OF MARU SCHIST BELT, SHEET 53 MARU SE, NORTHWESTERN NIGERIA

BY

JUNGUDO, SALIHU MOHAMMED

DEPARTMENT OF GEOLOGY
FACULTY OF PHYSICAL SCIENCE
AHMADU BELLO UNIVERSITY ZARIA
NIGERIA
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DECLARATION

I declare that the work in this thesis titled **TECTONIC SETTING AND STRUCTURAL ANALYSIS IN SOUTHEASTERN PART OF MARU SCHIST BELT, SHEET 53 MARU SE, NORTHWESTERN NIGERIA** has been carried out by me and in the Department of Geology, Faculty of Physical Science, Ahmadu Bello University, Zaria. The information derived from the literature has been dully acknowledged in the text and the list of references provided. No part of this thesis was previously presented for another degree or diploma at this or any other institution

JUNGUDO, SALIHU MOH'D
Name of student

Signature

25/08/2018
Date

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CERTIFICATION

This thesis titled **TECTONIC SETTING AND STRUCTURAL ANALYSIS IN SOUTHEASTERN PART OF MARU SCHIST BELT, SHEET 53 MARU SE, NORTHWESTERN NIGERIA** by Jungudo, Salihu Mohammed meets the regulations governing the award of degree of master of science in Geology of Ahmadu Bello University, and is approved for contribution to knowledge and literary presentation.

Dr. A.A. Ibrahim		27/08/2018
Chairman, supervisory committee	Signature	Date
Dr. I.Y. Abubakar		28/8/18
Member, supervisory committee	Signature	Date
Dr T. Najime	DEPT. OF GEOLOGY SIGN DATE	29/08/2018
Head of Department	Signature	Date
Dean, School of Postgraduate studies	Signature	Date

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DEDICATION

To my Late Father, Alhaji Mohammed Jungudo.

ABSTRACT

The Maru belt is one of the schist belt located in NW Nigeria that exhibits complex structural patterns as a consequence of poly metamorphism. The structural geometry of the rocks within the study area has been investigated by analysis of different structural elements from mega, meso, to micro scale using satellite imagery, fieldwork and photomicrographs respectively. The study reveals that the area encompasses the imprints of lineaments and multiple phases of folding. The extracted lineaments reveal a NNE – SSW trend reflecting early Pan – African Orogeny and exhibits some uniform breaks indicating E – W fault/fracture lines. The first generation folds (F_1) though very rare are light, isoclinal or reclined. The second generation folds (F_2) are light to open, isoclinal and co-axial with the F_1 folds. The widespread nature of folds controls the structural configuration of the Dan-Zara and Yar'awala hill antiforms which were formed during E – W compressional episode of the Eburnean Orogeny. The third generation folds (F_3) are open and appear in form of synform around Dan-Jukku village (Dan-Jukku synform), reflecting the late Pan-African Orogeny (NE – SW). The rocks of the study area show heterogeneity in the bulk strain and the orientation is essentially concordant to the metamorphic deformation connected with the latter but brittle Pan – Africa and predominantly NE – SW fracture system. At least three deformational episodes have been identified in the Maru belt corresponding to D_1, D_2 and D_3 structures.

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CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND TO THE STUDY

Nigeria, lies within the vast Pan-African (650±150 Ma) mobile belt, which separates the West African and Congo Cratons (Kennedy, 1964; Wright *et al*., 1985); it is well endowed with metasediments within its basement complex (Fig. 1.0). Based on available data the metasediments are classified as; "Ancient metasediments" and "Younger Metasediments" (e.g., Rahaman, 1976; 1988; McCurry, 1976; Rahaman and Ocan, 1978). The "Ancient Metasediments" consist of calc-silicate rocks, arkosic quartzites and high grade schists that occur as lensoid relicts in regional gneisses or as paleosomes of migmatites, and are the oldest rock types in the basement of Nigeria. The "younger metasediments" are found in both the western and eastern parts of the country especially in the Oban massif (Ekwueme, 1987). In the western half of the country, they occur as discontinuous N-S trending schist belts within the basement. They have been variously termed the "Newer Metasediments", (McCurry, 1976 and Rahaman, 1976), and "rocks of the schist belts" by (Ajibade, 1976 and Turner, 1983).

The Nigerian schist belts are highly deformed mineralized and formed a major diversified lithostratigraphic unit of the Precambrian Basement Complex. Most of the earlier works on the Nigerian schist belts were concentrated on regional geology, structural grain and economic mineralization. There are more than twelve of such schist belts and they include Birnin Gwari, Kushaka, Malumfashi, Kazaure, Wonaka, Maru, Anka, Zuru, Toto, and Iseyin-Oyan River, Ife-Ilesha, Igarra belts (Ajibade 1976; Turner, 1983; Danbatta, 1999) (Fig. 1.1). There are convincing evidence of similarities in structures, lithologies and metamorphism between the Nigerian schist belts (Danbatta, 2001). In recent years, much attention has been

given to the evolution of the schist belts (Annor, 1995; Adekoya, 1996; Olabaniyi, 1997 Annor *et al*., 1998 and Danbatta, 1999; 2001; 2003a).

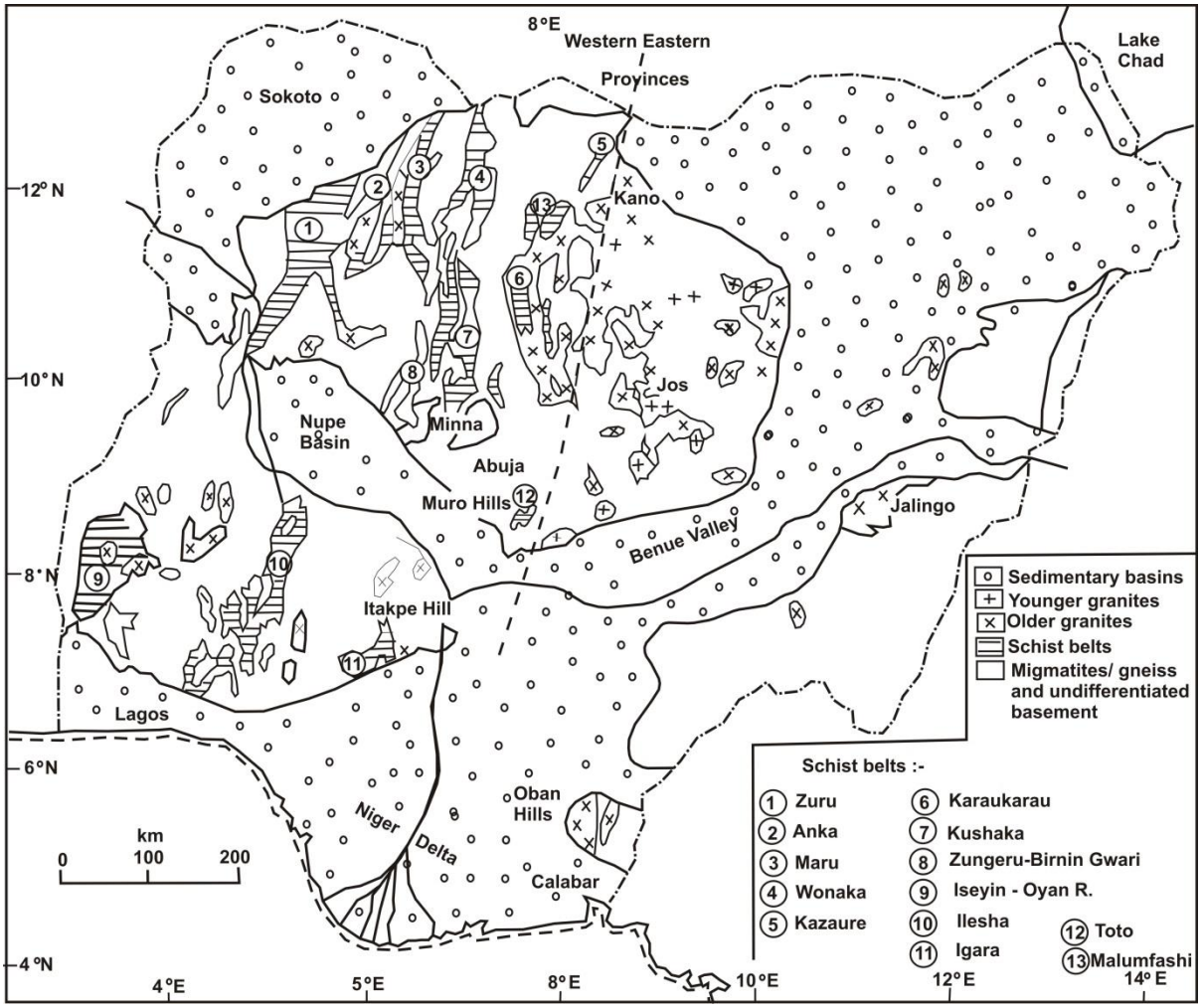


Figure 1.1: Geological Map of Nigeria showing the schist belts: 1-Zuru, 3-Anka, 3-Maru, 4-Wonaka, 5-Kazaure, 6-Karaukarau, 7-Kushaka, 8-Zungeru-Birnin Gwari, 9-Iseyin-Oyan, 10-Ilesha, 11- Igarra, 12- Toto, 13-Malumfashi (modified after Ajibade *et. al*., 1987).

1.2 LOCATION AND ACCESSIBILITY

The study area which is a part of Maru schist Belt lies within the northwestern Nigeria crystalline basement complex. It is bounded by latitude 12° 00″ N and 12° 15″ N and longitude 6º 15″ E and 6º 30″ N (Fig.1.2) in Zamfara State, Nigeria. The area is traversed by a trunk (A3) Zaria – Funtua – Gusau –Sokoto road running roughly NW. Much of the area is

accessible via a few tar-macked roads which in turn lead to other minor laterite motorable roads. Numerous cattle tracts link up with all these roads. Most of the minor laterite roads are seasonal as they become inaccessible during the wet season.

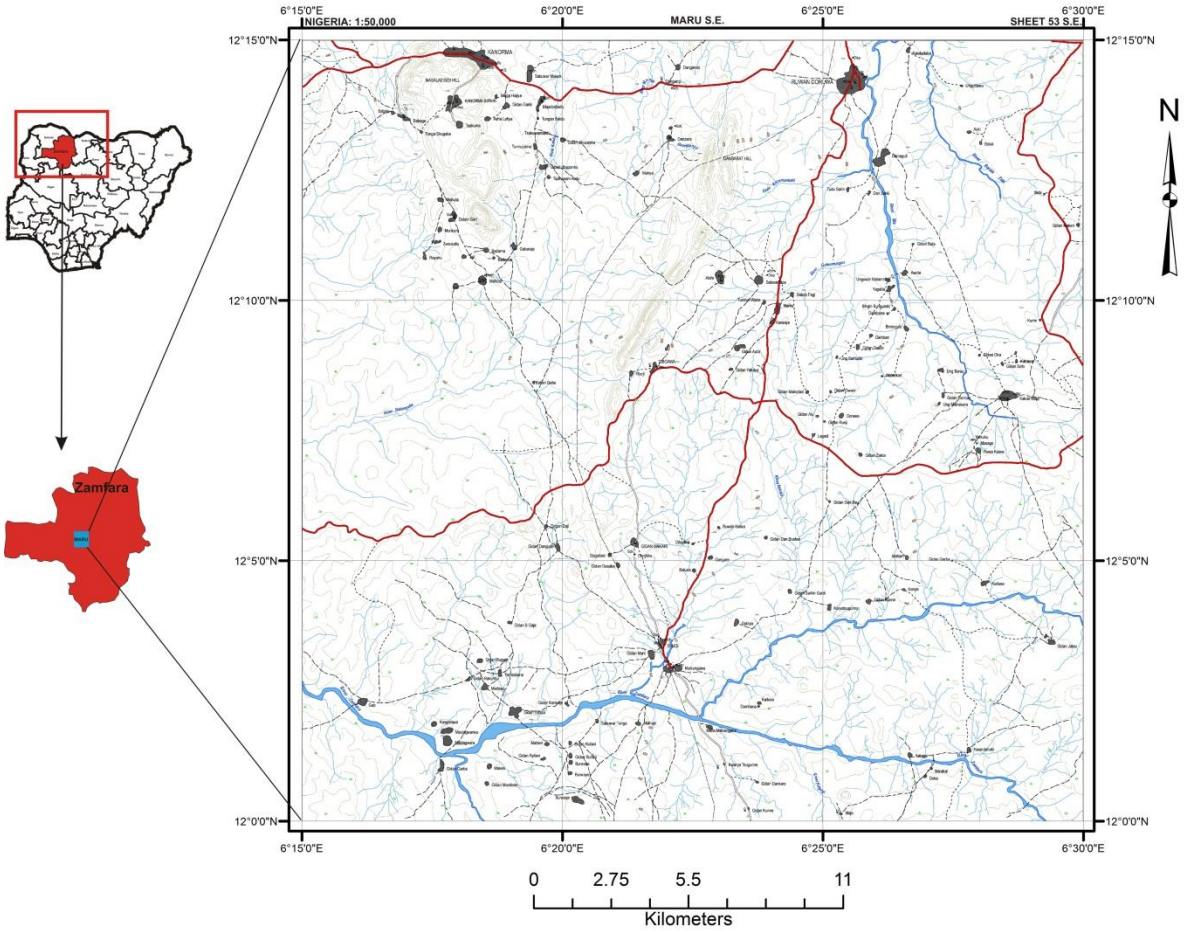


Figure 1.2: Sketch Maps of Nigeria showing NW zone, Zamfara state and the study area

1.3 CLIMATE AND VEGETATION

The area of study has tropical Savannah climate with distinct wet and dry seasons. The rainfall is concentrated in the short wet season, which extends from late April to September with mean annual precipitation of about 450 – 550 mm, whilst the dry season lasts for over seven months; October to April being particularly dry. Day time temperatures are generally high usually, 30º – 40º C except during the Harmattan and result of rapid transpiration, the nights are very cold.

1.4 RELIEF AND DRAINAGE

The area is generally an elevated plain rarely exceeding 460 meters above sea level. Commonly, the undulating topography is broken by the spectacular ridges of the metasedimentary units of the Maru Formation. The isolated hills of quartzite, granite and gneisses give the area a rugged landscape.

The area is well drained by numerous rivers and streams. The underlying geology appears to control the drainage pattern. River Zamfara is the major river in the area and it traverses the southern part of the Maru (SE) belt in an E – W direction. Tributaries of the River Zamfara include Baban Gebe, Kulgagi, Bakura and Kadusa; while the northern part is drained by River Gagere (Fig. 1.3).

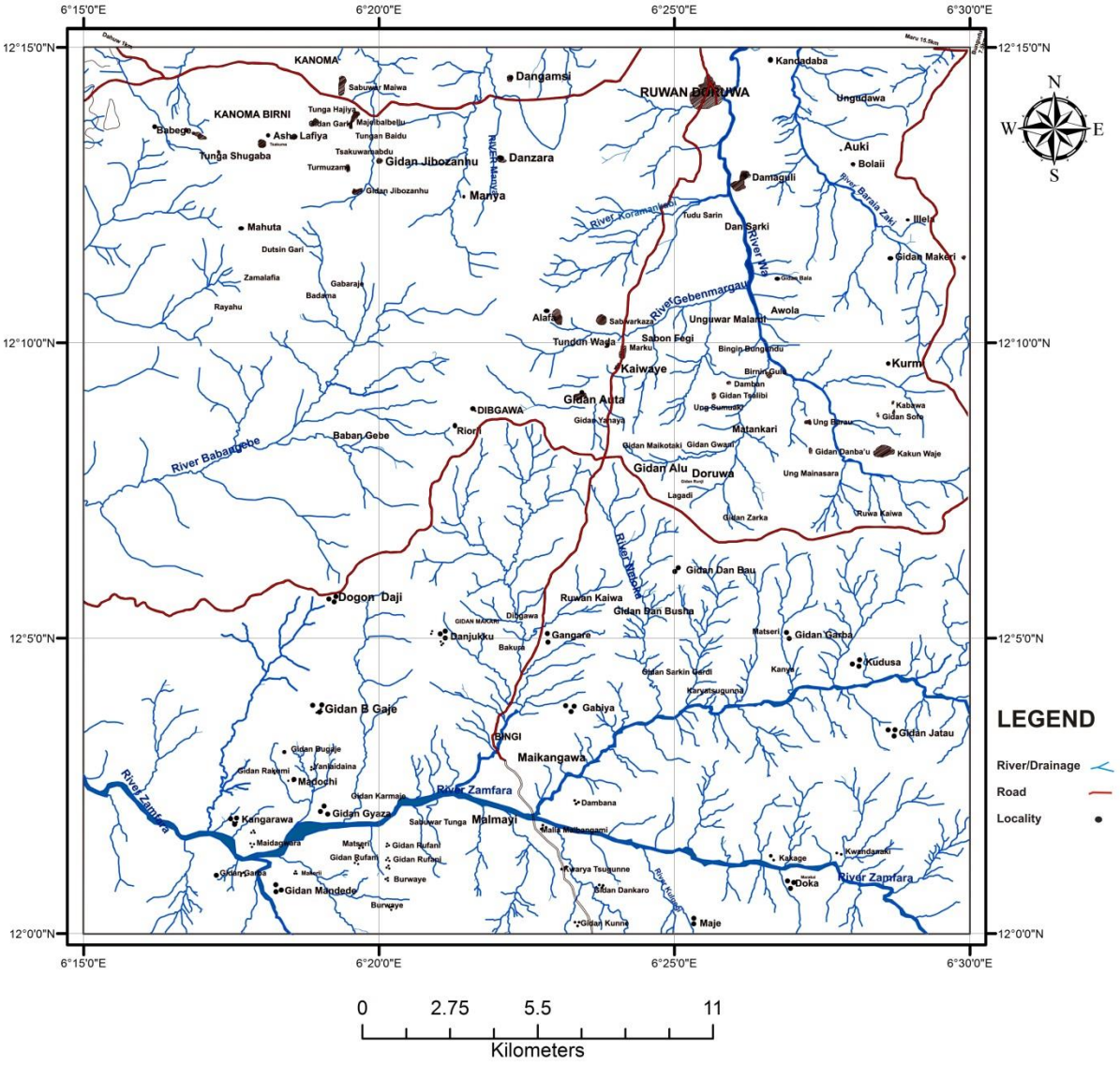


Figure 1.3: Drainage of the study area

1.5 STATEMENT OF RESEARCH PROBLEMS

Egbuniwe (1982) summarized the lithologies and models suggested for the evolution of other well-known schist belts in northwestern Nigeria and interpreted the Maru Belt as a pre- or early Kibaran ensialic basin formed as a result of crustal extension and vertical movements caused by mantle diapirism. The Nigerian Basement Complex evolved through polyphase tectono-metamorphism, during Liberian (2700±200 Ma), Eburnean (2000±200 Ma) and Pan-African (600±150 Ma) orogenesis (Grant, 1970; Ajibade *et al*., 1987; Dada 1998). Ibrahim (2010) considering the lithological association of the BIF in this study area, it may be said that the Maru Schist Belt dates back to the Paleoproterozoic, since it has been shown that BIF are restricted to the above age groups and that they do not have modern analogues.

The only strain analysis of the entire Maru Belt was carried out on deformed pillow lavas which occur in the River Sokoto, on the western limb of the Geben Ture Synform. It is doubtful whether the strain data obtained from this locality represent typical strains over the whole belt (Egbuniwe, 1982).

1.6.1 Research questions

i. What is the magnitude and orientation of the strain in the southeastern Maru schist belt? Did the strain correlate with the strain analysis carried out on the western limb of the Geben Ture Synform by Egbuniwe, (1982), thus reflecting that of the Schist belt entirely?

ii. What is the character of the D_3 deformation? Is the character in line with the regional trend or is it locally deformed?

iii. Does the tectonic evolution of the study area correlates with the model proposed by Egbuniwe (1982)

1.6 SCOPE OF THE STUDY

This research work is limited to the structural and petrographic analyses of rock types of the area. These analyses are carried out through remote sensing, field mapping and laboratory analysis of rock samples.

1.7 AIM AND OBJECTIVES

The aim of this research work is to study the geology i.e petrography, tectonics, structural framework with view to establish relative ages of the deformational fabric.

The specific objectives are to

i. Determine the style of deformation and the geometry of mega, meso and micro scale structures in the area.
ii. Study the deformation pattern of the area through strain analysis.
iii. Carry out joint analysis by measuring the density and orientation of joints
iv. Delineate linear (major) structures using remote sensing
v. Undertake detailed petrographic description of the various rock types

CHAPTER TWO

LITERATURE REVIEW

2.1 REGIONAL GEOLOGY

Nigeria lies within the Pan-African reactivated mobile belt east of the West African Craton which has been stable since approximately 2.0 Ga (Küster, 1990). This mobile belt extends from Algeria across the southern Sahara into Nigeria, Benin and Cameroon. The Pan-African mobile belt continues southwest into northeast Brazil, and consist of a set of orogenic cycles (the Brasiliano – Pan-African cycle) that lasted from about 850 to 550 Ma (Pinto and Pedrosa-Soares, 2001).

The Pan-African system of orogenic belts in Africa, Brazil and eastern Antarctica has been interpreted as a network surrounding older cratons and essentially resulting from closure of several major Neo-Proterozoic oceans (Fig. 2.1). In Nigeria, the granitoids associated with the Pan-African Orogeny belong to the Older Granite suites (Jacobson and Webb, 1946; Grant 1970, Matheis 1979, Küster 1990), which have been dated 600 ± 150 Ma old (Matheis and Caen-Vachette, 1983). In Brazil, comparable granitoids especially in the Borborema province, have been associated with the Brasiliano Pan-African Orogeny where analogous mineralized rare-metal pegmatite also occur.

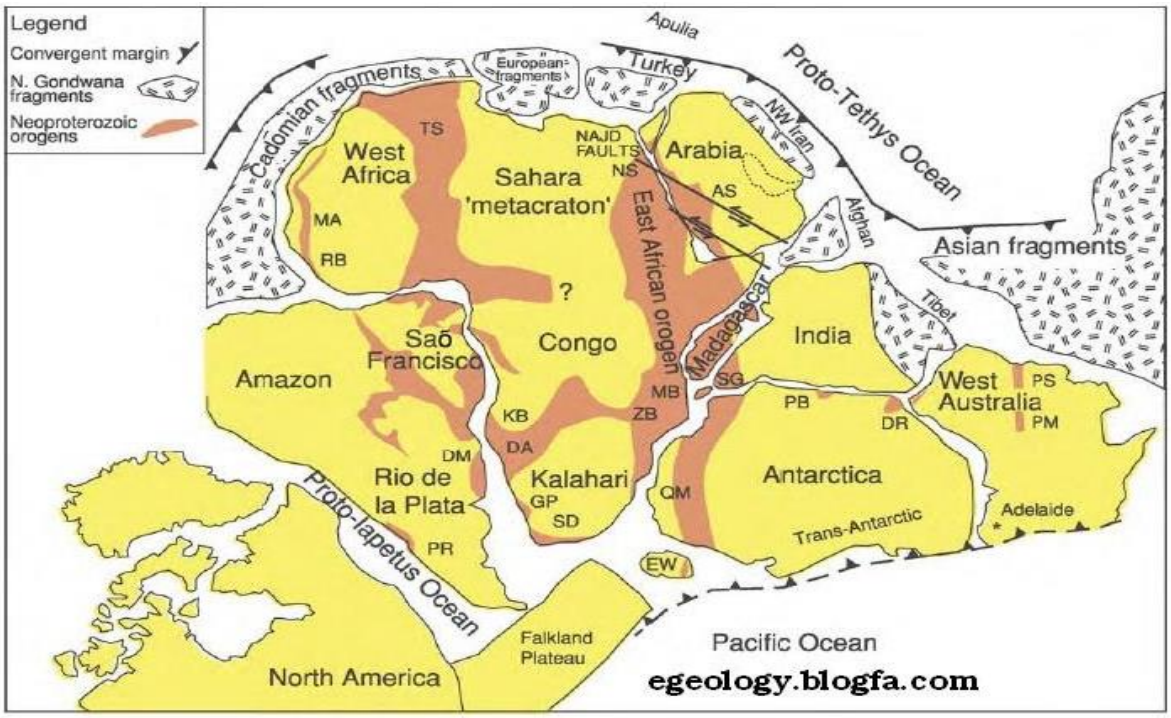


Figure 2.1: Map of Gondwana at the end of Neoproterozic time showing the arrangement of Pan-African belts (after Kusky *et al*., 2003).

2.2 THE STRUCTURAL FRAMEWORK OF THE PAN-AFRICAN MOBILE BELT

Ball (1980), carried out detailed photo-interpretation of two selected areas, firstly, the eastern Hoggar and secondly, the Adrar des Iforas aerial photographs. These interpretations show that a major conjugate system of strike-slip faults have affected the whole area. Both fault directions have consistent trend and senses of displacement; a NE--SW trending system having a dextral sense of movement, and a NW-SE trending system with a sinistral sense of displacement. Both sets cut all the major Pan-African structures, including the N-S trending shear zones and the late Orogenic granites. These faults are mainly the result of brittle deformation. There is no observable folding, but fault drag is observed on some of the faults. Evidences of brittle deformation as in the field comprises of fault breccias, which are often silicified, and occurrence of epidote-quartz-bearing veins. The faults vary in length (from 10^2 to 10^3 m), and frequency. These parameters are probably linked with variations in lithology.

A relationship between fault frequency, length, and displacement, certainly exists because with higher frequencies smaller displacements and shorter faults are found. It is of interest to note that both NE – SW and NW - SE directions of the conjugate system exist everywhere in the belt. However, NE - SW is often predominant. This variation of the pattern can possibly be attributed to competency differences. Local variations in direction also exist, and are visible on both Landsat Imagery and geological maps. For instance, in the central Hoggar the NE-SW dextral system tends towards an E-W direction, whereas in the western Adrar des Iforas, the sinistral system tends towards a N-S trend. This implies a local rotation of the maximum stress axis σ_1, within the horizontal plane.

2.2.1 The Nigerian Pan-African shield

The Nigerian Pan-African belt has been considered as the southern prolongation of the central Hoggar (McCurry, 1976). It is similarly cut by N-S trending shear zones of Pan-African age, which are displaced by late orogenic slip faults. Like those in the Tuareg shield, the dextral faults display a NE-SW strike, and the sinistral faults a NW-SE strike (McCurry, 1971). In the north of the belt (Mc Curry, 1971, 1973; Holt, et. al., 1978), the dextral set is the best developed, and offsets the mylonites by more than 10 km in some places. It is important to note that outcropping in Nigeria is poor compared to the Tuareg shield, and that the number of faults drawn on present-day maps is probably a gross under- estimation. In the south of the belt, field observations are sparse, and the existence of the slip-fault system cannot be demonstrated; however, a normal fault system was responsible for the Cretaceous basins (i.e., Benue trough) and has the same NE-SW trend. This could possibly represent a rejuvenation of a late Pan-African fault system (Ball, 1980). Two important NE-SW trending transform faults (Romanche and Chain) defined in the Atlantic by Francheteau and Le Pichon (1972), are situated on the prolongation of two dextral wrench faults of Pan-African age in southern Nigeria (Wright, 1976). The transform faults may have been formed preferentially

on preexisting zones of weakness. Similarly, Almeida and Black (1967) emphasized that these same directions can be found in the Pan- African terrains of Brazil if allowance is made before the opening of the Atlantic (Fig. 2.2).

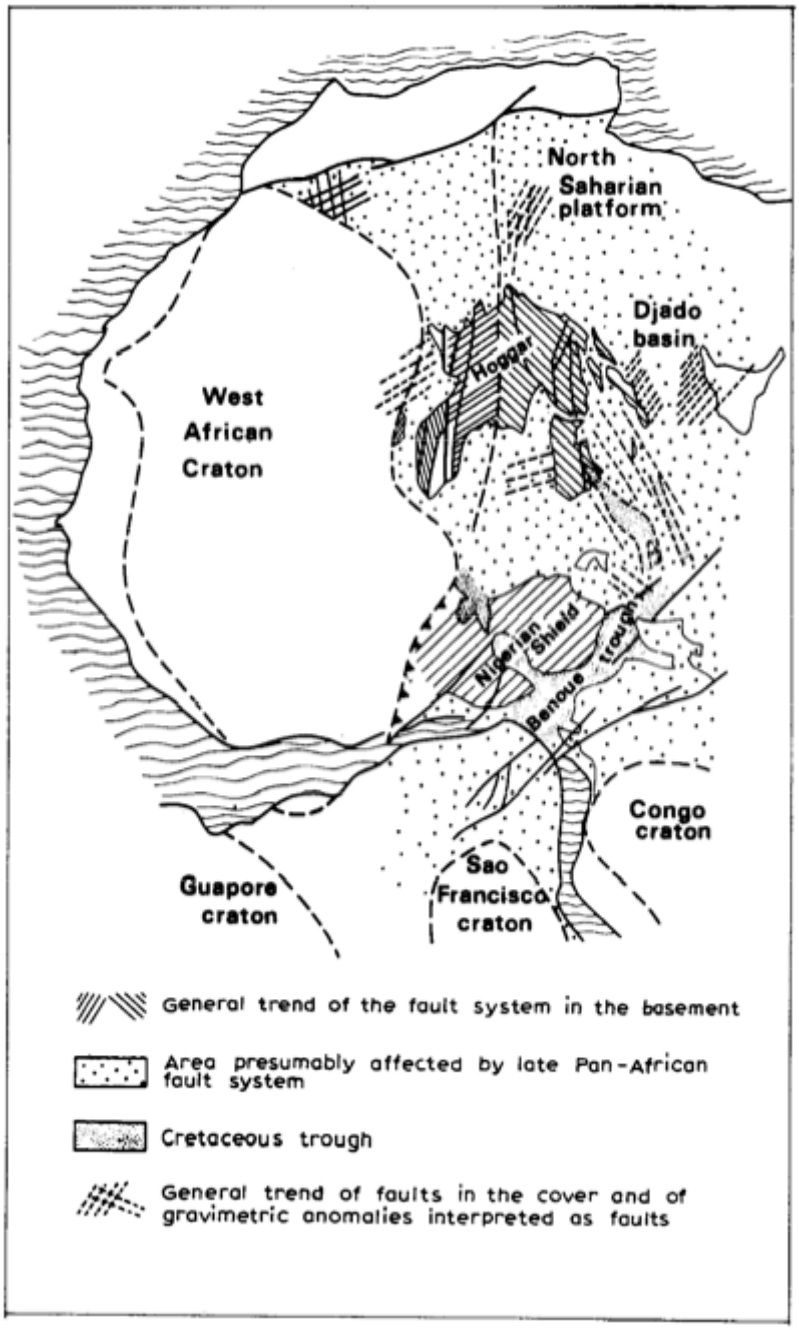


Figure 2.2: Geographical extent of the conjugate fault system in the Tuareg and Nigerian shield, and its possible extension into Brazil (Ball, 1980).

2.2.2 Original Age of the Faulting

As previously noted by Ball (1980), the brittle deformation cuts the mylonites, the late orogenic granites, and the younger ring-complexes of Adrar des Iforas (586 Ma). An example from the eastern Hoggar shows the extended time scale during which this deformation took

place. The late erogenic Honag granite was emplaced along an active dextral mylonitic wrench fault which now borders the granite in both sides. The geometry (style) of fracturing within the pluton itself (Fig. 2.3) suggests that this brittle deformation was progressive and occurred during movements on the bordering faults. The evidence is shown by planar fractures trending NE-SW to ENE-WSW which crosscut earlier sigmoidal fractures (Fig. 2.2). It is tempting to suppose that during dextral movement on the NNE-SSW trending border faults under an E-W compression (Fig. 2.3), NE-SW fractures were formed, and have subsequently been deformed by progressive dextral rotation to give the sigmoidal shape, and were then crosscut by a NE-SW trending fracture system (Ball, 1980). A more recent granite then crosscuts the eastern border fault of the Honag granite. Brittle deformation within this granite is only represented by E-W trending tension fractures across which there is no displacement. The major fracturation is thus considered essentially to postdate the main granitic event but to predate the ultimate injections of granite.

In the western Hoggar, the fault system is poorly developed. A late orogenic distensional episode was marked by the deposition of the molassic "serie pourpree" (spotted series) into subsiding grabens. Ignimbrites underlying the molasse have been dated at 530 m.y. (Rb-Sr isochron; Allegre and Caby, 1972). The "serie pourpree" (spotted series) was subsequently folded with the formation of a locally developed cleavage. It is considered that the compressional episode which caused this folding, is the same event which was responsible for the conjugate fault system in the rest of the shield. Thus the brittle deformation must have occurred after 530 ma.

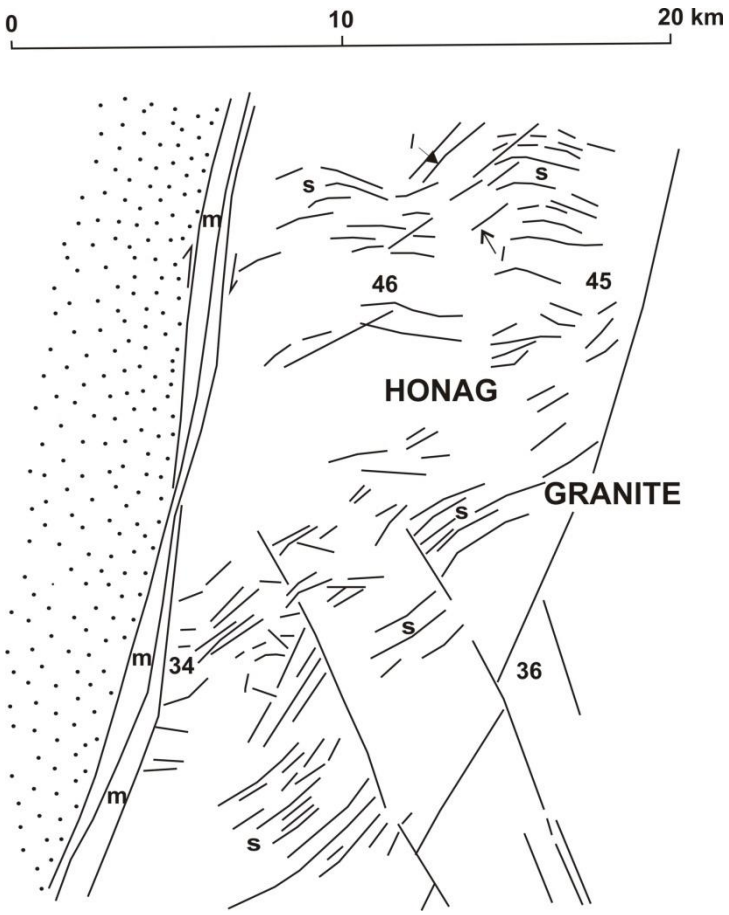


Figure 2.3: Fracturation of the Honag granite (eastern Hoggar). m = mylonites; l = linear fracture; s = sigmoidal fracture (Ball, 1980).

2.3 THE NIGERIAN BASEMENT

The Nigerian basement lies in the area east of the West African Craton and northwest of the Congo Craton, and south of the Tuareg shield (Hoggar massif (Fig. 2.4). The region was affected by the Pan-African orogeny about 600 Ma. It is believed that the Pan-African belt evolved by plate tectonics processes which involved collision between the passive margin of West African Craton and the active margin of the Tuareg shield about 600 Ma (Black *et al*., 1979; Ajibade *et al*., 1987). The collision at the cratonic margin led to the reactivation of the internal region of the Pan African belt.

The geology of the basement rocks of Nigeria has been described and reviewed by many workers including (Oyawoye, 1970, McCurry, 1976, Rahaman,1976, Turner, 1983, Fitches *et al*., 1985 and Ajibade *et al*., 1987, McCurry, 1976, Garba, 2003, Dada, 2006, 2008, Baba *et al*., 2006, developed a general geochronological classification of the Precambrian basement complex rocks of Nigeria, shown in Table 1.1. The Nigerian Basement Complex (Fig. x) consists of six major rocks groups (Rahaman, 1988)

i. Migmatite – gneiss – quartzite complex
ii. Slightly migmatised to non-migmatised metasedimentary and meta-igneous rocks which are often referred to as Newer metasediments (Oyawoye, 1964) or younger metasediments (McCurry, 1976). Schist Belts
iii. Chanockitic, gabbroic and dioritic rocks
iv. Members of the Older Granite suite.
v. Metamorphosed to unmetamorphosed calc-alkaline volcanics and hypabyssal rocks (McCurry, 1976, McCurry and Wright, 1977).
vi. Unmetamorphosed dolerite dykes, basic dykes and syenite dykes etc.

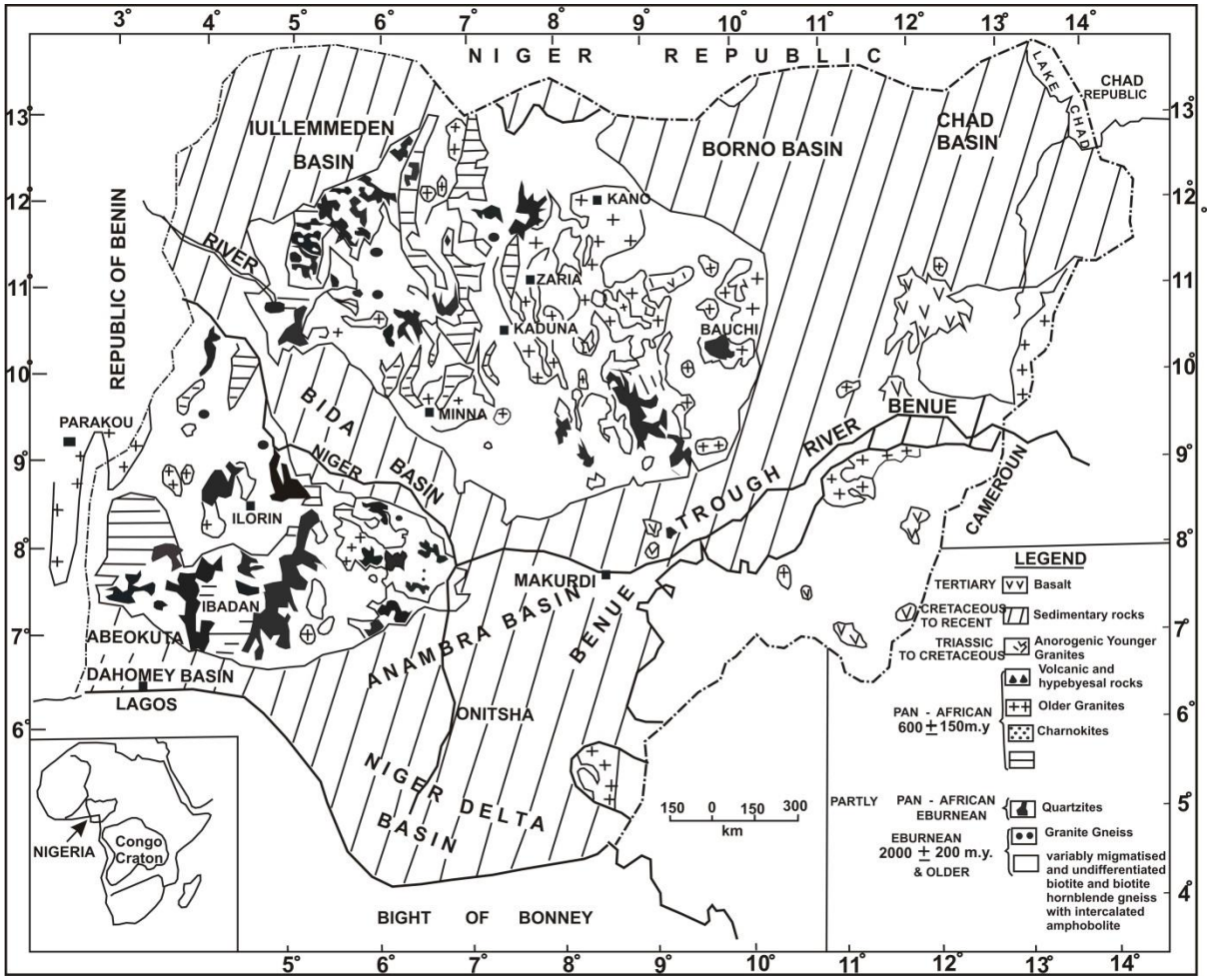


Figure 2.4: Location of the Nigerian Basement Complex (Rahaman, 1988).

Table 2.1: Generalised geochronology for the basement rocks of Nigeria (McCurry, 1976; Dada, 1997)

Age (Ma)	Period (or epoch)	Activity	Remarks
540 ± 40	Late Pan-African	Uplift, cooling, faulting, high level magmatic activity	
650 ± 580	Pan – African	Granitic intrusion, pegmatites and aplite development	Older Granites Magmatization
650 ± 850	(Main phase)	Orogensis: deformation, metamorphism, migmatisation and reactivation of pre-existing rocks.	
800 – 1000	Katangan	Geosynclinal deposition, intrusion of hyperstheoes-boaring rocks	Katangan Metasediments
1900 ± 250	Eburnean	Granite intrusion Orogenesis: folding, metamorphism and reactivation of pre-existing rocks	Eburnean granites
2500	Birimian	Geosynclinal deposition	Birimian Metasediments
3100 – 2750 Dada (1997)		Orogenesis and metamorphism	Emplacement of granodiorite magma
3500 Dada (1997)		Crystalline basement	Crustal addition

2.3.1 The Migmatites Gniess – Quartzite Complex

The Migmatite-Gneiss Complex is generally considered as the Basement Complex "Senso Stricto" (Rahaman, 1988; Dada, 2006). About half of the Nigerian Basement consists of the migmatite-gniess complex (Kroner *et al*., 2001). Composed of gneisses and migmatites with entrained supracrustal relics whose metamorphism is generally in the amphibolites facies grade. These rocks are mainly amphibolites, calcareous rocks, biotite-hornblende gneisses and pegmatites (Wrigh *et al*., 1985; Dada, 1999).

2.3.2 The Schist Belts

The Nigerian schist belts occur in a 300 to 400 km wide zone, and predominantly west of longititude 8^0 E, which trends NNE, parallel to the boundary between the Pan-African province and the West African Craton (Turner, 1983; Fitches *et al*., 1985; Ajibade *et al*., 1987; Adekoya, 1996). These schist belts are believed to belong to the Pan-African marginal basin development (Turner, 1983; Fitches *et al*., 1985). However, the Nigerian schist belts are believed to have evolved by plate tectonic processes. They are described as having been deposited on a back – arc basin, which developed after the onset of subduction at the cratonic margin at about 1000 Ma. Closure of the ocean at the cratonic margin about 600Ma and crustal thickening to the east led to the deformation and metamorphism of the sediments (Ajibade *et al*., 1987).

2.3.3 The Older Granites

The Older Granites of Nigeria occur in all parts of the Nigerian basement and the intrusions emplaced by diapiric processes (Fitches *et al*., 1985). They are generally regarded as syn – to post- tectonic with respect to the main deformation of the Pan-African Tectonism.

2.4 STRUCTURAL RELATIONSHIPS

Two major NE-SW trending regional fault systems have been established in Nigeria: the Anka-Yauri-Iseyin (AYI) and the Kalangai-Zungeru-Ifewara (KZI) faults (Fig 2.5). Both are dextral wrench faults with locally developed conjugate sinistral wrench faults (Truswell and Cope, 1963; Wright, 1976; Danbatta, 2003a; 2003b). The AYI traverses the Iseyin-Oyan River, Zuru, Anka and Maru belts area; and is considered as a deep strike-slip lineament and a possible Pan-African crustal suture (McCurry and Wright 1977; Ajibade and Wright 1988). A significant number of mafic/ultramafic and felsic rocks lie within or very close to it. Occurrences of the mafic-ultramafic rocks in the region is of particular importance in the genetic debate as there were at least ten different bodies associated with the fault zones in the area (Ogezi 1977); Ajibade and Wright 1989; Rahaman *et al*., 1988). Moreover, the work of Danbatta (1991) has clearly demonstrated the occurrence of amphibolites tectonically emplaced at the Zuru schist belt. The KZI traverses the Kazaure, Kushaka, Malumfashi, Birnin Gwari, Igarra and Ife-Ilesha schist belts and is probably an ancient fault that has been reactivated several times (Hubbard, 1975). These fault zones are considered to mark a major structural break in the western Nigerian basement (Danbatta, 2003).

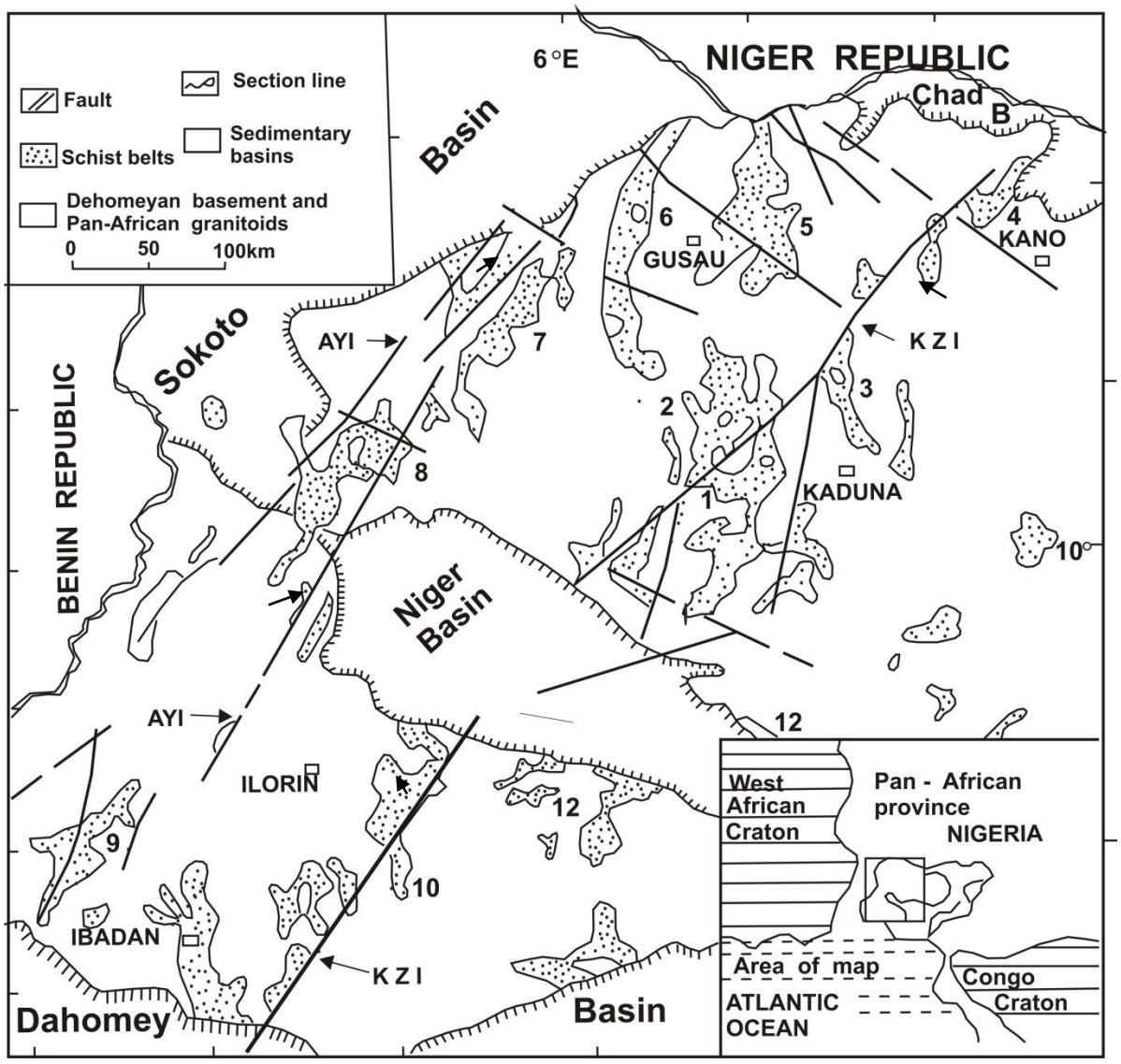


Figure 2.5: Geological map of the Northern and Southern part of the Western half of Nigeria, showing the distribution of the schist belts and locations of major lineaments (Modified by GSN, 1994). The schist belts are : 1.Birnin Gwari, 2. Kushaka, 3. Malumfashi, 4. Kazaure, 5. Wonaka, 6. Maru, 7. Anka, 8. Zuru, 9. Iseyin-Oyan River, 10. Ife-Ilesha, 11. Igarra, 12. Toto, AYI = Anka-Yauri-Iseyin fault system. KZI = Kalangai-Zungeru-Ifewara fault system. (Garba, 2003)

2.5 PREVIOUS WORK ON THE MARU SCHIST BELT

The earliest works on the Maru belt and the adjacent Anka and Gusau include a reconnaissance mapping carried out by Fargher, (1961), Truswell and Cope (1963) and Nehikarea, (1963). These workers laid emphasis on spatial distribution and the general petrographic characteristics of the rocks in the areas. Truswell and Cope (1963) correlated the

Maru Formation with the Kushaka Formation and showed that the formations have vertical attitudes and are isoclinally folded. Ogezi (1977) carried out geochronological and geochemical studies of parts of Maru belt (Gusau migmatities and granites, gneiss, Maru phyllites and amphibolites) and the Anka belt (Mainchi granodiorite batholiths, Sado-Maikwanaga mafic/ultramafic rocks and Sado sandstone) as part of regional study of NW Nigeria Basement Complex. Ogezi (1977) concluded basement was of Archean age that sedimentation and metamorphism occurred in the Maru and Anka belts during the Kibaran and Pan African episodes respectively.

The most recent work on the entire Maru Belt is that of Ibrahim (2010), who describes the petrology, geochemistry and genesis of Banded Iron Formation of Maru Schist Belt. He reported that the BIF in Maru Schist Belt are composed of rock associations similar to the Lake Superior type BIF. Egbuniwe (1982) worked out the geotectonic evolution of the belt based on the data collected from the northern part. This part of the belt is about 45 km long and 20 km wide, and constitutes about 70% of the entire Maru Belt. The lithological units are well exposed as outcrops of various sizes in the portion.

Egbuniwe (1982), Ibrahim (2010, 2012) showed that the Maru Belt comprises three major rock types, namely minor and major structures:-

i. Gusau migmatites,
ii. Maru Formation (Slate, Phyllite, Schist, BIF)
iii. Older (Pan-African) Granites.

Egbuniwe (1982) observed that the major questions that arise are when and how did the Maru Belt evolve (Table 2.2).Was it during Kibaran or Pan-African? Was it by ensialic process involving the development of and crustal mobility in a modified graben (or aulacogen) or was it through ensimatic plate tectonic processes involving the subduction of oceanic crust, ocean

closure and continental collision, or did both processes play a role at different times in the evolution of the belt. In attempting to provide answers to these questions, Egbuniwe (1982) summarized the lithologies and models suggested for the evolution of other well-known schist belts in northwestern Nigeria and interpreted the Maru Belt as a pre- or early Kibaran ensialic basin, formed as a result of crustal extension and vertical movements caused by mantle diapirism. The basin was formed on continental crust, largely controlled by the structural grain provided in pre-Kibaran cycles and which thinned without actually fracturing. Tholeiitic submarine basalts were erupted and formed at the same time with sedimentation, while BIF were produced as volcanic exhalites. Compression led to closure of the basin, producing the early deformation and metamorphism. Later during the Pan African episode, a marginal basin developed in the Anka belt, behind a magmatic arc possibly situated further west of the belt. Back-arc extension was perhaps sufficient for the development of oceanic crust in the basin, the remnants of which are the Maikwanaga-Sado mafic/ultramafics. Closure of the basin, contemporaneously with basin closure of the main ocean at the West African Craton margin caused deformation of both the sediments and syn-orogenic plutons for the first time in the Anka, and renewed deformation in the Maru belt. Late to post orogenic uplift led to unrooting of some the plutons which then supplied the coarse clastics of the Anka belt, while the late stage subduction caused extension of the acid/intermediate volcanic.

Table 2.2: Sequence of main events in the Maru Belt (after Egbuniwe, 1982)

STEP	EVENT	AGE
10	Localised D_4 deformation of the Maru Formation under greenschist facies condition.	
9	Emplacement of Kanoma and Sabon Gida per alkaline-peraliminous plutons; Localised deformation and contact metamorphism of metasedimentrary envelope.	<577 m
8	Localised deformation : D_2 in Gusau Granite Gneiss under greenschist facies conditions (retrograde) D_3 in Maru Formation under greenschist facies conditions D_4 in Gusau Migmatites under greenschist facies conditions (retrograde)	
7	Emplacement of Damaga and Riorji calc-alkaline plutons; localised contact metamorphism of the Maru Formation.	
6	Regional deformation: D_1 in Maiinchi batholiths and Gusau Granite gneiss producing regional trends and structures under amphibolites facies conditions. D_2 in Maru Formation under greenschist facies conditions. D_3 in Gusau migmatites under amphibolites facies conditions.	678-577 m.y
5	Emplacement of Gusau gneiss and Maiinchi batholiths	>679-577 m.y
4	Regional deformation: D_1 in Maru Formation under greenschist to lower amphibolites facies conditions.	1158-1068 m.y
3	Deposition of Maru Formation: contemporaneous subaqueous extrusion of tholeiitic pillow basalts	
2	Emplacement of basic dykes in gneissified rocks. D_1 deformation of Gusau migmatites under amphibolites facies conditions.	
1	Formation of parental rocks of Gusau migmatites of igneous or sedimentary origin.	

CHAPTER THREE

METHODOLOGY

3.1 INTRODUCTION

The methodology adopted for this research work consists of desk study, fieldwork and laboratory analysis.

The field study involved geological mapping on a scale of 1:50,000 and 1:10,000 in areas with complex geological structures which was undertaken with topographic map, geologic hammer, compass-clinometers and GPS. The laboratory work involved sample preparation, petrographic study and analysis of microstructures. The petrographic study was undertaken with the aid of transmitted high petrological microscope at the Petrographic Laboratory, Department of Geology, Ahmadu Bello University, Zaria.

3.2 FIELD INVESTIGATION

The field exercise was carried out in two (2) stages, first was a reconnaissance visit for five days, followed by the second field visit during which geological field mapping was undertaken on a scale of 1:50,000. Fresh rock and mineral samples were collected for hand specimen examination. Preliminary observation and identification of each constituent mineral were carried out using magnifying lens. Field data such as measurement of strike and dip directions of lineaments with compass-clinometer and recording of the co-ordinates of every sampling point using Global Positioning System (GPS) were also carried out. Other structural elements like trends of fractures, dimension of veins and dykes were also recorded.

3.3 STRUCTURAL ANALYSIS

The structural analysis was carried out in three (3) stages, starting from the mega-structures, meso-structures to micro-structures.

Google Earth Imagery obtained from Google Earth Pro was used to manually extract the mega-structures and in identifying major geological structures within the study area. Arc Gis v10.1 was used in sketching out the lineaments. RockWorks 15 was used in constructing Rose Diagram for determining dominant trend of the manually sketched lineaments.

Measurements of geologically oriented meso-structures and sampling were carried out from the field using compass clinometer, tape and Global Position System (GPS). Orientation analysis of joints was also undertaken using GeoRose software.

Thin sections of the rock samples were prepared and the various paragenetic minerals and microstructures were identified using a transmitted-light petrological microscope. Modal composition of the rocks types was determined, which allowed for both classification and delineation of the various deformational episodes in a micro-scale. Sketching of micro-structures using CorelDraw v13 from the thin sections for easy identification was conducted.

3.4 STRAIN ANALYSIS

Strain estimation was done on photomicrographs of the samples cut normal to the plane of foliation across the lithologies in order to establish the homogeneity and amount of strain. The centres of the quartz grains were digitized using the Fry method from which the axial ratios of the strain ellipsoids were used to estimate and compare the amount and orientation of strain across the different rock types in the study area.

CHAPTER FOUR

RESULTS AND INTERPRETATION

4.1 INTRODUCTION

In this chapter, the tectonic structures and fabrics of rocks in the study area were analysed in detail, the deformation sequence established and an attempt was made to define the relationship of this sequence to regional tectonics.

Rocks of the study area are identified along the river channels and some isolated outcrops occur sporadically. The structural interpretation is based mainly on an analysis of structures on different scales from mega, meso to micro level.

The study area has a regional N-S structural trend. However, presence of structure of different dimension and styles indicate that it has undergone at least three episodes of deformation. Analysis of strain estimate was carried out using relevant markers distributed within the photomicrographs of the various rock types in the study area.

4.2 GEOLOGY AND PETROGRAPHY

The study area is underlain mainly by metasediments (schists, phyllites, slates), migmatite gneiss, granodiorite and syenite (Fig. 4.1). Gradual contact relationships between the various rock types were encountered.

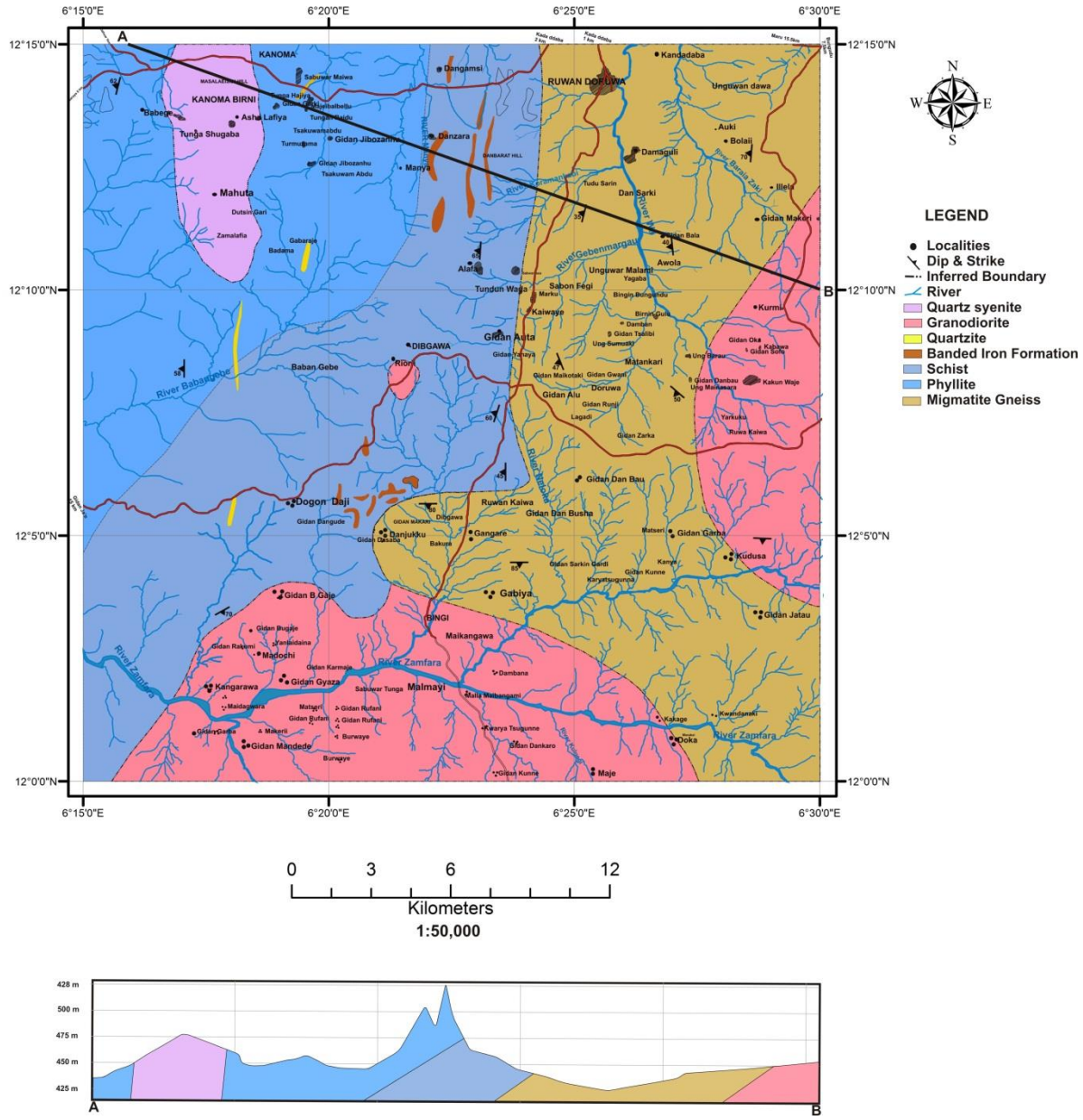


Figure 4.1: Geological Map and Cross Section of the Study Area

4.2.1 MIGMATITE – GNEISS COMPLEX (MGC)

This unit underlies about 25% of the study area, and was essentially mapped around Bingi, Ruwan Doruwa, Maji and Gidan Dan Ba'u. It is well/strongly foliated (Plate I).The migmatitic gneiss is medium grained and chiefly consists of feldspar (plagioclase), quartz, biotite and hornblende (Plate II). It is grey to light grey in colour. Biotite and hornblende form the major mafic components of migmatite gneiss complex in the area of study. The rock exhibits varying degrees of foliations defined by the orientation of feldspar grains. The alternating felsic and mafic bands range from 2 - 4 cm. These rock units were conspicuously mapped along the river channels east of Sarkin Rafi, South of Gidan Sarkin Gadi, South of Maaji and Dama Guli areas.

Foliation in migmatite gneiss is characterized by mineralogical foliation and ranges predominantly between NNE – SSW and NE – SW trends and generally dipping east or west.



Plate 1: Migmatite gneiss located about 1km east of Bingi (12º 03´ 18″ N, 06º 21´ 51.7″ E).

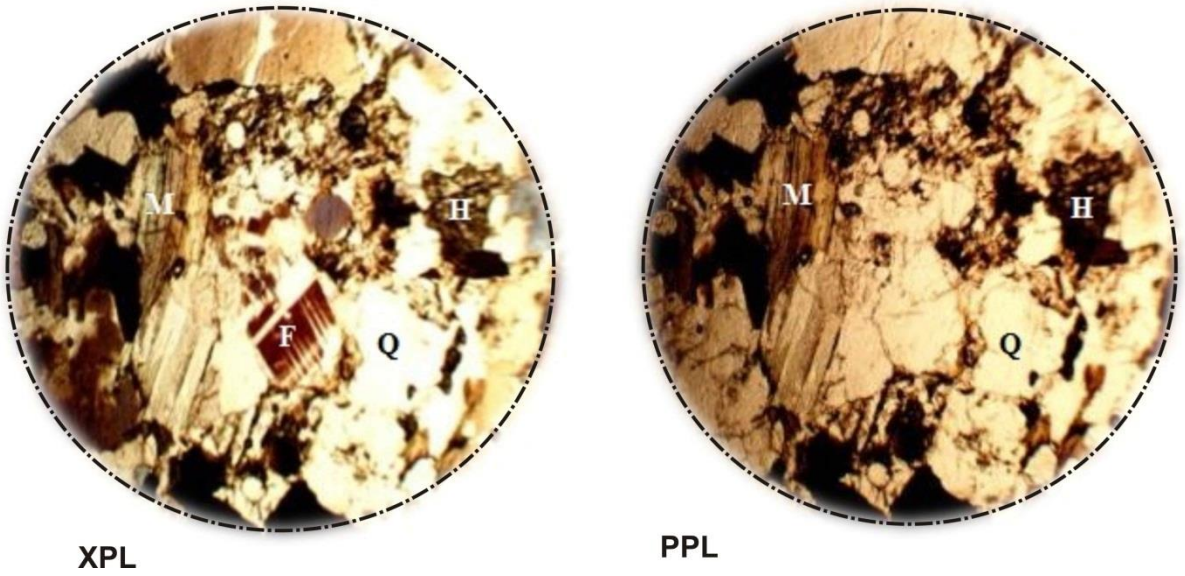


Plate II: Photomicrograph of Migmatite gneiss under XPL and PPL; Qtz - quartz, Bt - biotite, mcrn - microcline, F – plagioclase (Mag x40)

It contains of quartz, feldspar (plagioclase, microcline), hornblende, biotite and opaque minerals (Table 4.1 of Plate II). The rock is fine to medium-grained. Micas do not show any alignment.

Table 4.1: Showing mineral composition of Migmatite Gneiss

Minerals	Percentage (%)
Quartz	50
Microcline	20
Biotite	10
Muscovite	10
Orthoclase	5
Plagioclase	5

4.2.2 METASEDIMENTS

The slate, phyllite, schist, Banded Iron Formation (BIF), and quartzite constitute the metasedimentary units.

4.2.2.1 SLATE

This rocks unit is characterized by strong close spaced cleavage and planes. It is fine grained and ranges between brown to dirty brown to reddish brown in colour. Fresh field sample assume grey colour (Plate III).



Plate III: A low-lying outcrop of slate observed about 1.5km southwest of Asha Lafia (12º 12´ 30.1″ N, 06º 19´ 21.7″)

Exposures of slate were essentially mapped about 1.5 km south west of Asha Lafia and its environs. Field observation reveals that the slate occasionally interlayered other metasediments (schist and phyllite) as observed in about 2.2 km northwest of Mahutta.

4.2.2.2 PHYLLITE

Exposures of phyllite underlie about 20% of the mapped area. It is strongly foliated and medium grained. The foliation is characterized by interlayering of mica – rich and quartz – rich bands (Plate IV).



Plate IV: A flat/low-lying phyllite at about 3km southwest of Kanoma Headquarters (12º 12´ 16.4″, 06º 19´ 03.0″)

Phyllite outcrops substantially in the north western part of the area enveloping the syenite body in Rayo, Maje Sani and Kanoma.

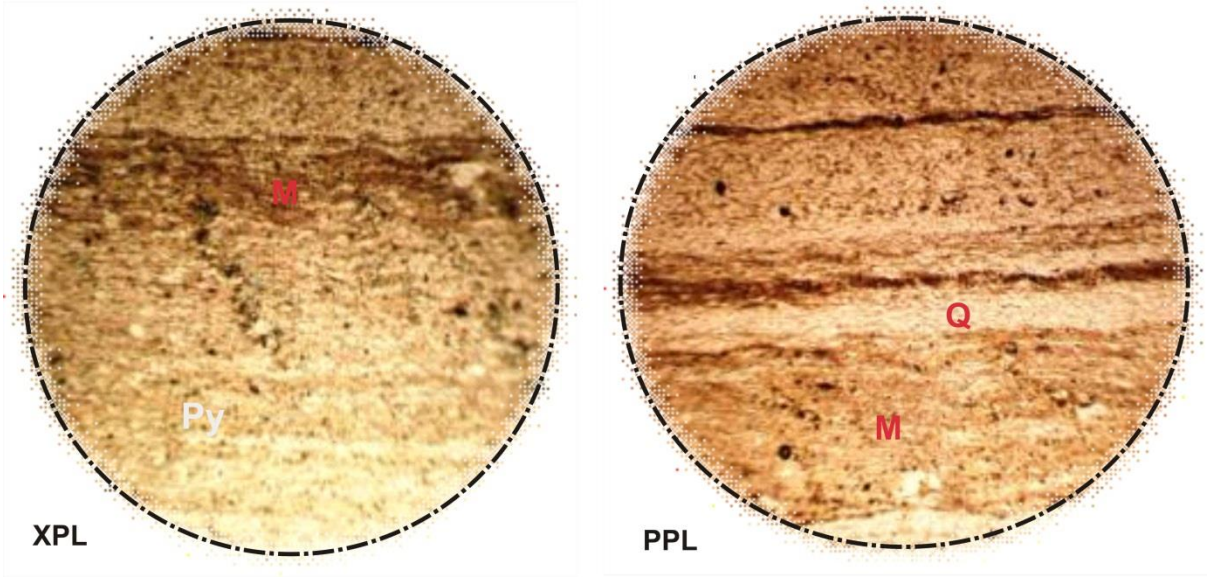


Plate V: Photomicrograph of Phyllite under XPL and PPL; Qtz - quartz, M – mica (Mag. X40)

It consists of alternation of quartz rich layers and mica rich layers. The quartz rich layers consist of fine to very fine foliated grains that are more or less striated. The thickness of the layers varies across the sample area. The mica rich layers consist of chlorite, and fine biotite (Plate V). They are parallel to the foliation of the quartz rich layers and are equally striated.

4.2.2.3 SCHIST

The schist underlies about 15% of the area under investigation. It is strongly foliated and display brown to dirty brown colour (Plate VI).



Plate VI: Fresh outcrop of schist exposed by excavator at about 2.1km north of Dan-Zara (12º 13´ 06.2″, 06º 22´ 23.0″)

Close field observation reveals that the schist contains specks of mica. This outcrop stretch NE - SW of the area mapped. It is medium to coarse grained.

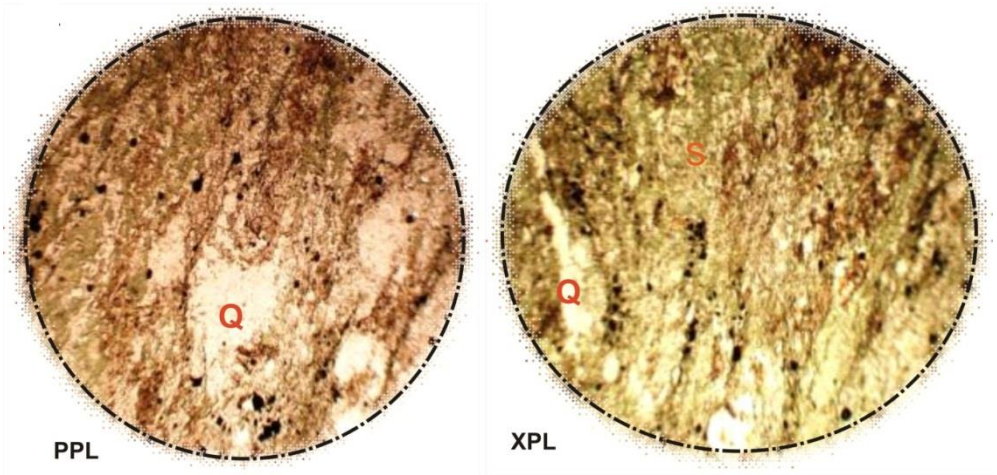


Plate VII: Photomicrograph of Schist under XPL and PPL; Q - quartz, S - sericite (Mag. X40)

It consists of alternation of quartz rich layers and mica rich layers. The quartz rich layers consist of fine to coarse-grained that is sparsely distributed across the rock in grains and in veins. The mica rich layers consist of greenish colored chlorite and sericite, and fine brown biotite. They are generally foliated.

4.2.2.4 BANDED IRON FORMATION (BIF)

The Banded Iron Formation (BIF), sometimes referred to as Taconite (USA), Jaspilite (Australia), Itabirite (Brazil) or Gebänderte (Germany), overlies most of the ridges in a discontinuous pattern in the mapped area (Plate VIII).



Plate VIII: A fairly hilly ridge of Banded Iron Formation around Dogondaji. Note the trend along mineralized vein by the artisanal miners. (12º 05´ 08″ N, 06º 20´ 05″ E)

It is dark grey in colour and is banded with clear rhythmic alternation of light/grey silica- rich band and dark band suspected to be iron rich. The compositional band varies in thickness ranging between 0.5 – 3 cm. Field evidence shows that Banded Iron Formation (BIF) appear as intermittent bands within the predominant schist and phyllites.

Individual ridges were observed to be separated by lowlands schist and phyllites. The interlayered bands were mostly observed to have been strongly fragmented forming boulders and rubbles that litter the pediment surrounding the ridges. The Banded Iron Formation constitute about less than 10% of the study area.

4.2.2.5 AMPHIBOLITE

This unmappable unit mostly occur as boulders along the river channels and at the base of ridges. However, at about 2 km NNW of Mahutta, fairly hilly outcrops of amphibolite were mapped. Also, at about 1.5 km north west of Kanoma, amphibolites were mapped in close association with schist and quartzite (Plate IX).



Plate IX: Amphibolite around northeast of Kanoma (12º 19′ 17.5″ N, 06º 23′ 57.5″ E)

The quartzite and amphibolite lies conformably with the schist in a NNE-SSW direction. It's brown to dirty brown in colour. Fresh field samples appear green in colour with weak foliation.

4.2.2.6 QUARTZITE

Quartzite outcrops essentially in close association with the pelitic rocks and medium grained granodiorite. An exposure of the quartzite encountered in the area of study generally trend NW – SE. However, NE – SW trending outcrops occasionally occur in few localities. This probably suggests different generations for the quartz ridge emplacement (Plate X).



Plate X: A N – S trending quartz vein mapped southwest of Asha Lafia (12º 12´ 30.3″ N, 06º 19´ 21.7″ E)

Prominent quartzite intrusions were the N – S trending outcrops mapped south west of Asha lafia and north east of Kanoma.

Field observation reveals the quartzite has been fairly weathered resulting into boulders. It ranges between white to grey white to brown in colour. Quartzite lies either conformably with the planer fabrics of the country rocks.

4.2.3 OLDER GRANITES SUITES

Members of the older granite suites mapped in the area of study are the granodiorites, syenite granites with pegmatites.

4.2.3.1 GRANODIORITE

The medium grained granodiorite occur mostly as inselbergs particularly around Maje Sani, Mai-dagaruwa, Tungan Kamduru, Kandusa and Sabon Gari. However, flat lying and boulders of varying sizes and shapes were conspicuously observed in Kanoma, Rioji and Rayo. Field observations suggest that the boulders were probably product of weathering (Plate XI).



Plate XI: Part of boulders of Mai – Dagaruwa granodiorite (12º 02´ 37.4″N, 06º 17´ 49.1″ E)

The granodiorite constitute less than 30% of the study area. At about 1.5 km SSW of Rioji, a contact between the Banded Iron Formation (BIF) ridge and granodiorite were mapped (Plate XII).



Plate XII: An exposure of definite boundary structural features between the granodiorite and banded iron formation at about 1.5km SSW of Rioji (12º 07´ 49.9″ N, 06º 21´ 01.3″ E)

The rock varies, in colour, from greyish to greyish brown. Just at a distance of about 800 m south east of kanoma Birni, the granodiorite becomes progressively sheared.

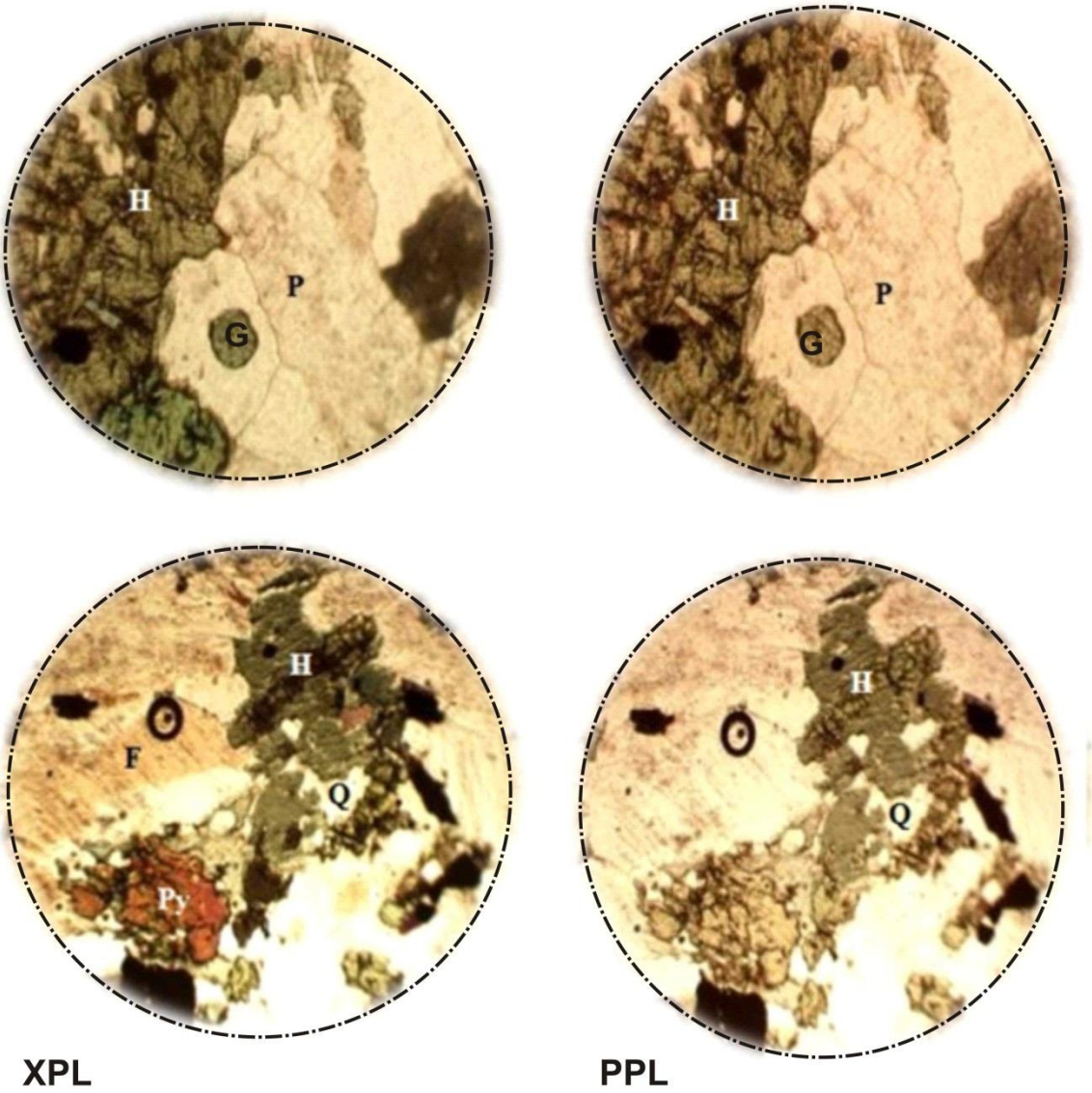


Plate XIII: Photomicrograph of granodiorite under XPL and PPL; Q - quartz, H – hornblend, B - biotite, F & P – plagioclase feldspar, G-garnet

The granodiorite consists of quartz, feldspar, mica, hornblende, and pyroxene. and opaque minerals (Table 4.2 of Plate XIII).

Table 4.2: Showing mineral composition of Granodiorite

Minerals	Percentage %
Plagioclase	50
Muscovite	15
Microcline	10
Honblende	5
Opaque Minerals	5

4.2.3.2 SYENITE

Plutons of syenite were restricted to Kanoma headquarters. At about less than 50 m ESE of Kanoma headquarters, a pluton of sheared or deformed syenite granite were mapped. A very clear definite contact between the phyllite and syenite granite were observed at about 1.2 km west of Kanoma headquarters (Plate XIV).

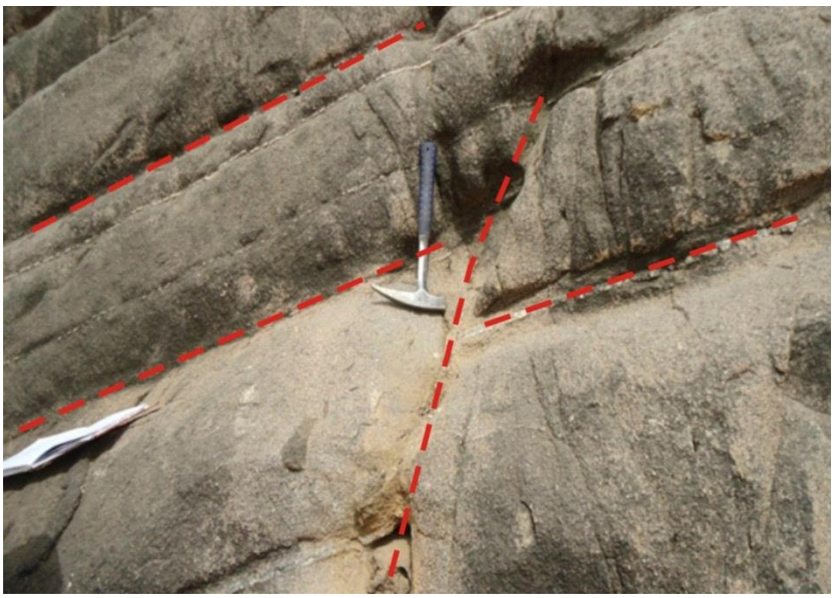


Plate XIV: Sheared or localised quartz syenite around Kanoma headquarters. Note the bands and joint healed up by quarterzofeldspathic vein (12º 14′ 48.6″ N, 06º 17′ 55.9″ E)

It is dark coloured locally deformed and chiefly consist of quartz, feldspar, biotite and or hornblende (Plate XVI).



Plate XV: Boundary between pluton of syenite and the phyllite ridge. The location is about 1.2km west of Kanoma (12º 14′ 44″ N, 06º 17′ 09.1″ E)

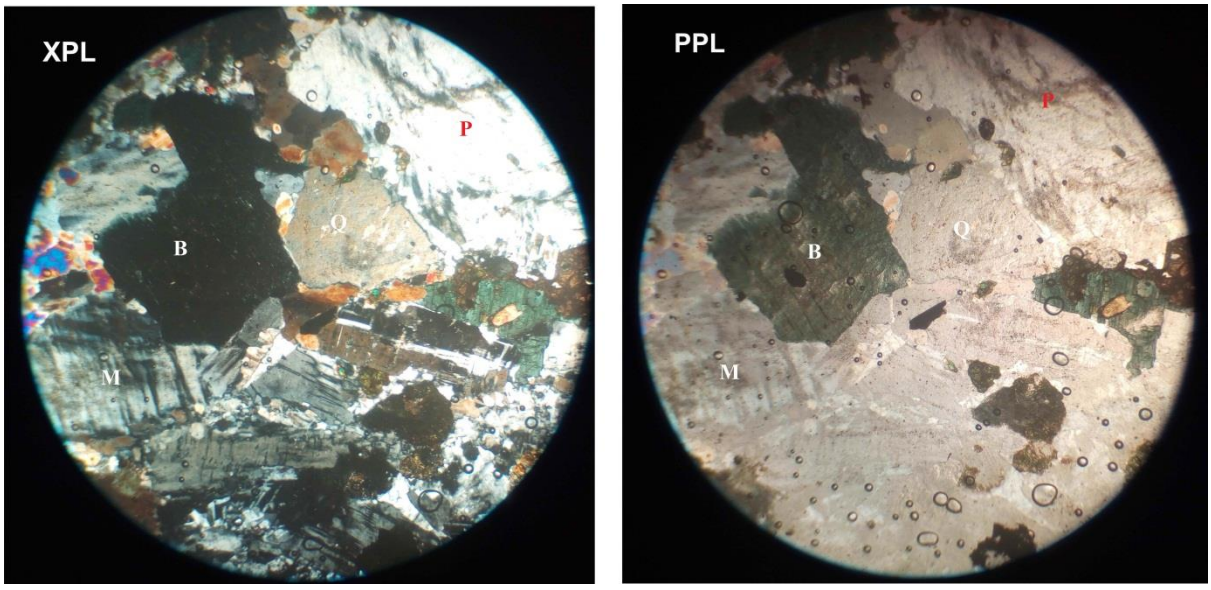


Plate XVI: Photomicrograph of Syenite under XPL and PPL; Q - quartz, B - biotite, M – microcline.

4.2.4 APLITE

Aplite occur in close association with syenite in Kanoma with thickness measuring about few centimeters (Plate XVII).



Plate XVII: Aplite dyke in a quartz syenite southeast of Kanoma headquarters. Note the sinistral (left) and dextral (right) displacements (12º 14′ 32.1″ N, 06º 16′ 36.5″ E)

It is granitic in composition and consists chiefly of quartz and feldspar.

4.3 STRUCTURAL ANALYSIS

Deformational structures include folds, foliations and lineation. In addition, faults and joints of various dimensions are also present in the area. The polyphase deformations along with planar and linear features are well documented in the area. The rocks of the region have suffered different distinct phases of folding in chronological order. The fully observable folds vary in scale from microscopic to mesoscopic (meters in size) while the regional folds are traced in kilometres (mega).

4.3.1 MEGA STRUCTURES

Satellite images have been extensively used to extract lineaments for different purposes. Since satellite images are obtained from varying wavelength intervals of the electromagnetic spectrum, they are considered to be a better tool to discriminate the lineaments and to produce better information than conventional aerial photographs (Casas *et al*, 2000). A comprehensive study of the Google Earth Imagery is a complicated work that comprises several steps. For example, extraction of lineaments from images or photos and generation of a final lineament map is a task that involves several enhancement techniques and manual interpretation in delineating lineaments in parts of the Maru Schist Belt (Maru SE), North-Western Nigeria.

4.3.1.1 STUDY AREA

Imagery from Google Earth Pro (Fig. 4.2), showing the study area at resolutions of 1-3 m/pixel and reveals detail that is hidden below the resolution of Landsat imagery. This detail makes it possible to study mega-scale features with high degree of certainty and evaluate what is responsible for the patterning in this largely accessible region.

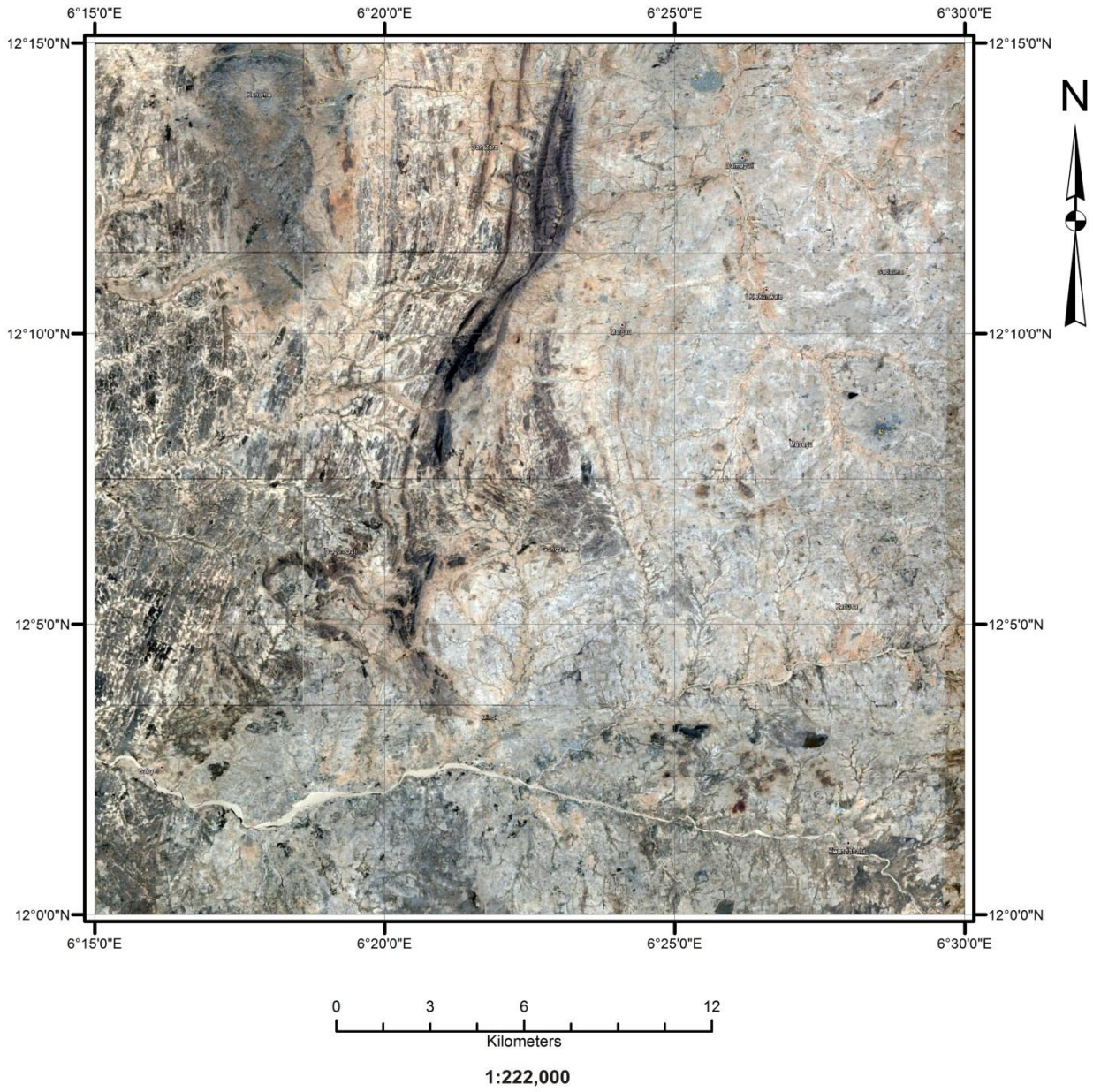


Figure 4.2: Google Earth Image of the Study Area

4.3.1.2 LITHOLOGICAL DISCRIMINATION

From Google Earth imagery (Fig. 4.3), three (3) major distinct lithologic units are identified with one of the rock type (rock type 2) hosting prominent structures. The structures include linear features mostly trending N-S, folds and other deformational structures.

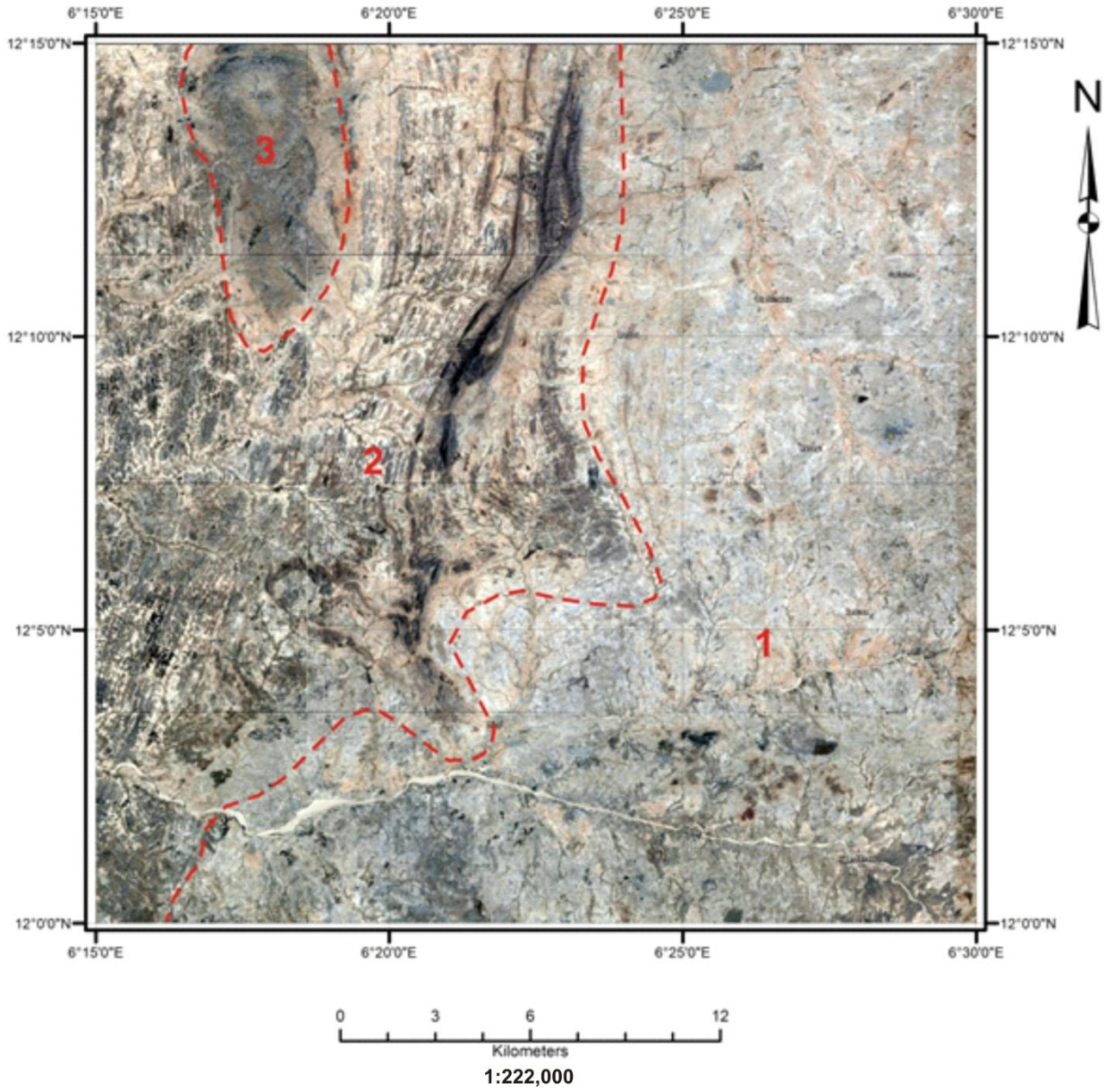


Figure 4.3: Google Earth Image of the study area showing boundaries clearly between some of the lithologies

4.3.1.3 MANUAL LINEAMENT EXTRACTION

Lineaments were manually extracted by digitising using ArcGis 10.1 software. The result reveals a lot of interesting mega structures exhibiting different structural patterns within the study area (Fig. 4.4).

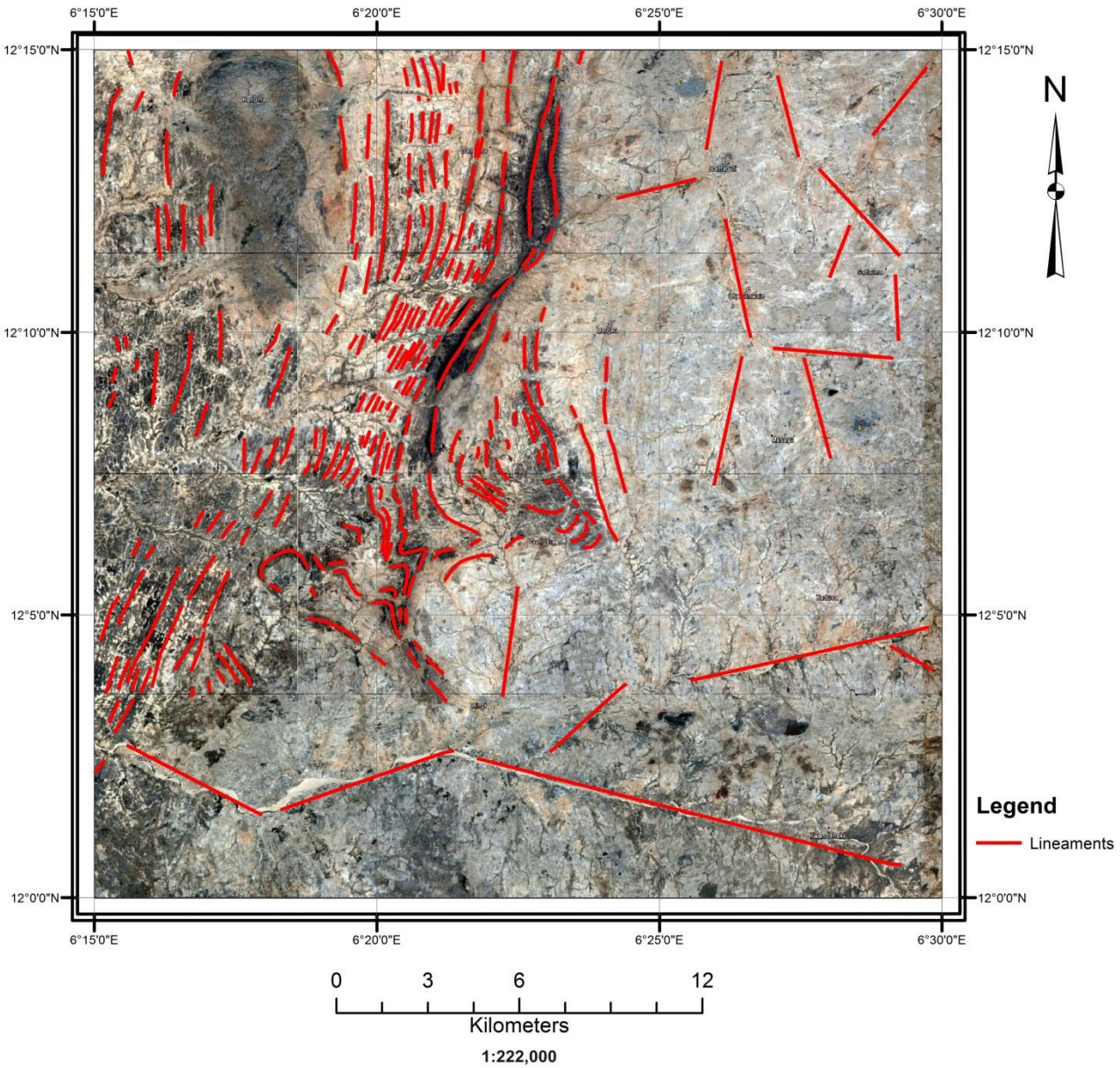


Figure 4.4: Sketched/traced lineaments

4.3.1.4 DIGITISED/EXTRACTED LINEAMENTS

Final lineaments Map sketched/extracted from the Google Earth Pro Imagery revealing a lot of structural features (Fig. 4.5).

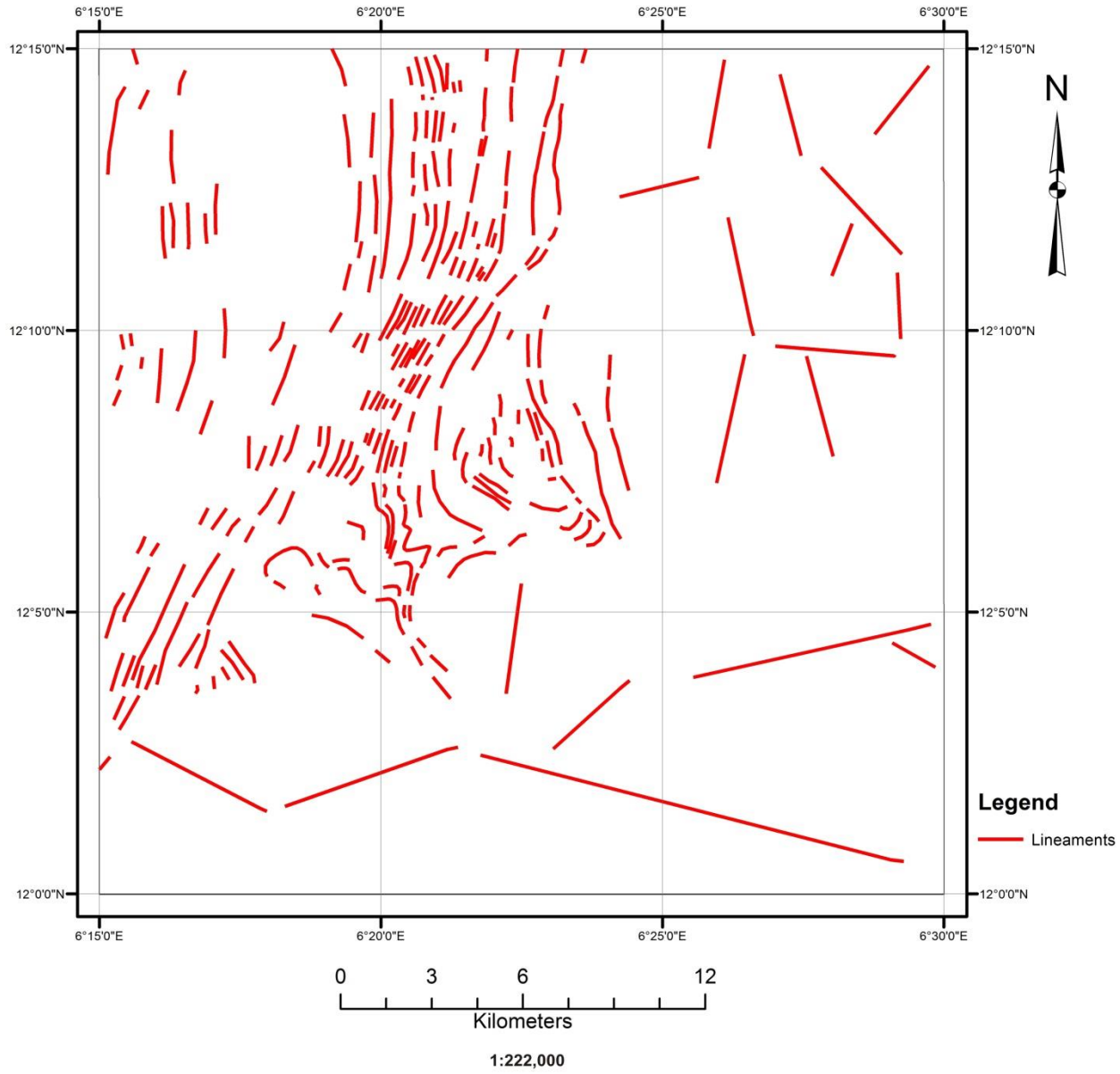


Figure 4.5: Final Lineaments Map

4.3.1.5 LINEAMENT DENSITY

Lineament density can be defined as the number of lineaments per unit area. This lineament density was performed on the study area. It is observed from the lineament density map that areas of high lineament density are located in the central and western part of the study area (Figure 4.6). Also areas of low lineament density are observed in the north eastern and south eastern part of the study area.

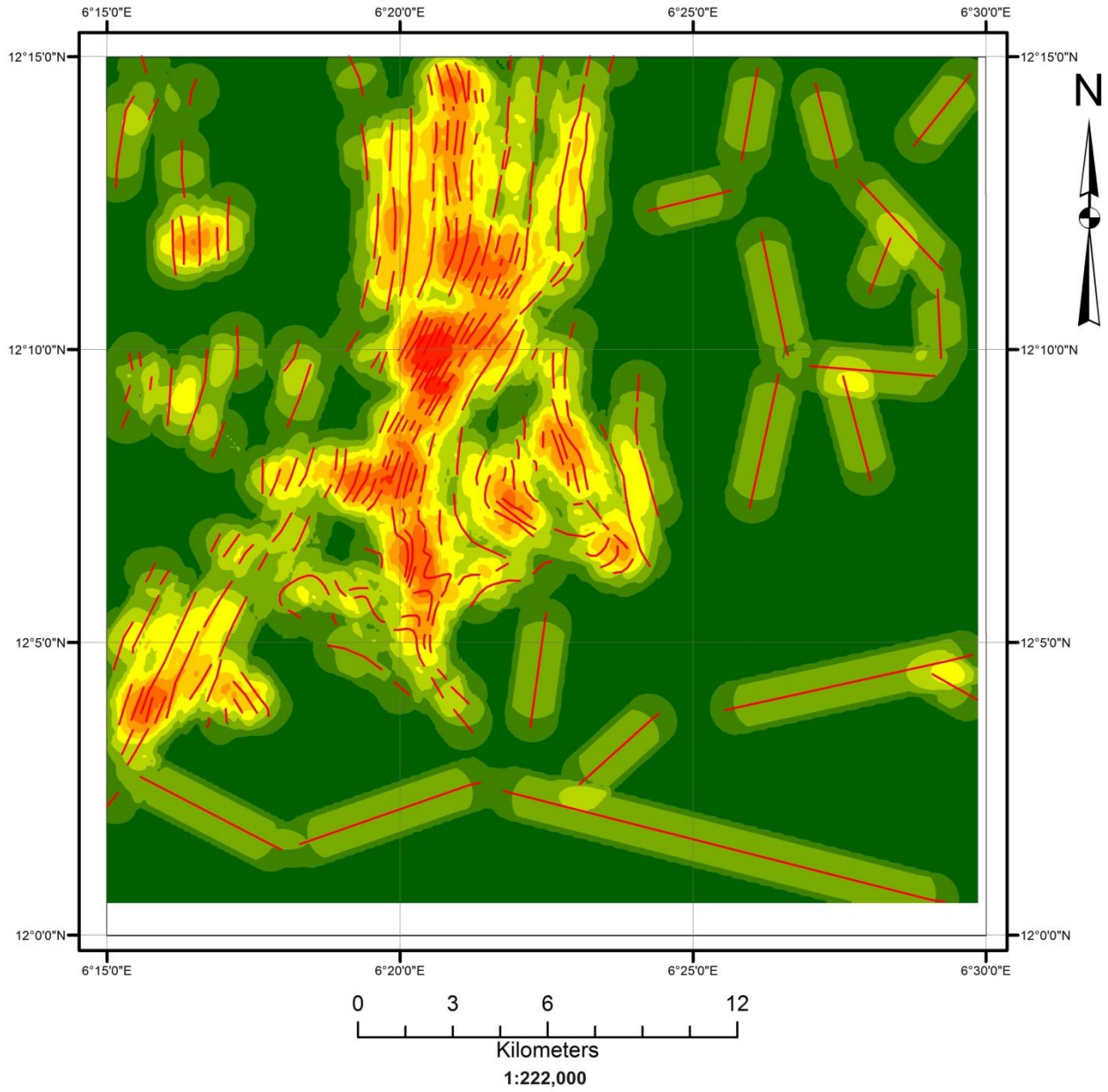


Figure 4.6: Lineament Density of the Study Area

4.3.1.6 ORIENTATION/TREND ANALYSIS

Orientation analysis using rose diagram for the manually extracted lineaments reveals a dominant NNE-SSW direction accompanied by a less dominant N-S direction (Figure 4.7).

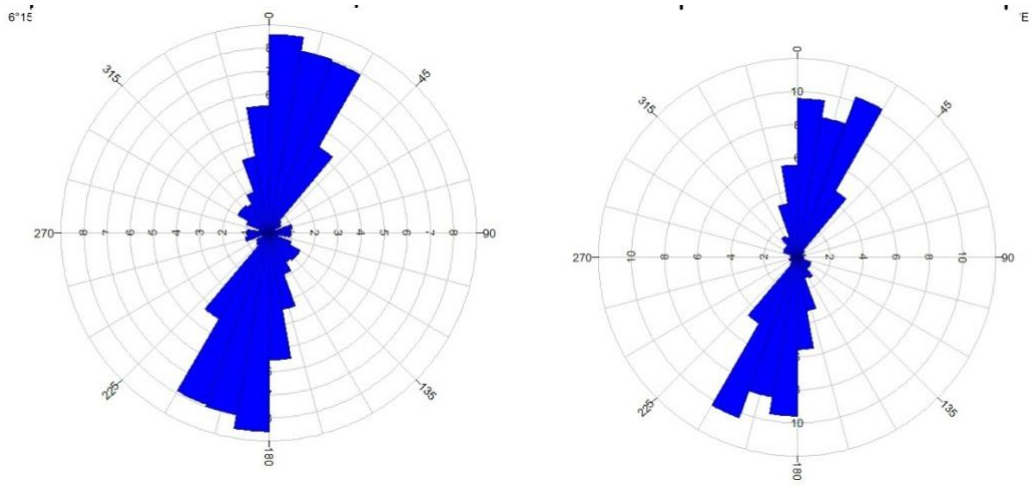


Figure 4.7: Rose Diagram of the Extracted Lineaments in the Study Area

4.3.1.7 MAJOR STRUCTURES

Major geologic structures such as faults and folds are the architecture of the earth's crust. They influence the shape of the landscape, determine the degree of deformation, bring old rocks to the surface, bury young rocks, trap petroleum and natural gas, shift during earthquakes, and serve as conduits for metallic mineralization such as gold and silver.

Folds, faults and other geologic structures accommodate large forces such as the stress of tectonic plates jostling against each other, and smaller forces such as the stress of gravity pulling on a steep mountainside. An understanding of the structures that shape the earth's crust can help you see when and where the crust was subjected to pushing or pulling, terrane accretion or crustal rifting.

Ductile rocks behave plastically and commonly become folded in response to stress. Folding can happen in the shallow crust if the stress is slow and steady and gives the rock enough time to gradually bend. If the stress is applied too quickly, rocks in the shallow crust will behave as brittle solids and break. However, deeper in the crust, where the rocks are more ductile, folding happens more readily.

The study area is exhibited with such complex and interesting mega structures ranging from antiforms (Dan-Zara and Yar'awala), synform (Dan-Jukku) and faults/fractures. Detail study of them reveals a lot on the tectonic setting of the area.

Faults/Fractures

The manually extracted lineaments facilitate the identification of fractures/faults that are perpendicular to the lineaments. Detailed study of the sketched lineaments (N – S trending), shows E - W uniform breaks crosscutting the linear structures (Fig. 4.8). Preferential weathering often takes place along the fractures, and the rivers then follow this course.

4.3.1.8 FAULT EXTRACTION

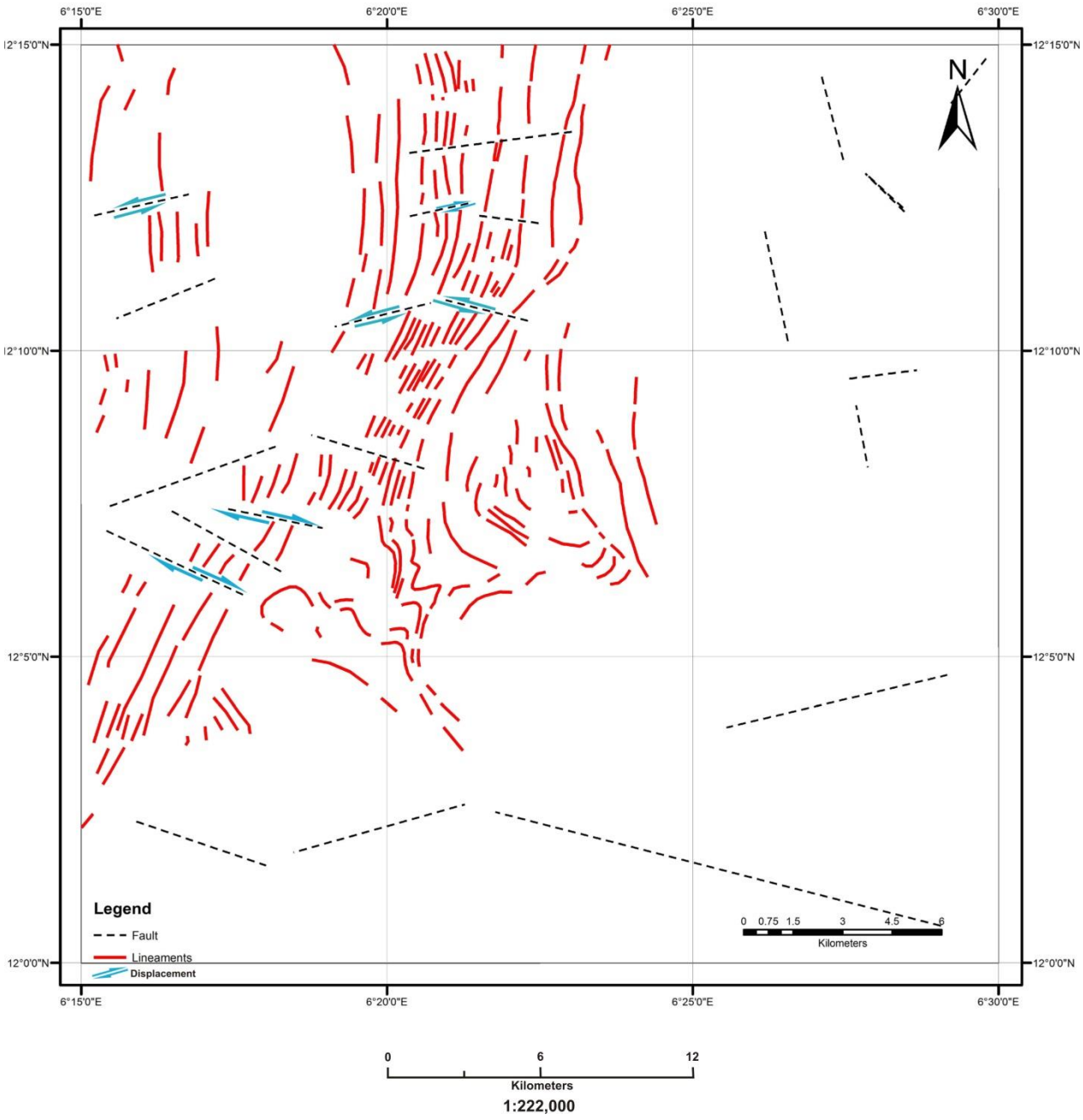


Figure 4.8: E – W trending faults system identified with the aid of N – S trending sketched lineaments

4.3.1.9 EXTRACTED FAULT STRUCTURES

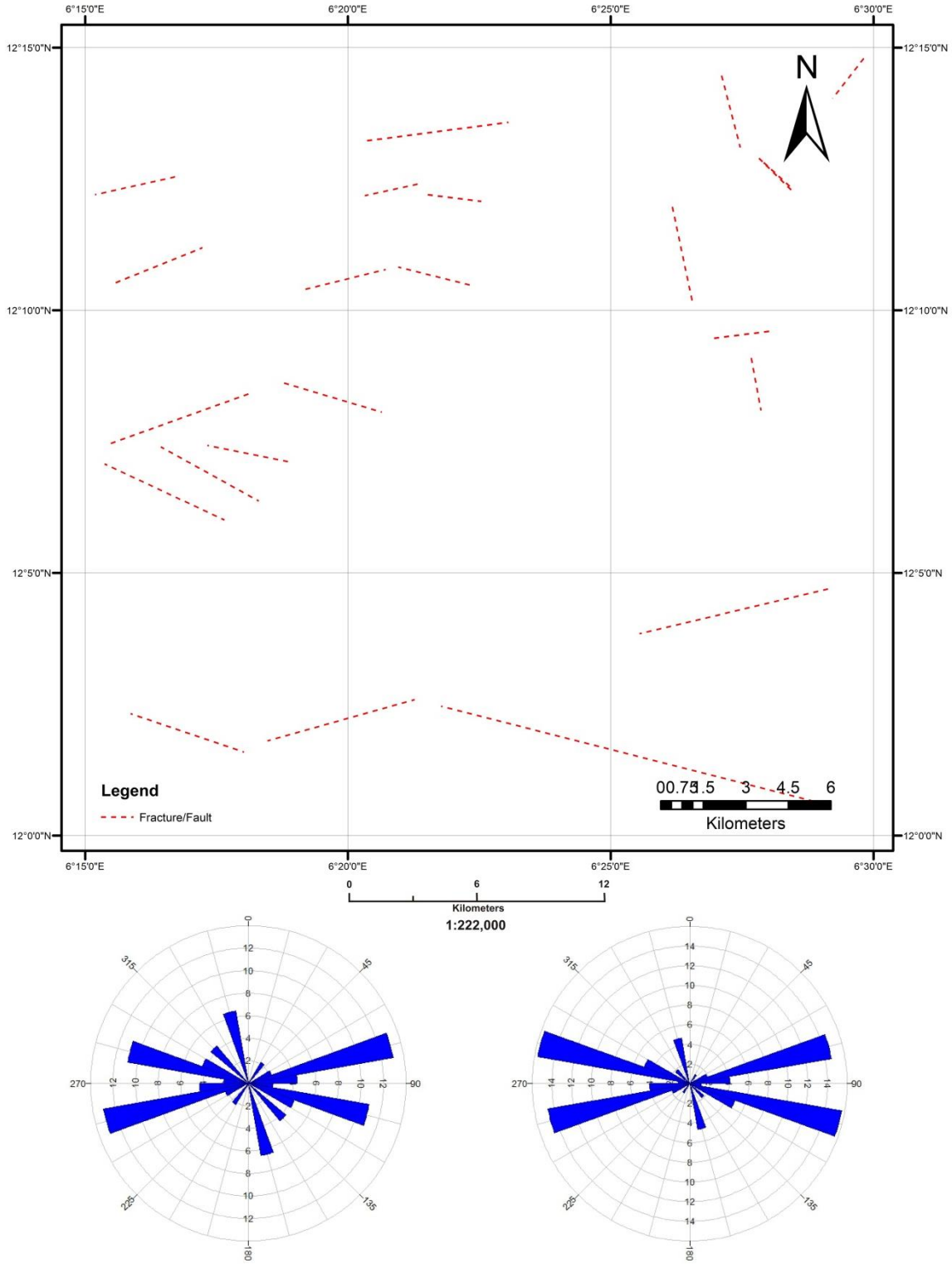


Figure 4.9: Extracted E – W faults lines with the rose diagram showing dominant trend and fault frequency

Orientation analysis using rose diagram for the brittle structures (Fractures/Faults) reveals two dominant direction of NEE - SWW and NWW- SEE directions accompanied by a less dominant NNW - SSE direction (Figure 4.9).

4.3.1.10 SUPERIMPOSED LINEAMENTS MAP ON THE DRAINAGE MAP

The final digitised lineaments map from Google Earth Pro (Fig. 4.5) is superimposed on the produced drainage map (Fig. 1.3) and the drainages were perfectly emplaced within the cross cuts (fracture/faults) along the lineaments as shown on the Fig 4.10 below. Therefore, confirming with high degree of certainty that the drainages are structurally control.

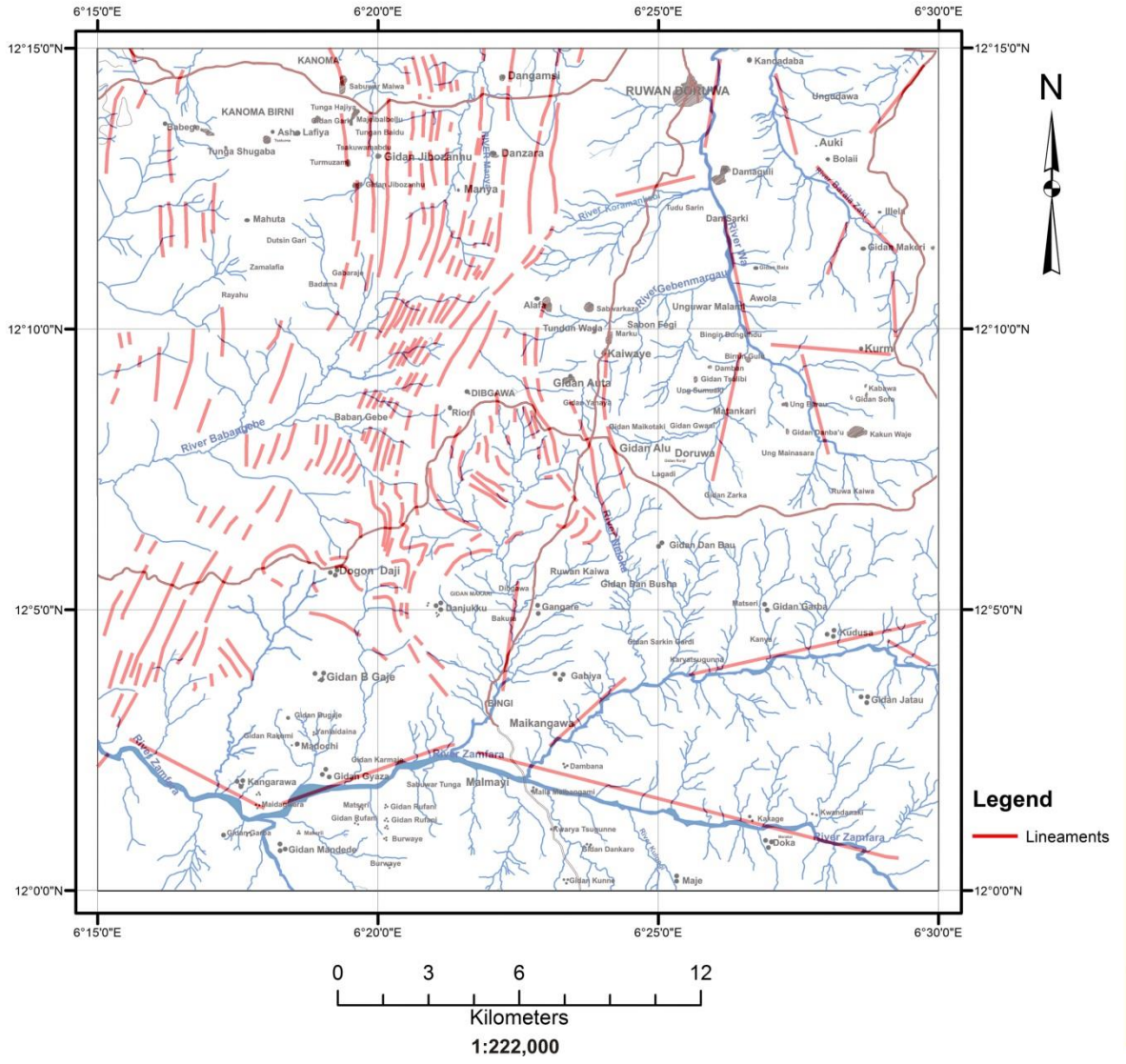


Figure 4.10: Superimposed lineament map on drainage map of the study area

4.3.1.11 FOLD BELT

A set of folds distributed on a regional scale constitutes a fold belt, a common feature of orogenic zones. Folds are commonly formed by shortening of existing layers, but may also be formed as a result of displacement on a non-planar fault (fault bend fold), at the tip of a propagating fault (fault propagation fold), by differential compaction or due to the effects of a high-level igneous intrusion.

Widespread F_2 folds of transposed layering and S_1 schistosity coupled with refolds of sporadic rare F_1 folds show that the Maru Formation was folded into a series of NNE-SSW trending F_2 antiforms and synforms, termed the Maru Fold belt and they form several upstanding ridges (Egbuniwe, 1982).

Antiforms and synforms within the study area that constitute part of the Maru Fold Belt have been identified, analysed clearly from the Google Earth Imagery.

Antiform

Arch-shaped rock structure which closes (i.e. arches) upward, but in which it may not be possible to determine the oldest rocks. It is frequently observed in complex orogenic regions

Two Antiform structures have been identified within the study area with little difference in orientation.

The Dan-Zara Antiform is an Antiform structure few kilometres east of Dan-Zara village. The Antiform appears in form of upstanding hilly ridges running in a NNE – SSW direction (Fig. 4.11).

Yar'awala Antiform is an antiform structure south of Dan-Zara village. It may be a continuation or extended part of Dan-Zara Antiform but with a little difference in orientation on fold axis. The fold axis is trending NE – SW (Fig. 4.12).

Synform

Arch-shaped rock structure which closes (i.e. arches) downward, but in which it may not be possible to determine the youngest rocks. It is frequently observed in complex orogenic regions

The Dan-Jukku synform which is clearly visible from the Google Earth imagery is formed by two different layers of rocks (Banded Iron Formation and schist), folded together forming a recumbent fold with an axis of NE-SW (Fig. 4.13).

Dan-Zara Hill Antiform

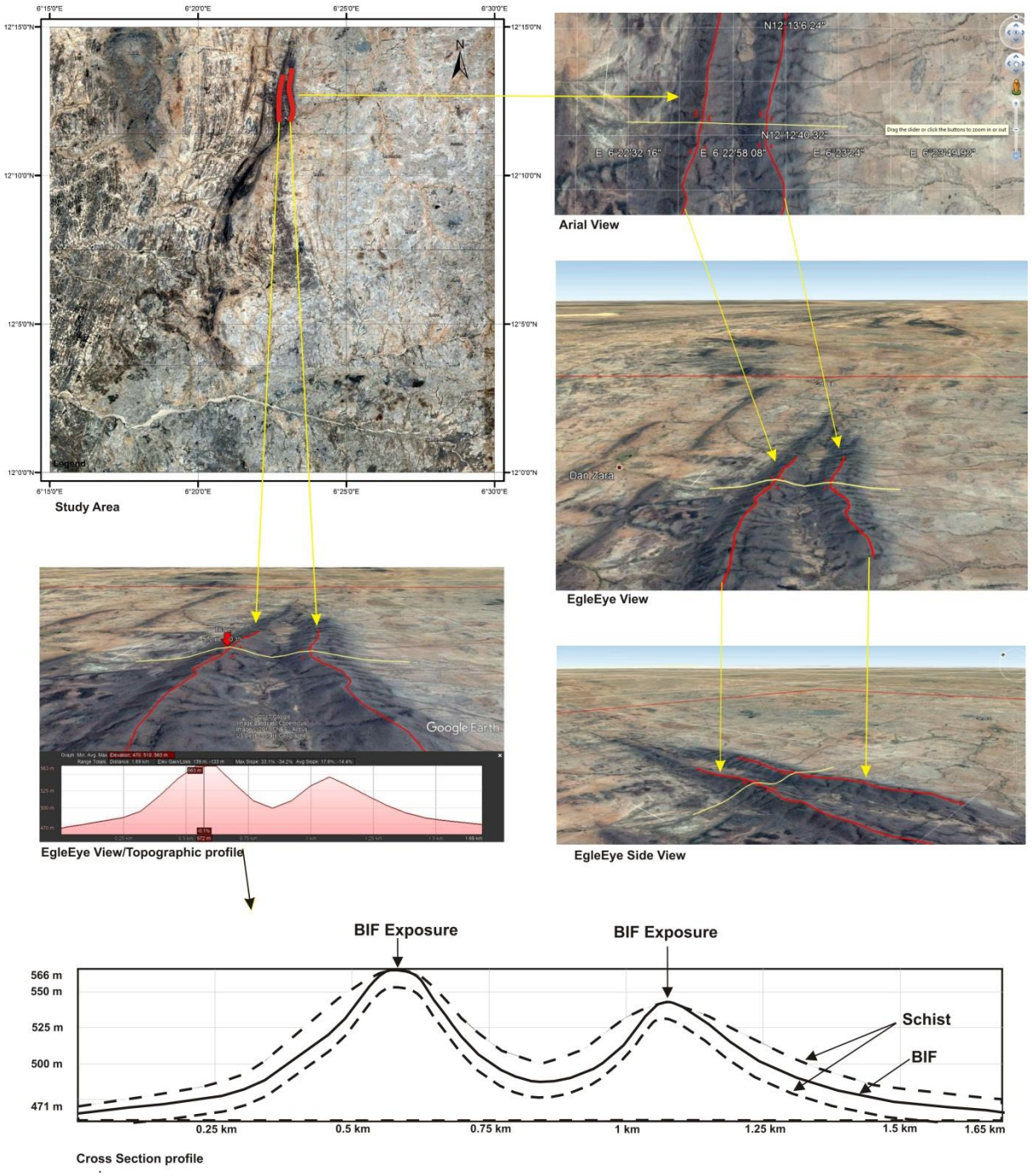


Figure 4.11: Google Earth images showing an Antiform structure with topographic profile around Dan-Zara village

Yar'awala Hill Antiform

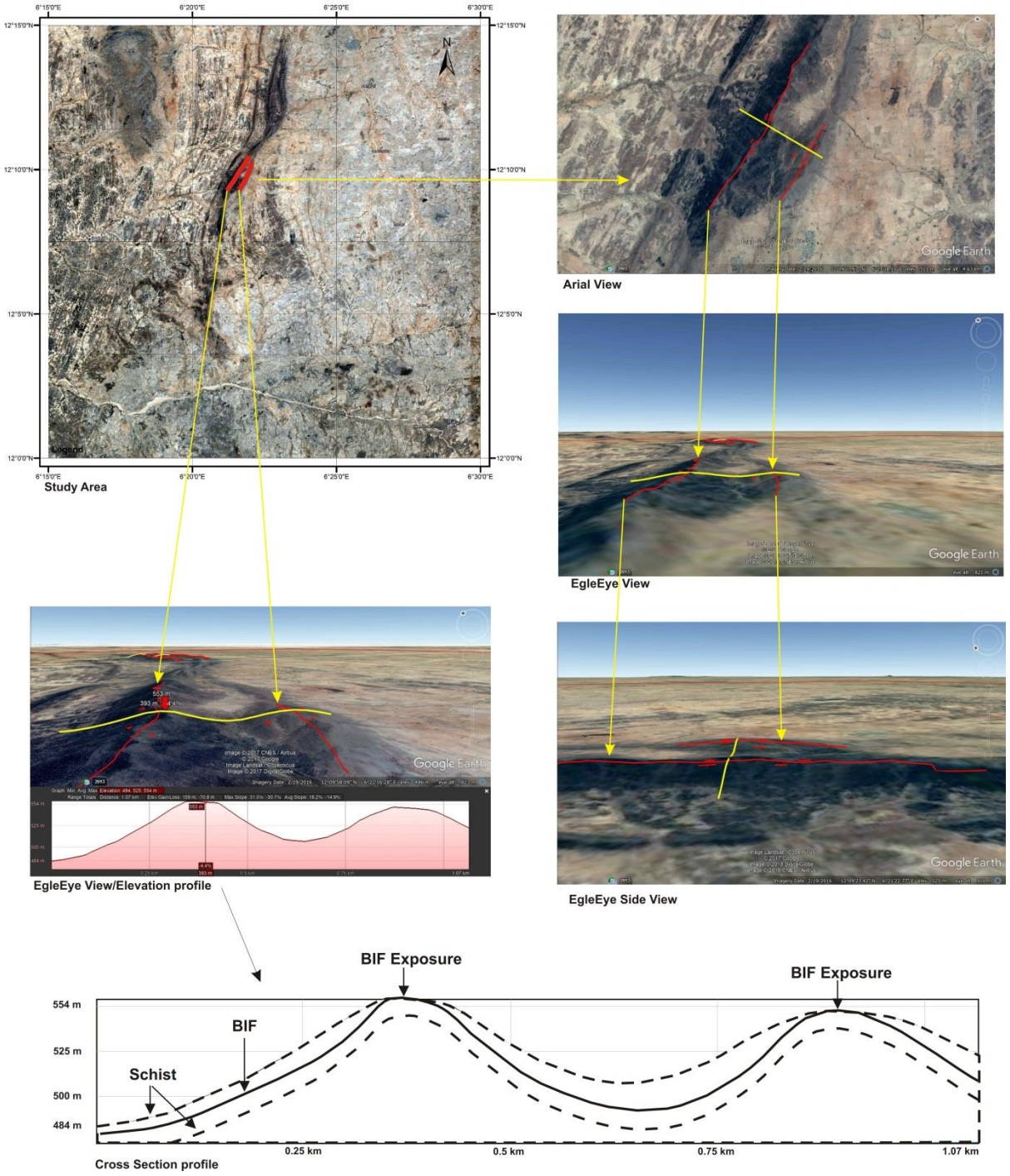


Figure 4.12: Google Earth images showing an Antiform structure with topographic profile around Dan-Zara village

Dan Jukku Synform

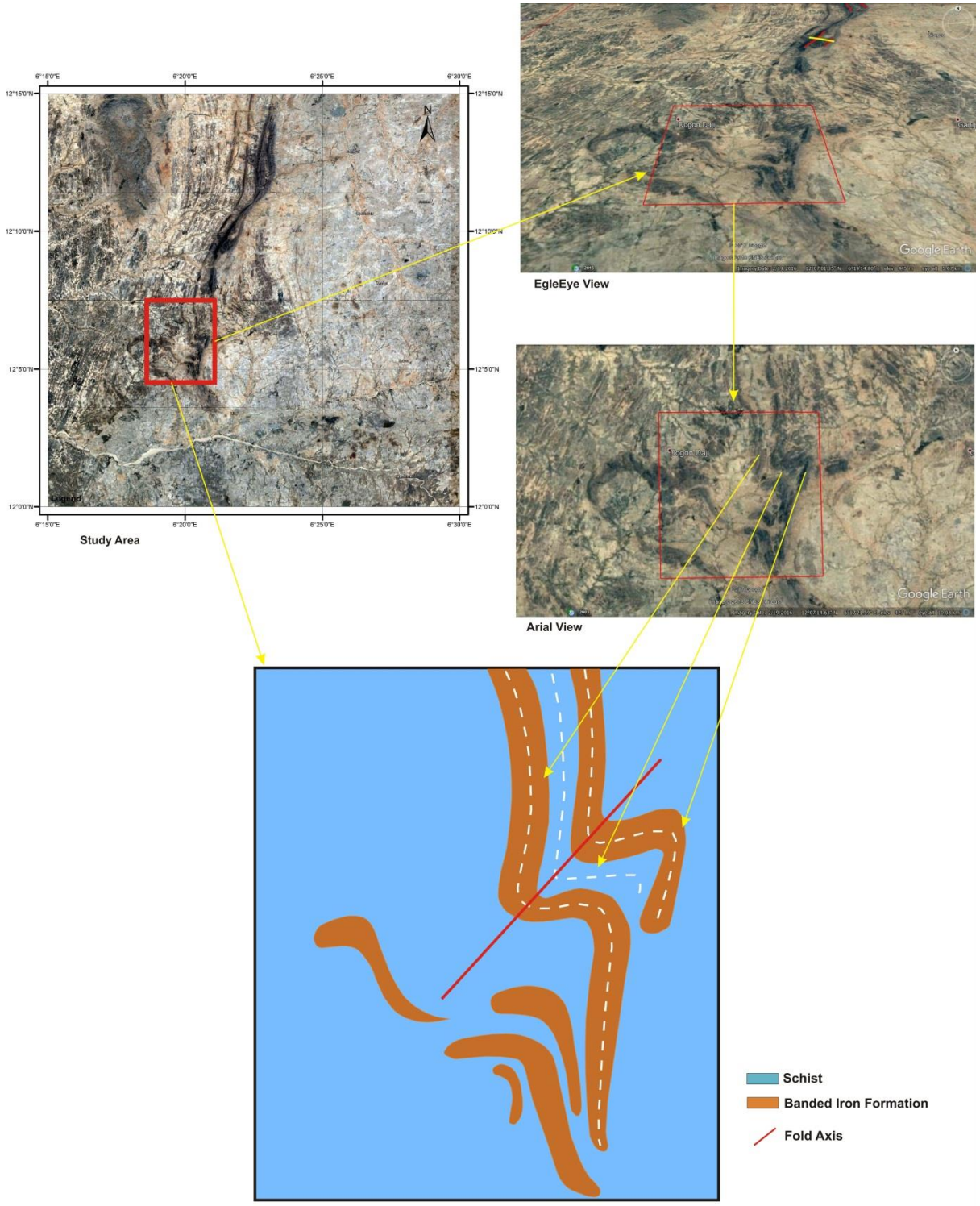


Figure 4.13: Google Earth images and geological map of the area showing a Synform structure around Dan-jukku village

4.3.2 MESOSTRUCTURES

The metasediments of the area show planar structures at places where good exposures are available. The migmatite gneiss, syenite granite and granodiorite are devoid of any planar structure, except joints which are not considered genetically important.

4.3.2.1 BANDING

Banding is a common structural feature in Banded Iron Formation (BIF) in the mapped area. This may be due to the obliterating effect of deformation and metamorphism on the original sediments.

Field observation reveals that the banding in Banded Iron Formation (BIF) ranges between 2 – 5 cm. This structural feature is mostly observed to be conformable with the foliation of the enclosing rocks. In Banded Iron Formation (BIF), banding is characterized by clear alternation of light and grey silica – rich band and iron rich dark band (Plate XVIII).



Plate XVIII: BIF excavated by artisanal miners at the top of a hill around Dogon Daji (12º 05´ 41.6″ N, 06º 18´ 11.9″ E)

4.3.2.2 FOLIATION

The migmatite gneiss complex, schist, slate and phyllite display a very strong foliation. Foliation in migmatite gneiss in characterized by the alternation of mafic and felsic mineralogical bandings (Plate XIX).



Plate XIX: A weakly foliated migmatite gneiss around Bingi. Note the dextral displacement (pen) and planar fabrics (hammer) 12º 06´ 29.8″ N, 06º 21´ 52.2″ E

Foliation in the metasediments, schist, phyllite and particularly slate, show a very strong affinity to split into very thin, planar fabrics. The S_1 layer is a product of the first deformational episode, D_1, which is an axial planar to the F_1 fold (Plate XX).



Plate XX: A strongly foliated schist outcrop showing the NNW – SSE planar fabric. Note the concordant quartz boudins at the left flank of the outcrops. The location is about 2km NNE of Rioji (12º 12´ 43.4″ N, 06º 22´ 02.2″ E)

Generally, foliation in the mapped area conform with NNE-SSW trends of the Nigerian basement complex and mostly dip N - S. However, at about 2.3 km of Madochi, the foliation trend East – Westward.

4.3.2.3 LINEATION

Lineations are any linear fabric element related to deformation. Close field observation reveals the intersection of crenulated S_1 surface (earlier foliation) with the S_2 surface to form intersectional lineation (Plate XXI).

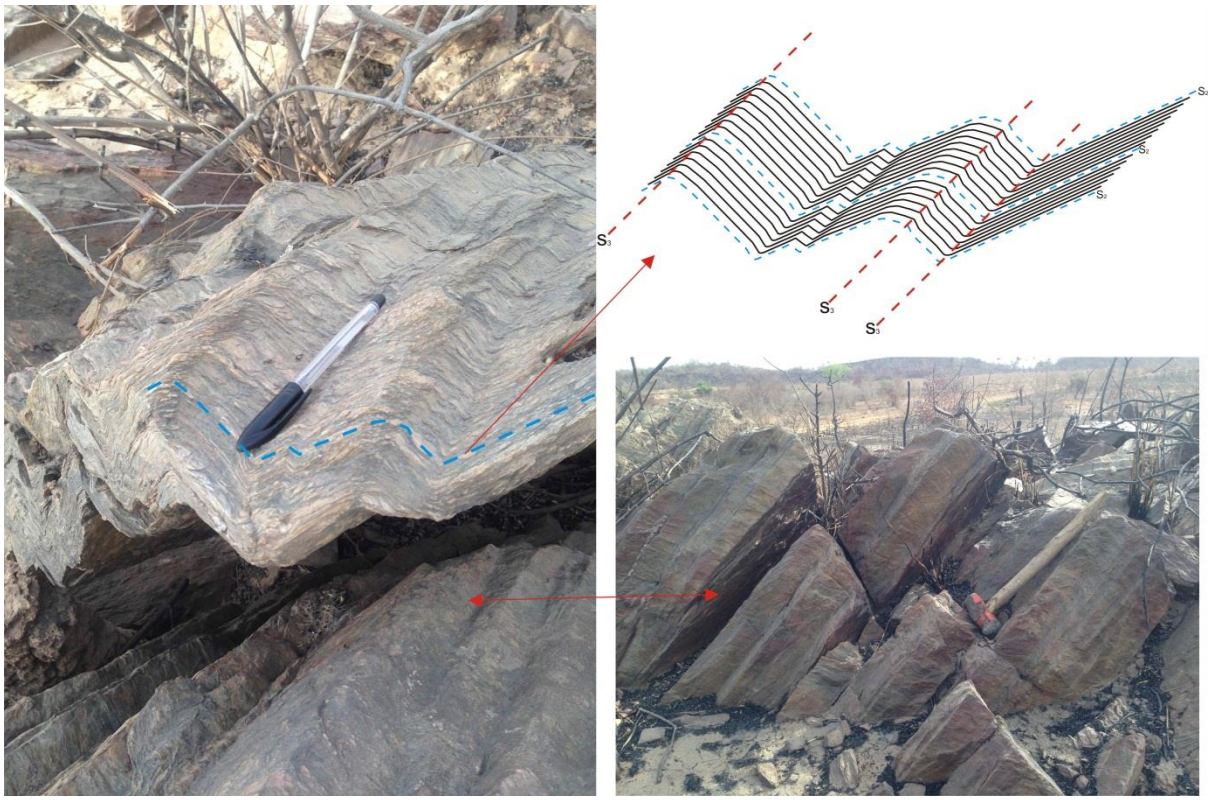


Plate XXI: A chevron fold observed on a fairly hilly phyllite outcrop. The locations is about 3.1km WNW of Dogondaji (12º 06´ 24.1″ N, 06º 19´ 55.8″ E)

The limb of the crenulation cleavage is close and asymmetrical. Silicate layer in the S_1 surface was observed to align along a preferred orientation.

4.3.2.4 MINOR FOLD

Pinch and swell structure, tight, isoclinals, close folds were frequently mapped in the study area (Plate XXII, XXIV). The secondary fold structure, F_2 is a product of refolded fold referred to as F_1.

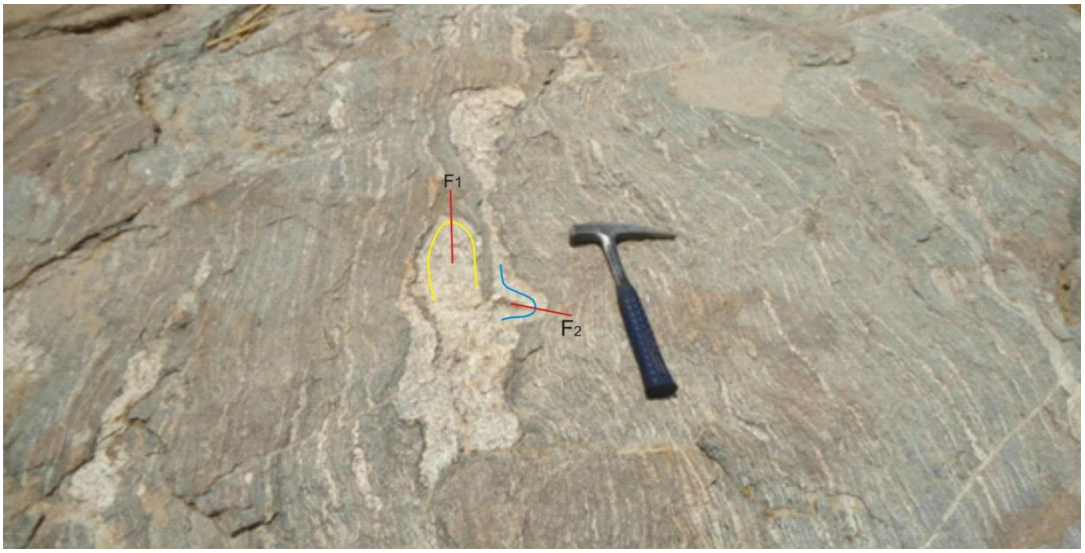
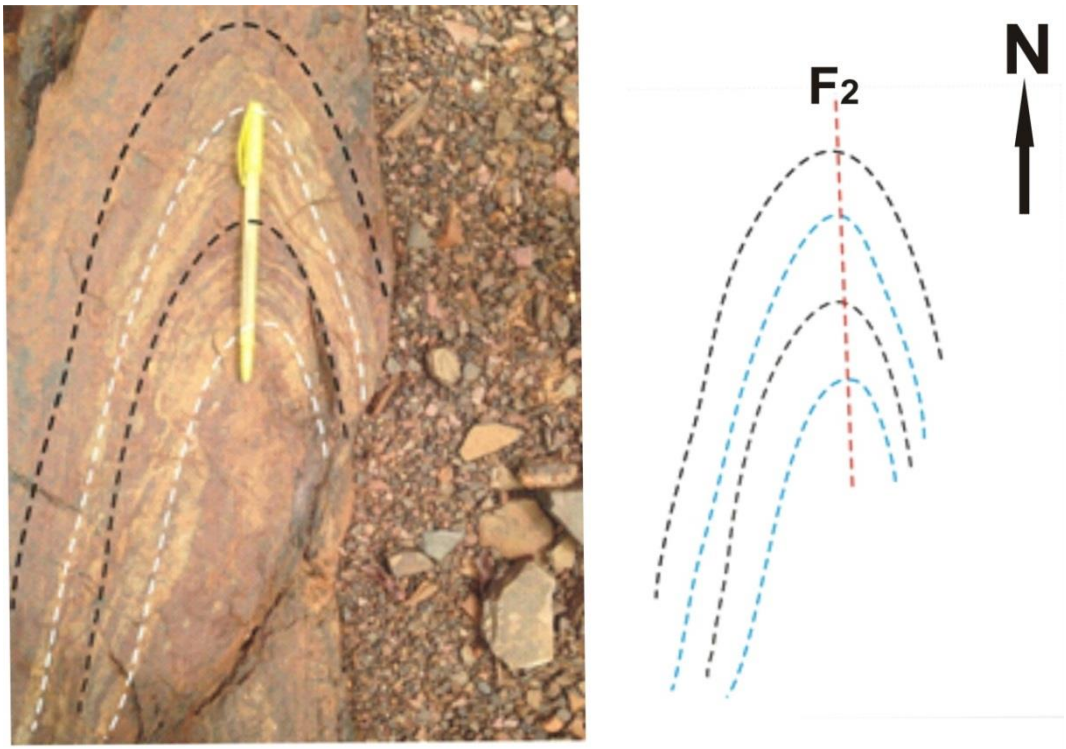


Plate XX1I: Ptygmatitic fold observed in the migmatite gneiss. The location is a about 1km east of Bingi. Note the F1 fold axial plane concordant with the planar fabric and the F2 axial plane perpendicular with the planar fabric (12º 03´ 29.8″ N, 06º 21´ 52.2″ E)



Plate XX11I: Pinch and swell structure within the BIF captured at about 3.2km WNW of Dogondaji (12º 05´ 44.5″ N, 06º 19´ 33.6″ E)



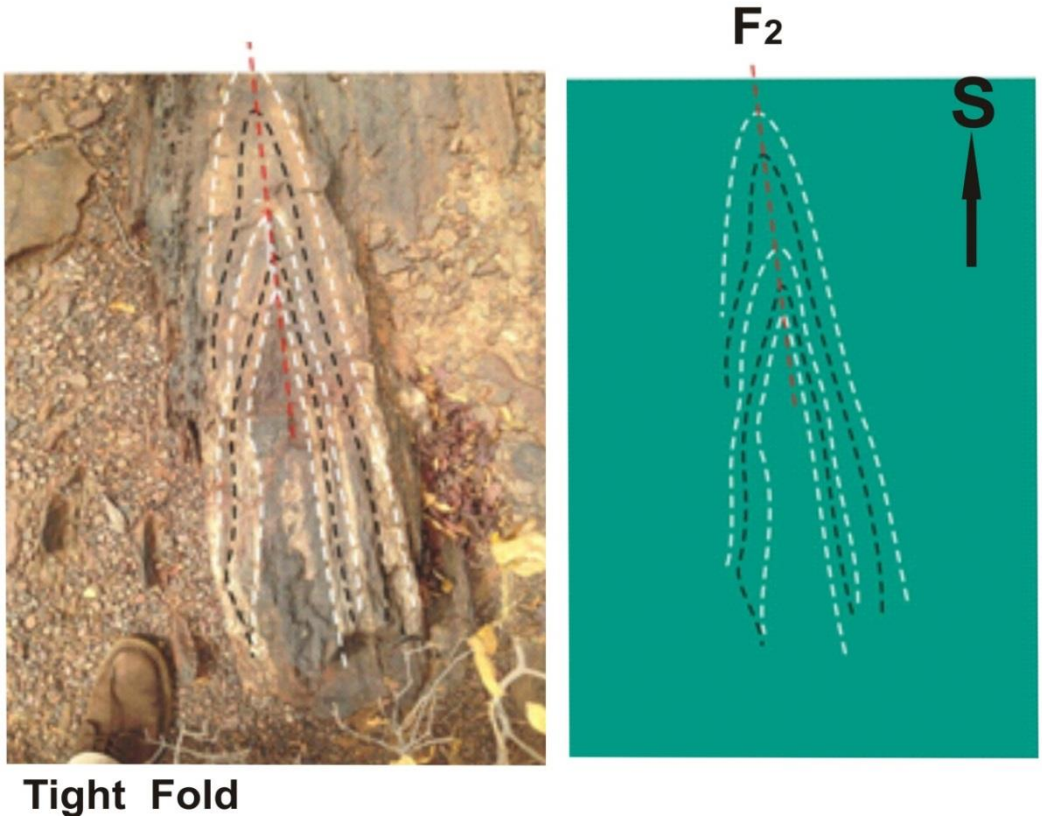


Plate XXIV: Local fold structure developed by the mesobands of BIF on the hill in Danzara village, the pen is about 15cm long: the boulder is in situ (12º 13´ 27.7″ N, 06º 32´ 18.1″ E).

4.3.2.5 QUARTZITE

Quartz ridge outcrops essentially in close association with the pelitic rocks and medium grained granite. An exposure of these intrusive bodies encountered in the area of study generally trends NW – SE. However, NE – SW trending outcrops occasionally occurs in few localities. This probably suggests different generations for the quartzite emplacement (Plate XXV).



Plate XXV: A NW – SE trending quartz ridge mapped southwest of Asha Lafia (12º 13´ 25.5″ N, 06º 19´ 23.3″ E)

Prominent quartz ridge intrusions were the NW – SE trending outcrop mapped south west of Asha lafia and north east of Kanoma. Field observation reveals that the quartzite have been fairly weathered resulting into boulders. It ranges between white to dirty white to brown in colour. Quartzite lies either conformably and disconformably with the planer fabrics of the country rocks.

4.3.2.6 MAJOR FOLD

About 1 km ESE of Dan-Zara, easterly and westerly structural dips were observed probably suggesting part of an antiform referred to as Dan-Zara hill antiform (Plate XXVI).



Plate XXVI: A fairly hilly schist antiform. Female geologist standing on the westerly dipping flank with the male geologist on the easterly dipping flank. The location is about 1km ESE of DanZara (12º 12´ 54.1″ N, 06º 22´ 38.5″ E)

4.3.2.7 SHEARING

Minor shearing is commonly associated with migmatite gneiss complex as mapped in Bingi with marked dextral and sinistral displacements (Plate XXVII).



Plate XXVII: Sinistral/dextral shearing in a migmatite gneiss outcrop around Bingi (12º 03´ 18.4″ N, 06º 21´ 51.7″ E)

4.3.2.8 FAULTS

Series of sinistral and dextral displacements occasioned by minor faults occur essentially within the migmatite gneiss complex, medium grained granodiorite and syenite. The amount of displacement ranges between few centimeters (Plate XXVIII).



Plate XXVIII: Sinistral and dextral displacement within the various rock types in the study area migmatite gneiss at about 1km east of Bingi. Note the contorted planar fabrics

4.3.2.9 JOINTS

Macro joints are common in the study area. The conspicuous joint surfaces in most outcrops have dimensions ranging between tens of centimeters to few meters. Both the phyllite, migmatite gneiss and schist were densely jointed. However, the granodiorite equally shows appreciable joints (Plate XXIX – XXX).

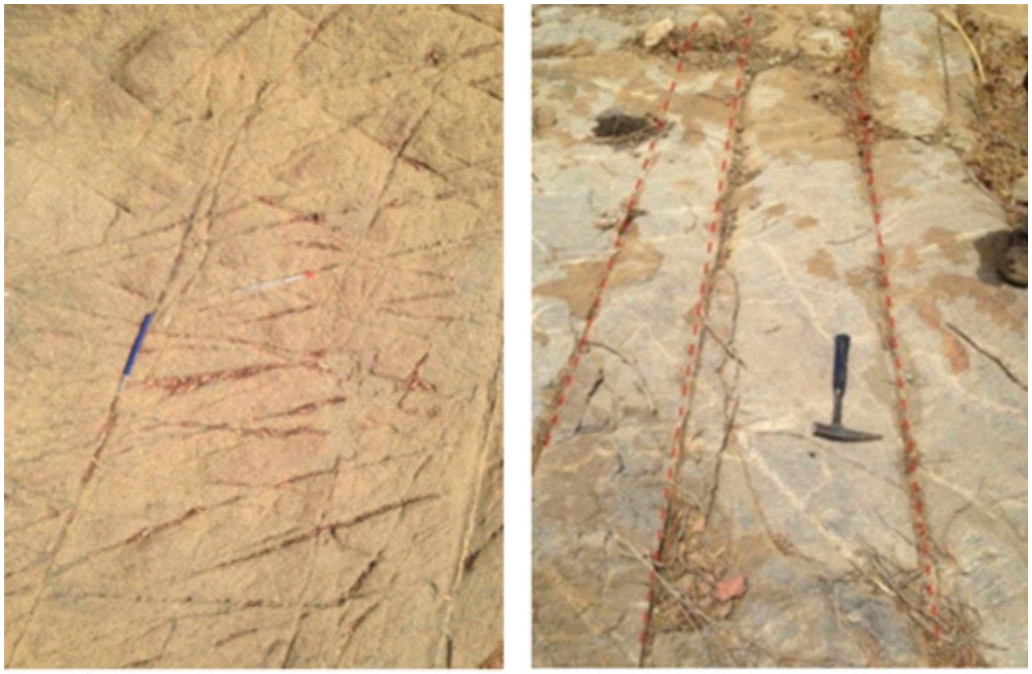


Plate XXIX: Joint sets forming blocks as captured in Syenite and sheared Migmatite Gneiss

Most of the joints are barren hairline cracks or empty fissures. However, joints which are healed up with narrow vein of secondary minerals, commonly quartz, were prominent in the medium grained granite and syenite plutons.

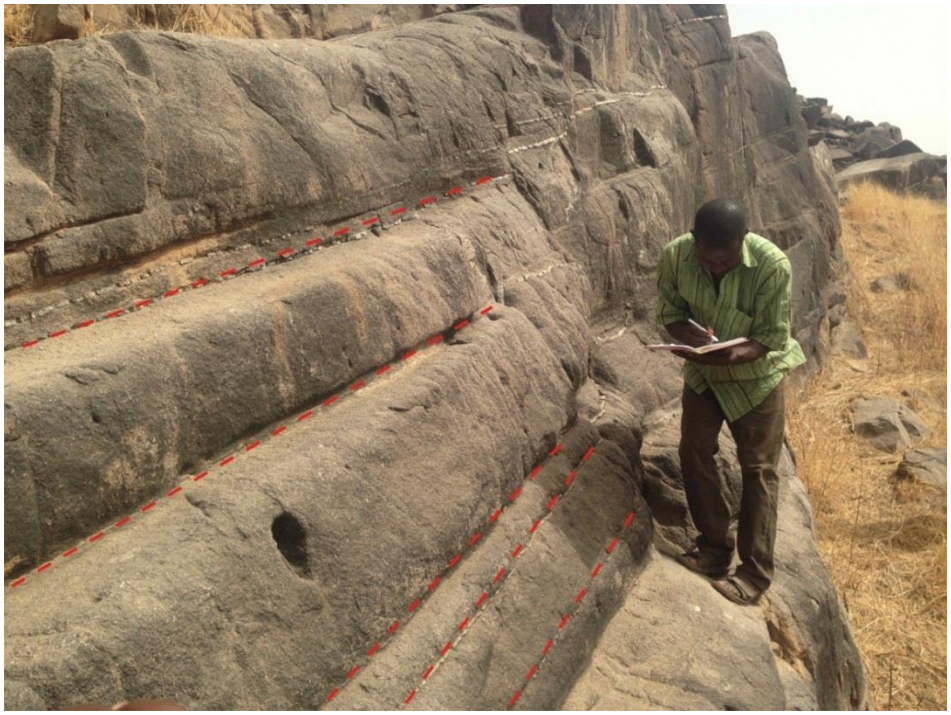


Plate XXX: Pluton of sheared or localised syenite granite around Kanoma. Note the bands and joint healed up by quarterzofeldspathic vein (12º 14′ 48.6″ N, 06º 17′ 55.9″ E)

The rose diagram reveals that the predominant joints trends essentially NEE – SWW and less dorminant direction of SE - NW for granodiorite, and migmatite gneiss (Fig 4.14).

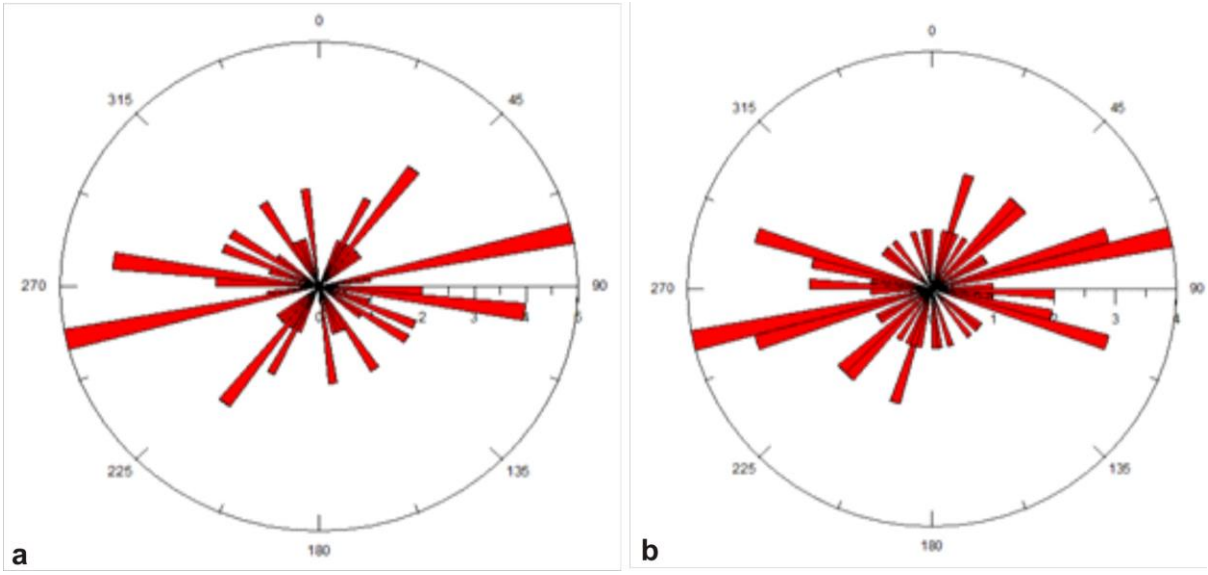


Figure 4.14: Rose Diagram of Joints on granodiorite (a) and migmatite gniess (b)

4.3.3 MICROSTRUCTURES

Thin sections were examined to characterize the microstructural aspects of important mesoscopic structures in the core of the rocks in the study area.

Thin sections observations allow us to find fine structures that may not be visible in an outcrop scale or a hand specimen. It also allows us to link metamorphic and structural histories together.

4.3.3.1 FOLIATION (S_1)

In this metapelitic rock that is composed of needle-like arrangement of micaceous minerals (muscovite and chlorite), few grains of fine to coarsed-grained quartz and opaque minerals occur. The rock is foliated (Plate XXXI).

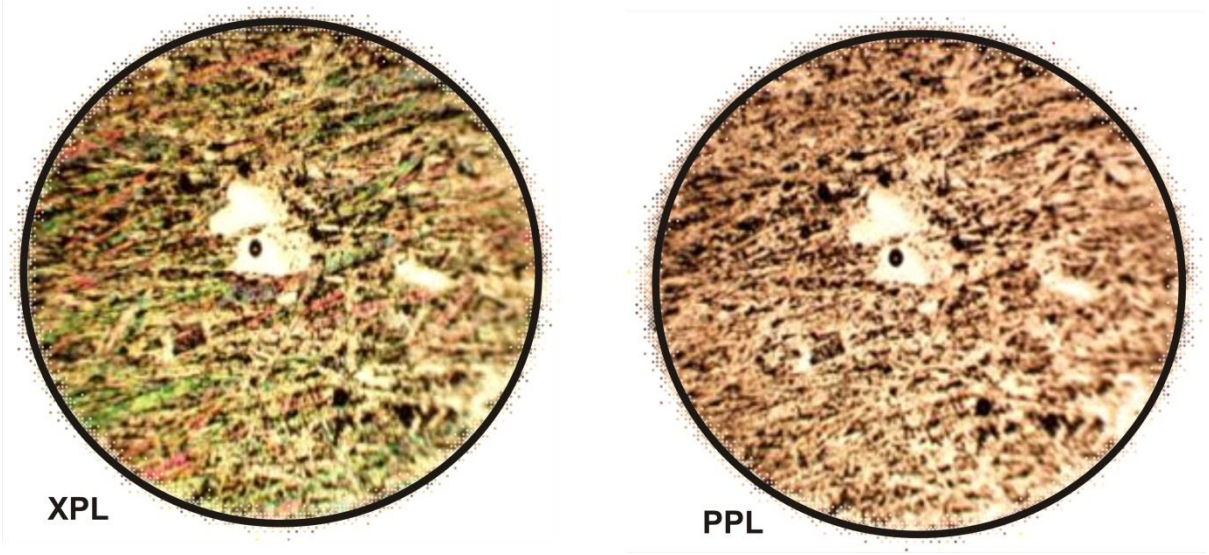


Plate XXXI: Photomicrograph of metapelitic rock showing a needle-like arrangement (foliation). Mag x40

4.3.3.2 CRENULATION CLEAVAGE (S_2)

Foliation is among the most prominent features of deformed rocks in the study area. Crenulations are small folds, typically axial planar to larger-scale folds, that deforms earlier foliations (XXXII).

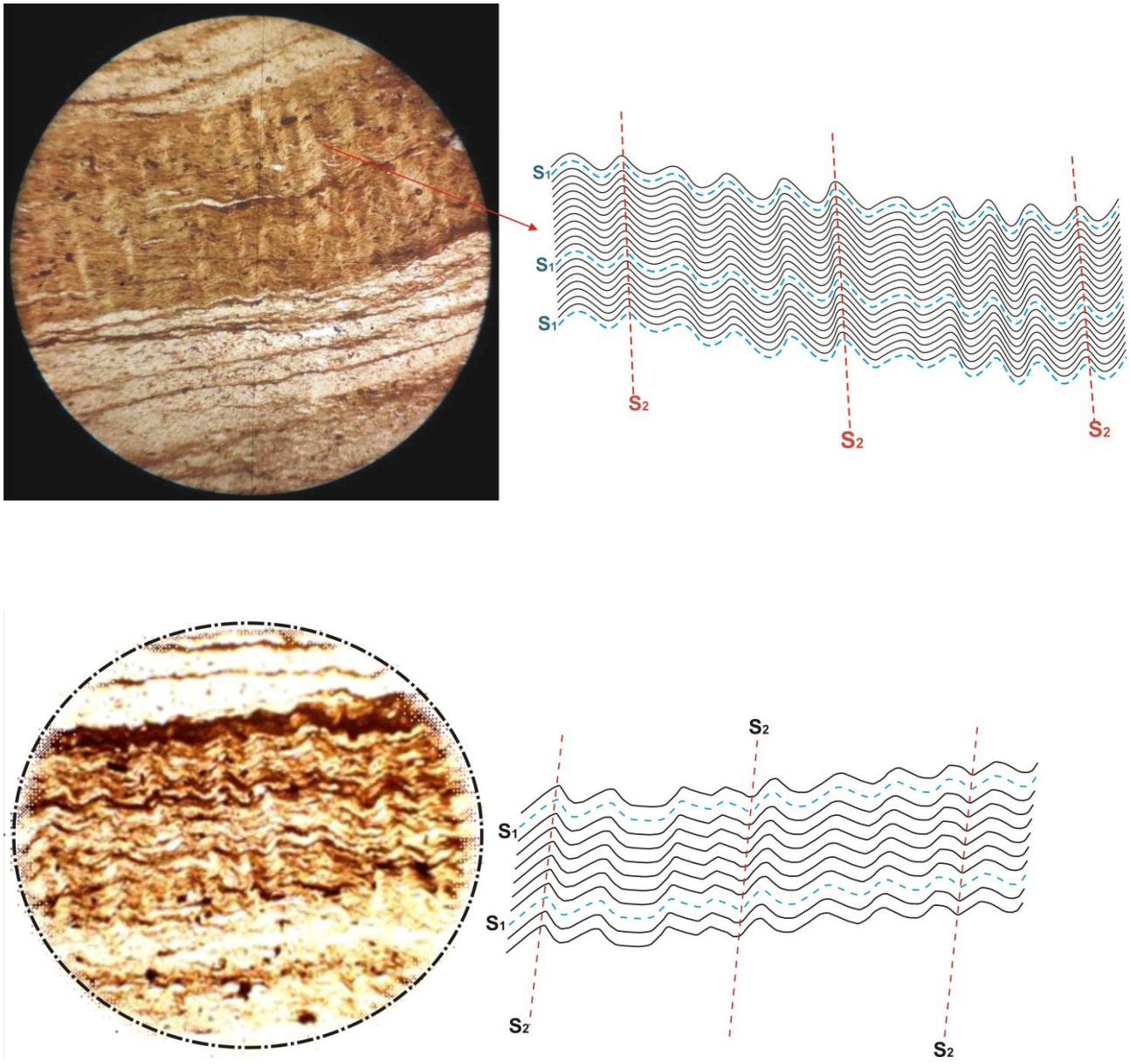


Plate XXXII: Photomicrographs of two different schists showing a crenulation cleavage

The schist has a strong foliation (S_1) defined by muscovite and quartz. That foliation has been deformed by crenulations (S_2), small folds in the foliation (Plate XXXII). During crenulation development, quartz (especially) can become concentrated in the crenulation fold hinges, leaving behind other, less soluble minerals in the fold limbs.

4.3.3.3 CHEVRON FOLD

The photomicrograph below (Plate XXXIII) is a chevron fold showing a folding (deformation episode) with a microfolds within it. The red dotted line is the axial traces of the obvious set of folding (F_1) formed by S_2. The dotted blue lines are axial traces of another set of micro-folding (F_2) within the mega-fold (F_1) formed by S_3, indicating two phases of folding (deformation).

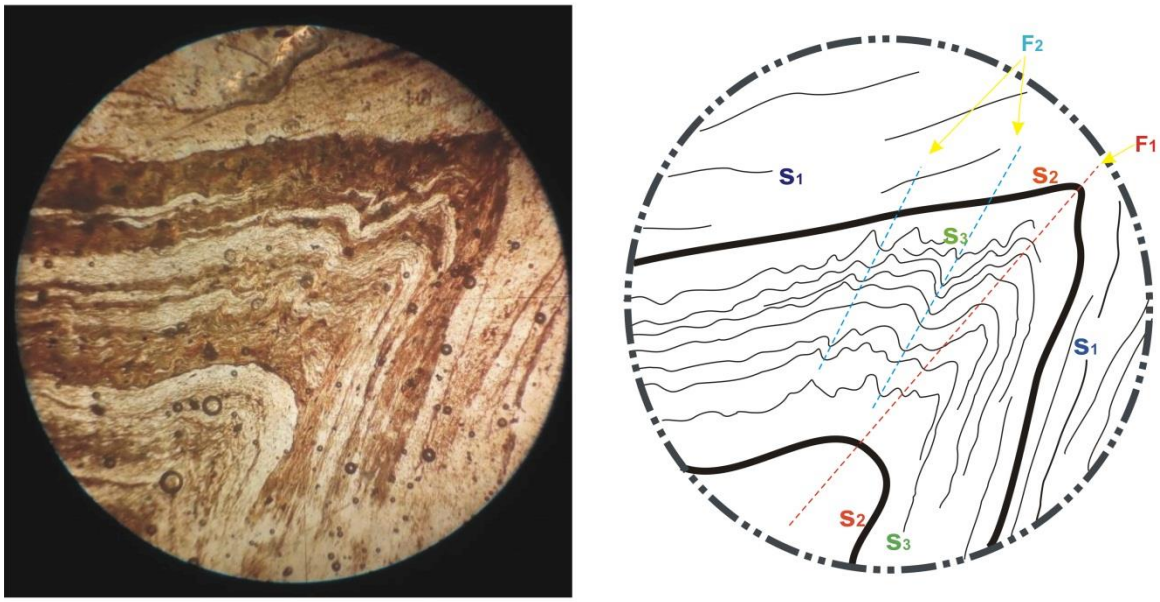


Plate XXXIII: Photomicrograph of chevron fold in a phyllite showing two episodes of deformation.

4.3.4 STRAIN ANALYSIS

Strain measurement involves the use of selected relevant strain markers that are consistently distributed within the studied rock body and which can be easily used. The choice of which method to apply is also dependent on a good exposure of the long and short axes of the strain markers as well as availability of the processing package (Ogezi, 1977; Ajibade and Wright, 1988; Annor and Olasehinde, 1996). The rock types in the study area do not show adequate exposure of macroscopic porphyroblasts that can be easily measured on the field. This posed a major challenge to field estimation of strain hence the Fry (1979) method was adopted. Deformation patterns on the basement rocks of Nigeria are so complex (Rahaman, 1988; Ogezi, 1977; Ajibade and Wright, 1988; Mc Curry, 1976) and hence require a detailed study to understand their strain history. Additionally, the homogeneity of deformation on the rocks which is dependent on the degree of response to the prevailing stress fields is important in elucidating the tectono-metamorphic conditions that affected the rocks. These, in addition to other geological and geochemical parameters can give clues to the geodynamic evolution of this Pan-African mobile terrain (Amadi and Olasehinde, 2010).

4.3.4.1 Micro-structural strain estimation and interpretation

Strain estimates were carried out to determine bulk strain and to interpret correctly the degree and variability of metamorphism as well as the extent of deformational effects on the different rock types, resulting from the different tectono-metamorphic cycles. Several methods of estimating two dimensional strains from the deformed rocks have been proposed, according to Hari (2009) most of which require the measurement of long and short axes of deformed objects called strain markers. The Fry method, according to Fry (1979) is based on the assumption that initially uniform anti-clustered distribution of points will change after deformation into a non-uniform distribution. In this method, centre of the entire grains screen digitized on the selected micrographs of the gneisses using EllipseFit v3.0 package which

creates a vacancy called Fry hallow of ellipsoidal shape giving directly the long and short axes (Figure 4.15). The orientation of the ellipse also gives the orientation of the strain ellipse. Consequently, the finite strain ellipsoid that is almost circular shows low degree of grain deformation, while the flattened type shows a greater degree of grain deformation.

The ellipsoidal shapes of the grains generated using the Fry method on the photomicrograph of the thin sections of rocks from the study area has revealed heterogenous and varying grain deformation as well as varying orientations corresponding also to the marginal N-S, NE-SW, and NNE-SSW (Figure 4.16). The shapes range from near circular type (axial ratio 1.036) on the granodiorite and syenite granite on the southern, eastern and north-western portion of the study area, which is indicative of low degree of deformation, hence average grain elongation in the directions of NE-SW and NNE-SSW on the migmatite gneiss showing a moderate degree of deformation, to the flattening type on the metasediments which show the highest grain elongation of axial ratio 3.267 signifying a flattening type (Genier and Epard, 2004) in the directions of the marginal NE-SW and NNE-SSW. The result is the strain and structural map shown in Figure (4.17). Critical observation of the ellipsoidal shapes of the different rock types across the study area shows progressive grain deformation from the granodiorite to migmatite gneiss down to the metasediments.

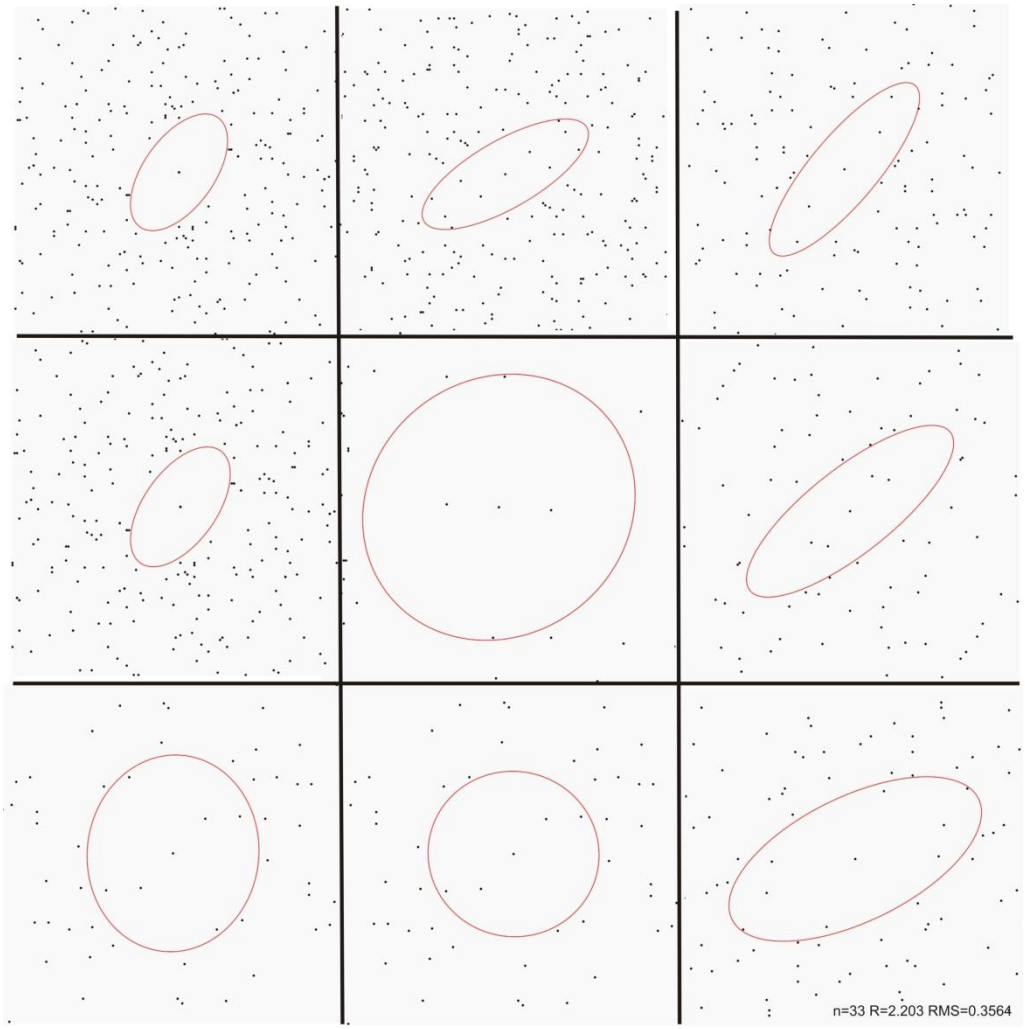


Figure 4.15: Fry haloes from selected samples generated from micrographs of the study area.



Figure 4.16: Micro-structural strain ellipsoids data from deformed quartz grains from the rocks.

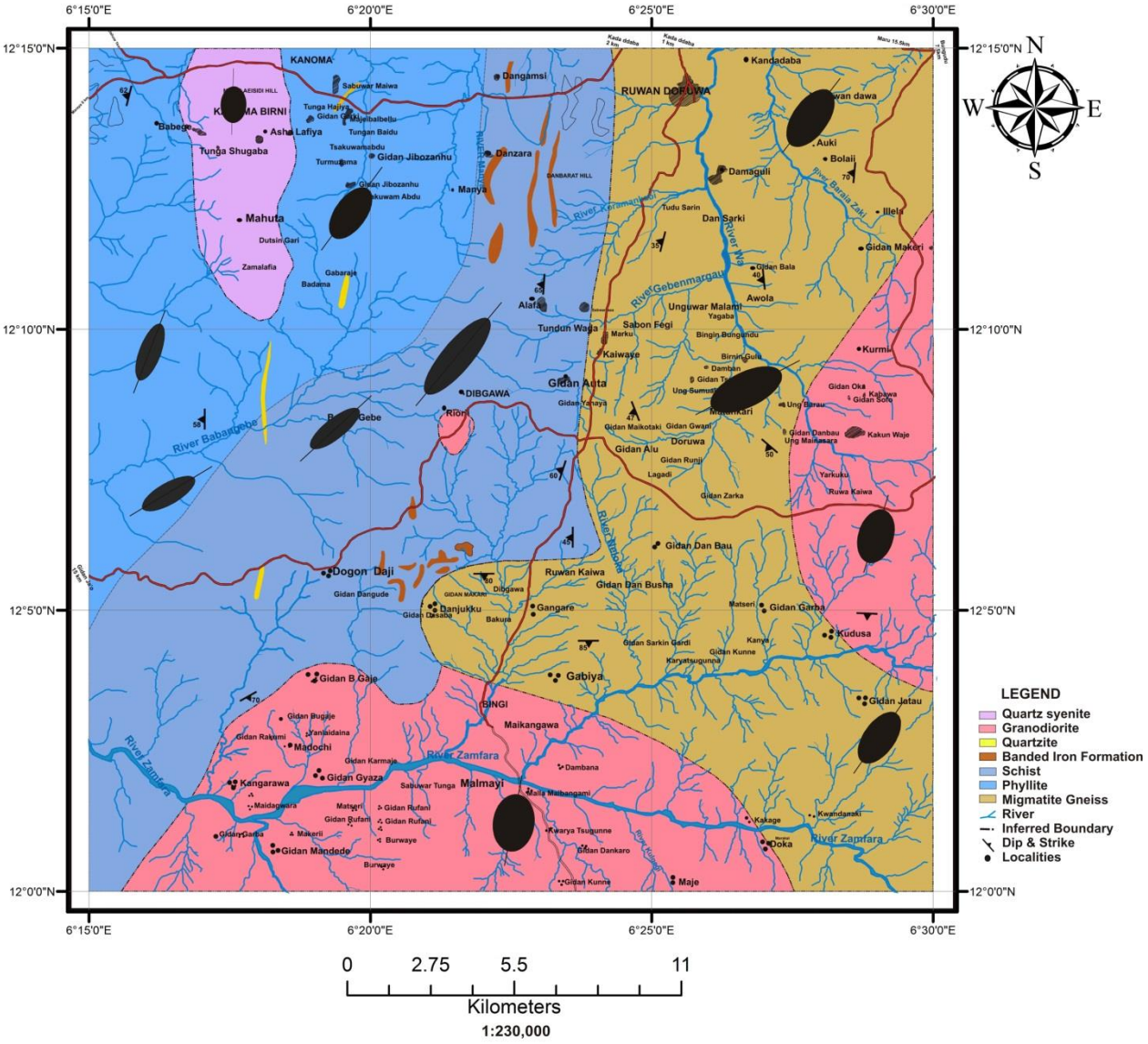


Figure 4.17: Strain ellipsoids and orientation distribution map of the study area.

CHAPTER FIVE

DISCUSSION AND CONCLUSION

5.1 GEOLOGY AND PETROGRAPHY

The study area (Maru SE) which is part of Maru Schist Belt consists predominantly of pelitic to semi-pelitic metasediments interlayered with psammites, granodiorite, migmatite gneiss, Banded Iron Formation (BIF) and metabasic rocks. The pelites are represented by phyllites and schist while the psammatites and the semi-pelites are represented by quartzites and quartz schists. Metabasic rock is amphibolites. The schist and phyllites predominantly consist of muscovite, garnet and quartz with subordinate chlorite, biotite, epidote and tourmaline.

5.2 STRUCTURAL ANALYSIS

Lineaments were manually digitised in this work as they are clearly visible and mostly restricted within the metasediments. A Rose Diagram of the lineaments revealed a major trend of NNE – SSW direction which is in accordance with the regional schistocity (S_2). The mega-structures, which are very prominent in the study area show that the Metasediment was folded into a series of synforms and antiforms as defined by large-scale structures. All the rocks strike approximately N – S, parallel to the structural pattern of the surrounding basement complex (Egbuniwe, 1982; Adekoya, 1998; Ibrahim, 2010, 2012).

Large-scale F_2 folds formed an antiform that lies east of Dan-Zara village. The axial trace of this antiform is trending NNE-SSW in relation to regional schistocity (S_2). Symmetrical folds in the crest of the antiform plunge steeply northwards, probably reflecting the attitude of the major structures. The limbs of the antiform are lost in the prominent S_1/S_2 cleavage which dip steeply east and west.

A minor swing in the axial trace of the antiform (large-scale F_2 folds) and the regional schistocity (S_2) from NNE – SSW to a NE – SW orientation. Thus, forming Yar'awala antiform structure with an axial trace of NE – SW, south of Dan-Zara village.

The synform is defined by a major swing in the S_2/S_3 schistocity of schist and Banded Iron Formation (BIF), the strike and dip of small-scale F_2 axial planes and by small-scale F_3 folds which generally strike NE-SW and dip towards the core of the synform. The axial trace of the major fold, as defined by the orientations of the small scale structures is curvilinear, from E-W to ENE-WSW. Local changes in the direction of F_3 small-scale folds suggest that a minor antiform which forms a fold pair with the synform lies to its north.

Deformational Structures of the First Generation (D_1 episode):

No major structure which can be attributed to the D_1 deformation has been recognised due to the rarity of F_1 folds and the common parallelism of lithological layering, S_1 and S_2 cleavages. Very little is known of the first deformation in the study area as much of the evidence has been obliterated by later events. Egbuniwe (1982).

Deformational Structures of the Second Generation (D_2 episode)

D_2 structures, which are the most prominent and widespread in the region show that the Maru Formation was folded into a series of synforms and antiforms as defined by large-scale structures during this deformation episode. F_2 large-scale folds are generally upright structures with NNE-SSW trending axial planes and gently to steeply plunging axes; the variable plunges, as argued in the preceding sections, are probably due to heterogenous D_2 strains. S_2 is an axial planar crenulation cleavage which deforms the S_1 transposed layering and schistosity is F_2 fold hinges. In the fold limb, it is a co-planar to both structures so that the three are indistinguishable in most places. Hence the NNE-SSW structural trends in the Maru belt is probably a combination of D_1 and D_2 structures (Egbuniwe, 1982).

Deformational Structures of the Third Generation: (D_3 episode)

The D_3 deformation is most pronounced in the Dan-Jukku village at the central part of the study area, where it caused a swing in the orientation of the regional fabric from NNE – SSW to ENE – WSW and produced the Dan-Jukku synform. F_3 structure is clearly visible from the Google Earth satellite imagery, and meso to micro scale structures are common as moderately in steeply plunging non-cylinderical asymmetric chevron folds.

The possible structures (deformation episode) that control the mineralization within the study area are the D_3 structures (Pan-African structures) which serve as conduits for metallic mineralization in the western part of Nigeria.

5.3 STRAIN ANALYSIS

Strain analysis using grain size distribution, the progressive increase in grain deformation is corresponding to the decrease in grain sizes across the study area. The heterogeneous and varying grain deformation could be attributed to variation in mineral assemblage, heterogeneity of rock composition and probably variation in temperature and pressure conditions of metamorphism across the study area or the entire region.

5.4 CONCLUSTION

The Maru belt, like other schist belts of Nigeria exhibits complex structural patterns, as a consequence of poly metamorphism. At least three deformational episodes have been identified in the Maru belt corresponding to D_1, D_2 and D_3 structures.

The new geotectonic model by Danbatta (2003) favours the evolution of the schist belts through both ensialic and ensimatic processes, by first postulating the existence of small pre-Pan-African ensialic basins that were compressed in Eburnean times. Schist belts without mafic and ultramfic rocks but with documented presence of Algoma BIFs are considered ensialic and Eburnean in age. BIFs are absent in those schist belts whose origin is ascribed to ensimatic processes and Pan-African age.

The BIF are reported to be confined to certain geologic ages, and that the BIF of Maru Schist Belt have been shown to belong to the Algoma type (Mucke *et al.,* 1996), or Lake Superior type (Ibrahim, 2010, 2012), in either case, the BIF is indicated to be older than the Mesoproterozoic. Therefore, since the BIF is syngenetic with the associated rocks, (Klien, 2005; Mucke *et al.,* 1996) the initial deformation of the Maru formation could not have occurred during the Kibaran (1100 Ma) as indicated by Egbuniwe, (1982) and Fitches *et al.,* (1985), since this age bracket does not fall within the metallogenetic epoch of BIF as shown by Gole and Klein, (1981); Walker *et al.,* (1983); Trendall *et al,.* (2004); Klein, (2005).

The development of atoll garnets in the BIF (Ibrahim, 2012), therefore supports the proposal of Dada, (1998) that the metasedimentary belts of Nigeria belongs to the Paleoproterozoic which is contrary to the views of Ajibade *et al* (1987) which supposes that the schist belts of Nigeria to be Pan African (600±150 Ma). However, the Pan African is regarded by many workers to have mildly affected the northwestern Nigeria basement complex. Large scale plutonism was however shown to be associated with the Pan African (McCurry, 1976;

Ajibade *et al.,* 1987) this Pan African plutonism led to the emplacement of the Kanoma pluton (Figure 4.0). It is envisaged that this pluton might have affected the Maru formation causing localized metasomatic changes to the rocks within the contact aureole.

Therefore, based on the above findings and detailed structural analysis of the present research, evolution of the Maru schist belt is ensialic in nature and the D_1, D_2 deformational episodes and structural pattern reflecting the Eburnean E - W compressional event with the principle maximum stress ($sigma_1$) been horizontal which is responsible for D_2 structures (Dan Zara and Yar'awala Hill Antiforms), while the D_3 deformational episode go in accordance to early and late Pan-African orogeny (NNE – SSW to NE – SW) reflecting in Dan-Jukku Synform as D_3 structure.

It concluded from this research that in response to the generally NE-SW tectono-metamorphic ductile deformation that produced the steeply dipping metasediments, migmatite gneiss of the area, there is heterogeneity in the bulk strain. The orientation is essentially concordant to the metamorphic deformation and probably connected with the latter but brittle Pan-African and predominantly NE-SW fracture systems.

5.5 CONTRIBUTION TO KNOWLEDGE

i. Geological map of the study area on a scale of 1:50,000 is updated
ii. The structural pattern and deformational episodes at mega, meso and micro scale in the study area has been defined.
iii. The tectonic setting of the study area is established.

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