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THE SEDIMENTOLOGY OF GAMBAGA MASSIFS OF THE NORTHEASTERN VOLTAIAN, GHANA.

BY

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DECLARATION

This thesis is the results of research carried out by Abu Mahamuda in the department of Earth Science, University of Ghana, under the supervision of Prof. D. K Asiedu and Dr. C. Y Anani.

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DEDICATION

This work is dedicated to the Almighty Allah for His guidance and for making it possible for me to complete this work.

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Abstract

The sedimentary facies of the investigated area of the northeastern Voltaian, with respect to the sedimentary structures, composition as well as the depositional environments, can be classified into six (6) facies. The sediments are deposited dominantly in a shallow marine environments with records of shoreface/foreshore, Aeolian and tidal environments. The sediments were deposited in the various environments by both low and high energy media. The area shows a shallowing and thickening upward facies sequence. The paleocurrents of the sediments show a dominant southwestern source with minor contribution of sediments from the south and south east eastern parts.

The sediments are composed of quartz, dominantly monocrystalline with undulatory extinction (strain) with minor polycrystalline, potassium feldspars, plagioclase feldspars, micas, sericites as the matrix, zircons and some accessory minerals from the petrographic study of the collected samples. The sediments studied are moderately – highly weathered in a relatively gentle – flat terrain. The composition of the clastic sediments shows high temperature regimes, dry/arid – moderate humid climatic conditions in a most probable poor rainfall environments. The sediments of the studied area from petrography, are the weathering products of granitic rocks, granitic gneisses and sedimentary rocks. The source area of the investigated area can be most likely traced to the adjacent Birimian Supergroup. Geochemically, the studied samples of the Gambaga – Nakpanduri area can be grouped into sublitharenite, subarkose and quartz arenites using log (Fe_2O_3/K_2O) versus log (SiO_2/Al_2O_3) bivariate plot. The weathering indices, thus, Chemical Index of Alteration (CIA), Chemical Index of Weathering (CIW), Thorium – Uranium ratio (Th/U) and Index of Compositional Variability (ICV) all supports a moderate – highly weathered and matured (ICV <1) sediments. Both the petrography and the geochemistry supports recycled sediments of

the study area with evidence of quartz overgrowth and Th/Sc versus Zr/Sc plot respectively. The source area of the sediments has experienced semi-arid climatic conditions in flat – gentle topographic terrain with accompanying high temperature regimes. The sediments are largely the weathered products of felsic rocks with subordinate contribution of mafic and an older sedimentary source. The major elements as well as the trace elements supports an active continents margin setting and a passive margin tectonic setting. The studied area based on lithological features has been classified into three formations of lower, middle and upper parts which correlates with Tossiegou, Poubogou and Panabako formations of the Bombouaka Supergroup rock suite of earlier workers. The lower formation is made up of sandstones with asymmetric ripple marks. The middle formation is made up of sandy shales, siltstones with minor sandstones. The sandy shales are cross stratified with papery fissility, bifurcated ripple marks, flute casts, climbing ripple marks. The upper formation is made up of feldspar and quartz rich sandstones. They are medium to coarse grained with characteristic cross beds, penetrative burrows (Skolithos), over turned cross beds, ripple marks and wavy laminations.

CHAPTER ONE: INTRODUCTION

1.1 BACKGROUND

The Voltaian Basin is one of the supracrustal basins of the West African Craton – WAC. It is moderately folded in its eastern margin and partially involved in the Pan-African Dahomeyide orogenic belt (Kalsbeek et al., 2008; Carney et al., 2010). The Voltaian Supergroup consist of three unconformable megasequences (Affaton, 1975; Deynoux et al., 2006), the Bombouaka/Gambaga/Kwahu, Oti/Pendjari and Tamale/Obosum groups.

The Voltaian Basin consists of well preserved sedimentary rocks that unconformably overlie the crystalline Paleoproterozoic basement (Birimian) rocks. Although the Voltaian occupies ~ 115,000km², thus, ~ 40 % of Ghana (Carney et al., 2010), interest in its geology has mainly been for academic purposes until recent years (Kalsbeek and Frei, 2010). Using asymmetric ripple marks from the Panabako Formation at northern part of the current study area, Viljeon et al., (2008) inferred an east – northeastern paleocurrent direction for the area. A typical sediments of the Amazonian source according to Kalsbeek et al., (2008), is a typical northerly paleocurrent direction. Using samples from the Panabako Formation, (Aka, 2008) supports the Amazonian source of the sediments of the Kwahu/Gambaga/Bombouaka reported by (Kalsbeek et al., 2008).

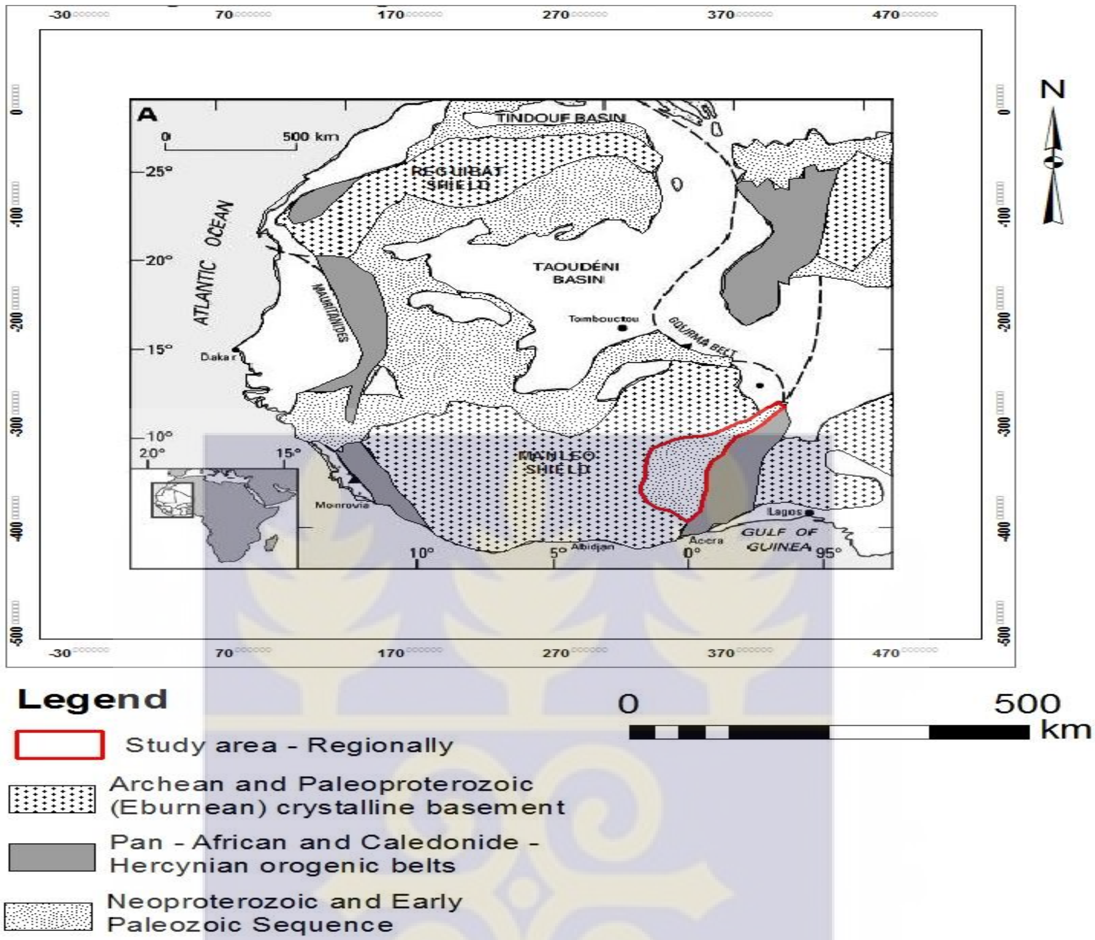


Figure1.1: Regional geological map of the study area (modified after Carney et al., 2010)

The Bombouaka group of Affaton, (1975); Affaton et al., (1980) can probably be correlated with the Kwahu Group in the southeastern part of the Voltaian Basin (Saunders, 1970), and with the Gambaga Group in the northeastern part of the Voltaian Basin.

The Gambaga Group is not extensively studied, the depositional environment, the paleocurrent directions of the depositional media has not been well documented. The proposed Amazonian source of the Kwahu Group by (Kalbeek et al., 2008) using samples from the upper parts of the group and supported by (Akah, 2008) with samples from the Panabako Formation of the Gambaga Group, needs to be looked at, as the samples are not representative of the Groups. Few workers on the area proposed three stratigraphic units of Lower, Middle and Upper Voltaian (Edmonds, 1956) and four stratigraphic units by (Ayite et al., 2008 and Carney et al., 2010).

Most of the conclusions and the lithostratigraphic successions in usage for the area are works carried out on its Togo extension (Affaton, 1975; Affaton et al., 1980) and on its southeastern lateral equivalence (Carney et al., 2010) where there is the report of poor exposure of outcrops (Anani, 1999; Sauders, 1970; Carney et al., 2010). The study will reveal some hidden information of the Gambaga Group of the Voltaian basin of Ghana from the northeastern perspective.

The current work on the Gambaga Group seeks to use the field relations, macroscopic, mesoscopic and microscopic as well as the geochemistry of the sediments to identify the various sedimentary facies, the depositional environment, paleocurrent direction, to discuss the geological history (provenance – paleoweathering, climate, relief/elevation, transportation and source rock), the tectonic setting and also compare the lithostratigraphic succession with other earlier workers in the area (Gambaga massif).

1.2 Objectives

The objectives of this study are:

1. To identify the various sedimentary facies within the area.
2. To identify the depositional environment of the sediments of the study area.
3. To identify the paleocurrent direction of the medium that deposited the sediments.
4. To discuss the geological history (Provenance – weathering, relief, climate, transportation, source and tectonic setting) of the sediments of the Gambaga massif.
5. To compare the local lithostratigraphic succession of the Gambaga massif to existing proposed successions of Carney et al., (2010), Viljeon et al, (2008) and Saunders, (1970).

1.3 Study Area

The study area falls within Lat. 10° 30' – 10° 36' and Long. 0° 15' – 0° 26' and also Lat. 10° 30' – 10° 40' and Long. 0° 05' – 0° 15' of FS 1001B3 and 1001B4 respectively, of the East Mampurisi district in northern region of Ghana (Fig. 1.2). Gambaga, Nalerigu, Sakogu, Bimbago and Nakpanduri are the major towns in the study area. Nakpanduri is the bordering town between the Gambaga district in the northern region and Garu – Tempani district in the Upper East Region. Morago river and the White volta are to the north with Bolgatanga municipality, Bawku East and West districts bordering the southern parts of the area. West Mampurisi and Gushiegu – Karaga districts are to the west and south respectively of the working area. It is approximately 90km southeast of Bolgatanga, the regional capital of the Upper East Region and connected by feeder roads. Gambaga – Nalerigu, Nakpanduri – Bimbago is however tarred with chippings. The study area is generally motorable during the dry season using a motorbike and pick – ups in some cases. Considering the nature of the roads connecting the villages, movement will be very difficult if not impossible in the rainy season as some parts of these roads are in bad state and without bridges in some cases.

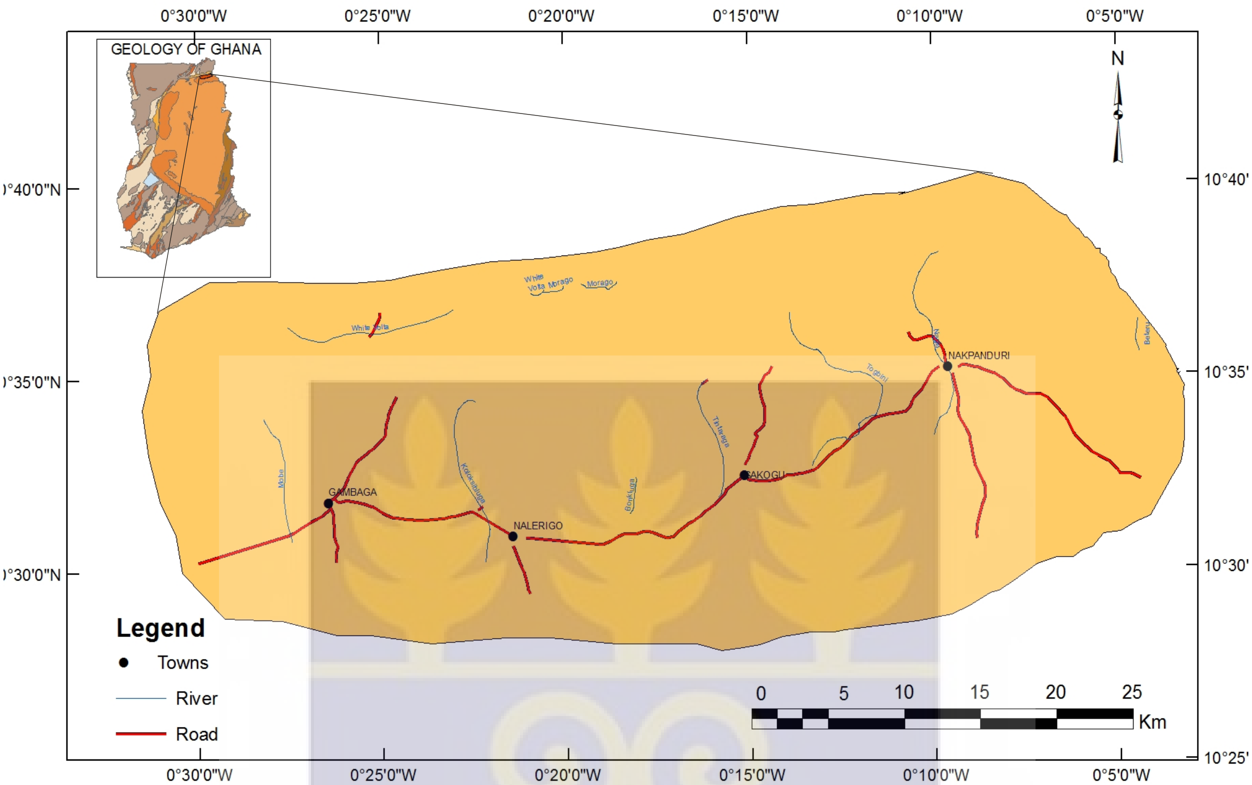


Figure 1.2: Map of study area

1.4 Physiography

1.4.1 Relief and Drainage

In the study area, the elevations vary from high areas in the northern part of the study area in both FS and lowest points in the south of the study area. The southern and central part of the study area is generally flat lying with isolated elevated areas due to exposures. From the north, the landscape of the study area slopes gently towards the south. The landscape in the central and southern parts of the study area is eroded, with the bedrock especially the sandstone of the Panabako Formation, becoming exposed due to erosion. The Gambaga scarp is exposed clearly in the northern parts of Gambaga, Sakogu and Napkanduri. Within field sheet (FS) 1001B4, there is one main drainage system within the study area the Morago river that runs northeast – southwest from Gumbare through the Morago forest reserve, and is parallel to the trend of the Gambaga scarp. There are two major drainage systems within the adjoining FS (1001B3), thus, the Morago river and the White Volta. The Morago river that runs northeast – southwest joints the White volta at the Gambaga area of the scarp. The White Volta drains major parts of FS 1001B3. According (Viljeon et al., 2008), the two rivers draining the sandstones of the Bombouaka Group in the north are deeper, with narrow floodplains. The rivers are mainly fed by precipitation in the rainy season, whereas in the dry season the only additional source of water to the rivers is groundwater, which appears insufficient to keep the Morago river flowing in the study area FS 1001B4. The White Volta, however, flows all year round through with reduced recharge.

1.4.2 Climate

The area is part of the Tropical Continental Climatic region that is affected by Southwest Monsoon and Northeast Trade winds and experiences one rainy season within a year (Zango et al., 2014). In this part of Ghana the wet season starts from April to May and peaking during August to September with last rain falling in October to November. The highest temperatures occur just before the rainy season (Zango et al., 2014), the mean monthly temperatures ranges from 42° C in March to about 26° C in August. In general, the evaporation is higher than the rainfall in this part of the country. From February to March, and the lowest temperatures during the rainy season from August to September (Junner and Hirdes, 1946). The climatic conditions renders the district vulnerable to bust fires in the dry season

1.4.3 Vegetation and Soils

The vegetation according (Dickson and Benneh, 1988), is almost of the Sahel Savannah type consisting of savannah grassland that is swept during the dry season by bushfires separating deciduous trees. The forest reserve within the study area borders the area to the north.

CHAPTER TWO: LITERATURE REVIEW

2.1 Geology of the Voltaian Supergroup

The Voltaian basin is part of the supracrustals of the West African Craton (WAC). It is located on the eastern margin of the Man – Leo Shield (Carney et al., 2010), which comprises of crystalline rocks of Archean to Paleoproterozoic age that stabilizes around ~2000 Ma, during the Eburnean orogenic cycle. This is overlain by Neoproterozoic rocks (Voltaian rocks) and younger sedimentary successions, along the western margins, the Voltaian rocks unconformably overlie the strongly deformed Paleoproterozoic basement of the Man – Leo shield consisting of metabasalts, metasediments and granitoids of the Birimian Supergroup and the slightly younger Tarkwaian sedimentary succession (Carney et al., 2010) and surrounded by Pan – African and Hercynian (360 Ma) of northeastern Africa orogenic belts (Trompette, 1994). The largest occurrences of sedimentary rocks is in the Taoudeni basin which covers most of the Western Sahara and consist of Neoproterozoic and Paleozoic formations. The Voltaian Basin is comparable in age to the Taoudeni but much smaller, which consist of Neoproterozoic to early Paleozoic strata (Kalsbeek et al., 2008). The Voltaian basin, (Junner and Hirdes, 1946; Bozhko, 1969; Affaton et al., 1980; Affaton, 1990) is up to ~ 5km thick succession of Neoproterozoic to lower Proterozoic sandstones and mudstones with subordinate proportions of limestone which occupies a surface area of ~115,000km² in Ghana as well as smaller areas in Togo, Burkina Faso, Niger and Benin. Over most of its outcrop areas, the Voltaian sediments are undisturbed, they have shallow dips (1 – 2º), however, to the east, the rocks are affected by Pan – African (~ 600 Ma) orogenic event and steeper dips occur (Affaton, 1975, 1990). In eastern Ghana, rocks of the Voltaian have been overthrusted by metasedimentary rocks of Buem and Togo structural units that belong to the Dahomeyide orogeny (Affaton, 2008). In contrast to Voltaian rocks, the latter are strongly folded and have undergone variable degrees of metamorphism, (Affaton et al., 1980). The Voltaian of Ghana is made up of three main disconformable lithostratigraphic units defined as megasequence or Supergroups (Deynoux et al., 2006). They are the Bombouaka/Gambaga/Kwahu, Pendjari/Oti and Tamale/Obosum group.

The Bombouaka/Gambaga group represents the lower lithostratigraphic unit of the basin, it shows an epicontinental characteristics. It consist of three disconformable subdivisions which are well presented in northern Togo as Dapango, Fosse – aux – Lions and Yemboure groups, (Deynoux et al., 2006). The lower Dapango and upper Yemboure groups, consist of fine to coarse grained and more or less feldspathic sandstones with the middle Fosse – aux – Lions groups characterized by various facies of shales and siltstones intercalated with thin lenses of fine grained sandstones and limestones, this is equivalent to the Tossiegou, Poubogou and Panabako of (Affaton, 1975; Affaton et al., 2008). Clay minerals from the shales of this group yielded Rubidium – Strontium (Rb – Sr) isochron age of 993 ± 65Ma (Clauer and Deynoux, 1987). According to Anani, (1999), it is ~1000m thick and much of the material of these bordering massifs came from the weathering and erosion of WAC rocks. The sandstone composition of the Tossiegou and Poubogou (Bombouaka Megasequence) indicates plutonic source rocks with associated metasediments derived from both transitional continental and craton interior provenances, confirming a passive margin setting for the Bombouaka Megasequence (Anani, 1999). Structural, petrographical and sedimentological evidence suggests that the source rocks for the Bombouaka were located in the Leo Shield to the west (Saunders, 1970; Affaton et al., 1980). However, age determination on detrital zircons shows that significant parts of the detritus probably came from the Amazonian craton, (Kalsbeek et al., 2008). In general, the Bombouaka group can be correlated with the lower part of the megasequence

1 in the southern part of the Taoudeni basin (Deynoux et al., 2006).

The Oti/Pendjari group represents the middle lithostratigraphic unit and can be subdivided into two disconformable formations of lower Kodjari and overlying Pendjari formation. The lower Kodjari group is composed of three lithological assemblages of various facies of tillites, barite – bearing carbonates and thin – bedded cherts defined as silexites. This assemblages shows a similar characteristic compared to the 'Triad' of the Taoudeni Basin (Leprun and Trompette, 1969) and termed as 'triad' of the Taodeni Basin (Kalsbeek et al., 2008; Kalsbeek and Frei, 2009). It is about ~80m thick (Affaton et al., 1980). Bozhko et al., (1971), described specimen of Riphean to Vendian stromatolites in the cap carbonates of the Tibagona area. Glauconites from the carbonates yielded a Potassium - Argon (K – Ar) age of ca. 620 Ma. The Pendjari formation is characterized by a greenish – grey thick and flyschoid sequence with phosphorite deposit (Carney et al., 2010). It consist mainly of shales and siltstones, wackes, limestone, silexites and tuff. Lithium – Hafnium (Lu – Hf) dating of the phosphorites, provided an age of 576 ± 13 Ma (Barfod et al., 2004). However, shales from the group provided Rb – Sr isochron age on illites to be 660 ± 9 Ma, (Clauer and Deynoux, 1987).

The upper Obosum/Tamale Group, according to Deynoux et al., (2006), is the upper lithostratigraphic unit of the Voltaian basin. This is partly equivalent to the 'Obosum beds' of (Junner and Hirdes, 1946). This includes highly distinctive lithic, feldsparthic arenites and conglomerates deposited as terrestrial/foreland molasses during the final stages of uplift within the Dahomeyide orogen (Deynoux et al., 2006; Carney et al., 2010; Kalsbeek et al., 2008). The Tamale/Obosum group probably spans the time from Cambrian to Ordovician, corresponding to the formation of the Dahomeyide belt, (Junner and Hirdes, 1946). It has subordinates of shales and siltstones of ~500m thick (Affaton et al., 1980).

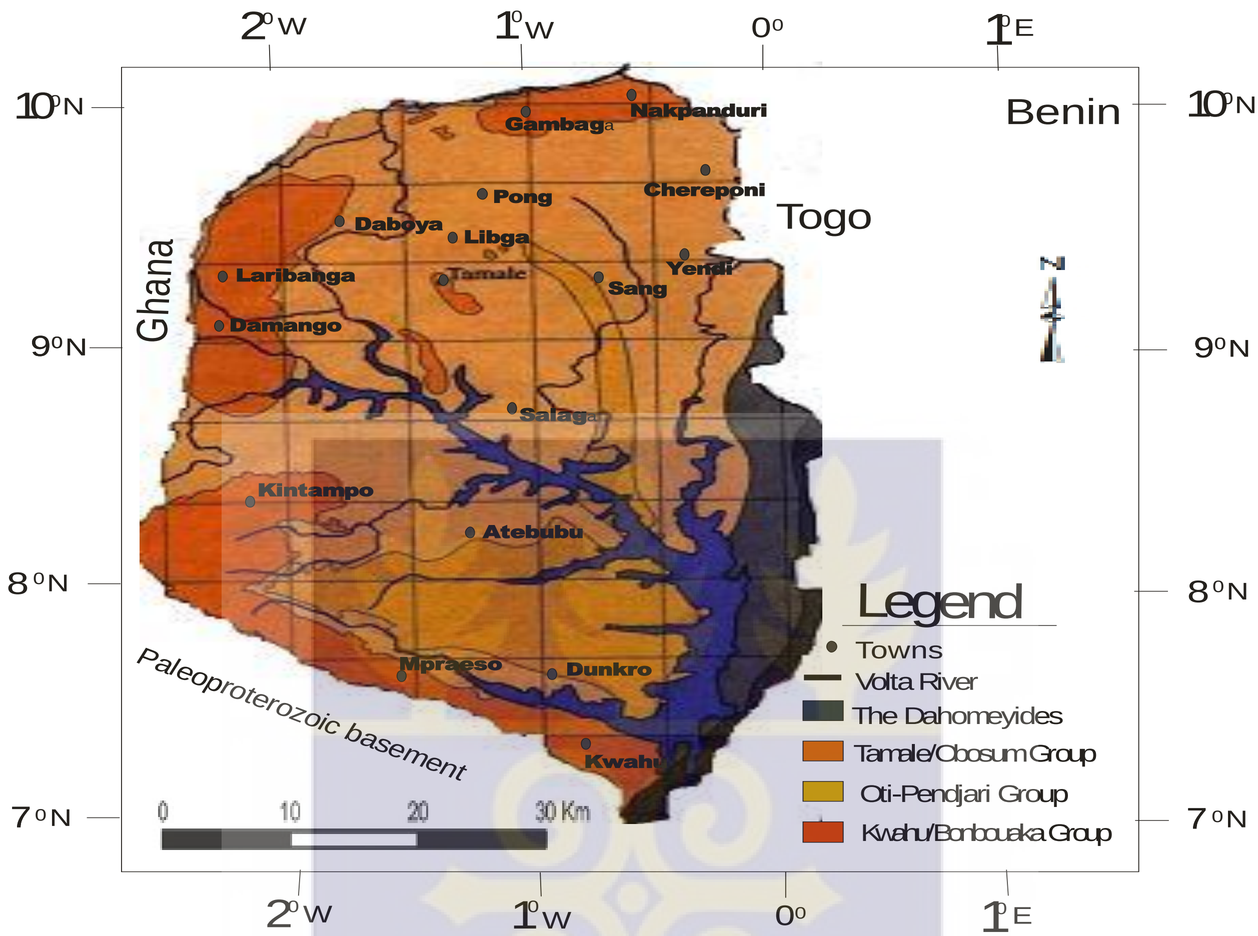


Figure 2.1. The Geological Map of the Voltaian Basin. (Modified after Carney et al., 2010)

2.2 The Gambaga Group

The study area covers the northeastern margin of the Voltaian Basin (Fig. 2.2) and has been identified to be underlain by the Gambaga Group according to Affaton, (1975, 1990); Kalsbeek et al., (2008). The Gambaga massifs is a sedimentary strata of about 500m thick (Carney et al., 2010), that were deposited in fluvial, deltaic, nearshore or shoreface environments. The Gambaga group represents the lower lithostratigraphic unit of the basin. It shows detrital and epicontinental characteristics. It includes three disconformable subdivisions which are well presented in northern Togo as Dapango, Fosse – aux – Lions and Yemboure groups (Deynoux et al., 2006). This classification is equivalent to the Tossiegou, Poubogou and Panabako grouping respectively, according to the francophone geologists (Affaton, 1975; Affaton, et al., 1980). The deposition of the Bombouaka group/Gambaga massifs took place between 1000 Ma and 600 Ma (Kalbeek and Frei, 2009) from recent geochronology data using youngest detrital zircons.

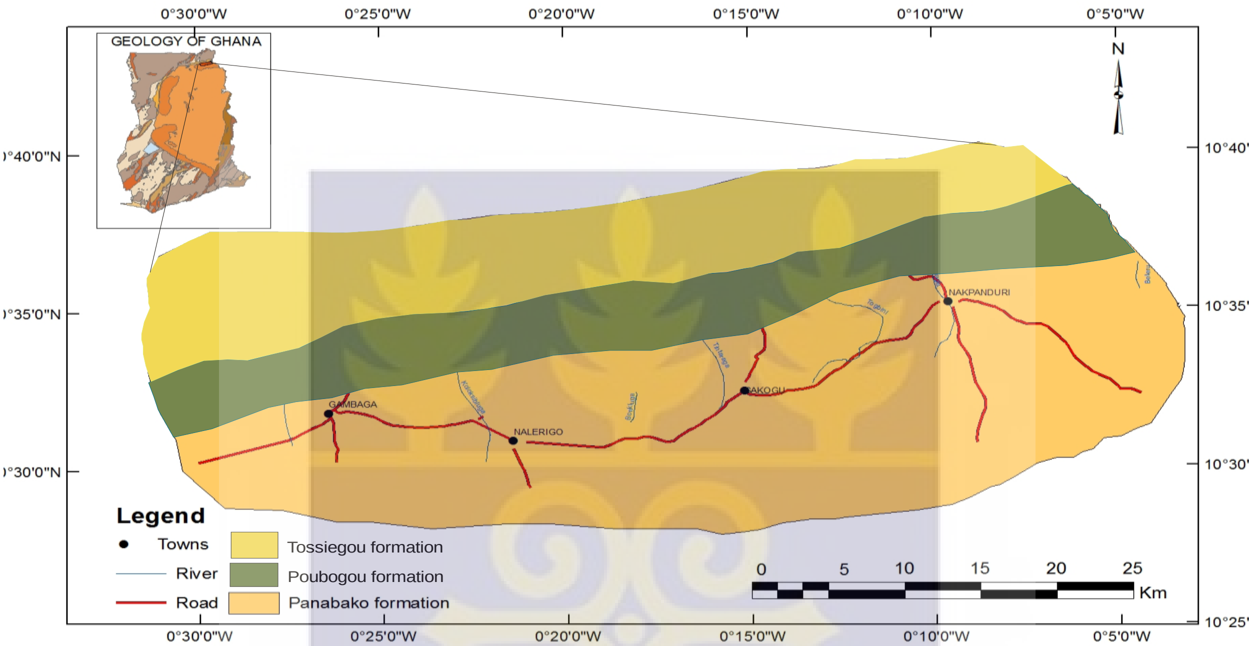


Figure 2.2: Geological Map of the study area

2.2.1 Tossiegou Formation

This overlies the crystalline basement rocks belonging to the Birimian Supergroup with a major angular unconformity. The formation consist of conglomerates, it grades into both feldspathic and coarse – grained quartzitic sandstones with characteristic ripple marks (Affaton, et al., 1980; Carney et al., 2008). Ayite et al., (2008) looking at the lithostratigraphy of the Gambaga massif, suggested an immature shieshie sandstone formation with a calculated 310 m thickness deposited in a fluvial environment, this correlates with the Tossiegou formation of (Affaton et al., 1980; Carney et al., 2010). Indications from remote data shows that the formation forms a broad, smooth dip – slope with gentle southernly dips taking the formation beneath the overlying Poubogou formation (Carney et al., 2010). Carney et al., (2010) considering the Damango formation (west of the Gambaga massif) to be part of the Gambaga massifs, indicates that the formation dips westward beneath the Poubogou formation. The presence of immature ripple marked sandstone with 'grits' and similarity in topography of the formation suggests that the formation is a direct correlation of the Yabraso formation of the Kwahu massifs of the southeastern Voltaian Basin.

2.2.2 Poubogou Formation

This formation disconformably overlies the Tossiegou formation (Carney et al., 2010), it comprises of greenish – grey shales, siltstones with intercalations of fine – grained sandstones believed to be of the Tossiegou formation with spectacular ball – and – pillow structures (Ayite et al. 2008). There is also records of limestone in the Poubogou formation according to (Affaton, 1975; Affaton, et al., 1980). The formation is characterized by flute casts and slump structures with indications of high energy depositional environments with S – SW dips of about 55m thick in the studied area (Ayite et al., 2008). The formation in the lower parts of the Nakpanduri area is with micaceous mudstone and shales with a characteristic papery fissility (Carney et al., 2010), these are intercalated with planar bedded medium grained sandstones. The formation according (Carney et al., 2010) indicates the pinching out of the northwestern outcrop unit southwards towards the Larabanga area implicating the formation to be wedge – shaped. The formation is about 170 m thick above the underlying Tossiegou formation in the Gambaga area (Carney et al., 2010).

2.2.3 Panabako Formation

This is the upper formation of the Bombouaka group and it overlies the Poubogou Formation. It is characterized by medium – coarse grained feldspathic sandstone and quartzite (Affaton, et al., 1980; Kalsbeek et al., 2008). The sandstones according to (Viljeon, et al., 2009), are with ripple marks (symmetric and asymmetric) and with slump structures locally. Feldspathic arenites and quartz arenites are recorded by (Carney et al.,2010). The Panabako Formation (Viljeon et al., 2009), is characterized by fine – medium quartzitic sandstones that are interbedded by less matured and more easily weathered fine grained sediments. The samples on mesoscopic scale glitters at some places showing autigenic quartz overgrowths. Subsequently eroded paleosol formation is probable with the presence of 'elephant skin' or pseudokarren weathering (Viljeon et al., 2009) which is typical with the Panabako Formation. The formation dominantly consist of quartz arenites, this probably correlates with the Mpraeso, Abetifi and the Obocha Formations of the Kwahu Group (Carney et al., 2010). Coarser grained sandstones are also present and restricted to the upper part of the formation (Viljeon et al. 2009), the formation is about 120m thick. Carney et al., (2010) indicates the presence of two sandstone units of the formation via remote sensing data with 150 – 200 m thickness. The upper sandstone has characteristically 'sugarloaf' capping the lower sandstone of this sequence, the upper sandstone unit of the formation (Carney et al., 2010) appears eroded before the deposition of the Oti/Pendjari Group. The formation is typified by cross – beds of planar contacts, syn – sedimentary deformational structures (Carney et al., 2010). Poorly developed herringbone cross beds together with reactivated surfaces has been described by (Viljeon et al., 2008) working on the southern part of this current study area where only the Panabako Formation was observed during their study. Paleocurrents shows a common NW and SE similar to the trends of the Kwahu Group (Viljeon et al., 2010), however, a predominant NNE over

NW and E are recorded in some exposures in the south of the Gambaga areas (Viljeon et al., 2010). Sedimentary structures of the Upper Nakpanduri Formation of (Ayite et al., 2008) suggests a shifting coastal and an Aeolian depositional environments. The age of the Panabako Formation according (Akah, 2008) is 1000 Ma from detrital zircon age geochronology suggesting the contemporaneity of the formation with that of the Kwahu Group.

2.3. Sedimentary Facies

Sedimentary facies which is the different types of sediments/sedimentary rocks, are an important aspect of sedimentology. Various authors (Kavoosi et al., 2009; Zakir et al., 2002) classifies sedimentary facies based on the composition, texture and color of sedimentary rocks. (Tucker, 2003) indicates that sedimentary facies can be comfortably grouped by considering the depositional environment, depositional processes and conditions together with the composition and the textures. The depositional environments of sediments is reflected by the sedimentary structures and features therein.

2.4. Provenance Studies

The composition of sedimentary rocks is basically indicated by mineralogical composition and by geochemical composition of the detritus (Hilmar et al., 2012). Dickinson, (1970) has clearly indicated that mineralogical composition, thus, petrography can provide information about detritus in the way that other methods will not be able to. This is largely supported by a good population of sedimentary petrologist (Dickinson, 1985; Dickinson and Valloni, 1980; Dickinson and Suczek, 1979; Dickinson et al., 1974) where point counting technique is employed during the petrographic study. Employing the point counting technique, it is well indicated by these authors that petrographic study can be used to decipher the tectonic setting as well as the provenance of the detrital materials. The source area aspects like paleoweathering, climate, relief and transportation according to (Boggs, 2006; Ernest and Blatt, 1995; Pettijohn, 1957) is reflected in the petrography. Minerals are made up of elements and the minerals in turn constitute rocks/sedimentary rocks. The chemical composition of sedimentary rocks has been used extensively (Bhatia and Crook, 1986; Suttner and Duta, 1986; Mclennan et al., 1983; Herron, 1988; Floyd and Leveridge, 1987; Roser and Korsch, 1988; Nesbitt and Young, 1984; Braccili et al., 2007; Shoa et al., 2012; Elzieni et al., 2014; Adel et al., 2010; Kroonenberg, 1994; Bhatia, 1983; Saeed, 1975) to indicate the aspects of the source area, thus, paleoweathering conditions, climatic, relief/elevation, transportation and source of the detrital materials. The tectonic settings are as well indicated using appropriate ratios, discriminating bivariate and ternary diagrams.

CHAPTER THREE: METHODOLOGY

To achieve the various objectives of the study, the work was carried out in stages of three; Preparation, Sampling/Data collection and Analysis

3.1 Preparation

At this stage of the work, previous literature related to the study area were reviewed to have a fair idea on the outcome of works carried out in the Gambaga massifs. Relevant literature connected to the current study and journals were gathered and studied.

Base maps were organized and gridded for the field work, compass - clinometer, geological hammer, GPS, hand lens (x10 magnification), tape measure, Meter rule, marker pens, field note book, pens and pencils, field boots, first aid, digital camera, sample bags/sags, dilute Hydrochloric acid (HCL), text books on sedimentary rocks in the field – Tucker, (2003) and Dorrik, (2005).

3.2 Sampling/Data collection

Geological mapping and sample collection were carried out by way of sampling/data collection. The field mapping was carried out on a scale of 1:50,000. The field mapping started with a reconnaissance mapping to acquire firsthand information/knowledge on the road network, the general distribution of outcrops on the study area and to also identify areas within the study area where more time is required and for how long following the exposures available and the objectives of the study. This serves as a guide in planning the field work. The reconnaissance mapping was followed by detail geological field mapping. The methods employed were the close – loop and compass method, tape measure and compass mapping and systematic traverse and sampling. The close – loop and compass method is one of the most effective and inexpensive method employed during the field work, during this, scouting for outcrops is in a loop form such that the traverses in a day ends at the starting point. The compass was used alongside to give accurate direction and to also ensure that the areas visited were not visited the second time. The systematic traversing controls the progress of the mapping. The Global Positioning System (GPS) helped to a greater extend in the mapping. The GPS showed the georeference coordinates of every point in the field as well as outcrop location in the field, it also to a larger extend, helped in the traversing as it was useful in giving location. The base map also played a significant role in the location of some villages and the road network within the study area. The base map indicated the roads and footpaths within the area which was used in accessing outcrops. The thickness of beds were measured using the tape measure and meter rule, detail description of the observed lithologies were made at each outcrop scale and also with the hand lens, the sedimentary structures were measured using the meter rule/tape measure and compass – clinometer. At outcrops/exposures, the detail lithological description of its mineralogical composition, the texture and color were observed with the help of a hand lens. The GPS locations of each outcrop was plotted on the topo – sheet in order to have a firsthand information on the sampling representation and also to be sure the work was within the scope. The structural attitudes were measured using the compass - clinometer. The structures measured in the field were lamination/bedding, cross – bedding, over – turned cross bedding, herringbone cross – bedding and ripple marks. Sketches and 3D drawings of some observed structures were done in the field which helped in the interpretation of the current direction. Soils which are weathered products of rocks, provided they are in – situ material reflects the rock beneath or the pre – existing rock. At the scarp where significant weathering has taken place, critical observation of these weathered material were made and the pre – existing lithology deduced from the in – situ sediments. The use of weathered in – situ material has over the years been used in drawing boundaries between geological contacts on geological maps. Samples were also taken from fresh rocks for petrological analysis and geochemical analysis. The locality numbers/communities were written on collected samples and kept in sample bag. Oriented image/pictures of observed sedimentary structures were also taken during the field work.

3.3 Analysis

The paleocurrent measurements recorded, were cross stratifications, cross bedding, over turned cross bedding and asymmetric ripple marks. These were inputted into Microsoft excel sheet, as a requirement for the rose diagram plotting of the structural measurements on the Steropro, Georient softwares for the paleocurrent analysis, (Odumoso, 2013). The structural measurement were plotted using SteroNet, StereoPro and GeoOrient softwares which helped in the structural analysis. The flow direction of the transporting media and distribution of structures were deduced from the plots of the structural measurements. The plots of the SteroPro is used for the discussion as that gives much finer rose diagrams thereby allowing accurate (conforming with the field trends) interpretations of the plots. The facies analysis and the depositional environment of the sediments was done considering the lithological compositions, textures and significantly, consideration of the sedimentary structures in accordance with some earlier writers on sedimentary facies (Kavoosi et al., 2013; Zakir, 2002). Thin sections of some collected samples were prepared and studied. The composition and textural properties of the samples like sorting and textural maturity as well as the compositional maturity were observed.

Whole rock geochemical analysis of the rock samples was carried out following standard preparation techniques, logging samples into the tracking system, weighing, drying, fine crushing entire sample to 70% - 2mm, split off 250g and pulverize split to better than 85% passing 75 microns, this was done at ALS laboratory. REE and major oxide analysis were carried using the following options; ME-ICP06 – Major elements by lithium metaborate or tetraborate fusion, followed by dissolution of the melt and ICP-AES analysis, with a precision of ±5%. ME-MS81 option was employed in analyzing the REEs by lithium borate fusion and ICP-MS at ±10% precision. The base metals component analysis was with ME-MS81 method by 4-acid digestion at ±10% precision. The geochemical data of these sediments was plotted using Delta Graph 5.5, GCDkit and CorelDraw X4 on some classification schemes. The composition of the major elements were used to geochemically classify the studied samples using the sandClass diagram of Herron, (1988), the paleoweathering condition of the sediments was also determined and the provenance determination was by plotting tectonic discrimination diagrams of Bhattia, (1983), McLennan et al., (1993) and Roser and Korch, (1988).

CHAPTER FOUR: DEPOSITIONAL ENVIRONMENT

4.1 Field Studies

4.1.1 Siltstone

Siltstones observed in the northeastern part close to the Morago river, moving from the Nakpanduri Township. They are highly weathered in – situ materials that were observed, they are pinkish – brown and brown (Fig. 4.1) in color at some points and occur as intercalations within the shales/sandy shales in outcrop scale.

These are with a characteristic sticky feel between wet fingers. They are found to alternate with shales within the Nakpanduri and Natapsori areas of the scarp.

Figure 4.1: Weathered Siltstone at the lower part of the Nakpanduri scarp

4.1.2 Shales

The scarp of the Gambaga massifs is accessible in three locations, Nakpanduri, North of Natapsori and North of Gambaga, shales were observed in all these areas.

Ripple marks were observed on floats of shales (Fig. 4.2) in all the three locations, they have well defined sharp, straight crest and with bifurcations in some areas (Fig. 4.4). Shales with sharp ripple crest are clearly observable at the Nakpanduri scarp with wave length and height of 7.9cm and 0.5cm respectively at Nakpanduri, 8cm and 0.4cm respectively at North Natapsori and 8.2cm and 0.4cm respectively at North of Gambaga.

Figure 4.2: wave ripple marks (RI=20.4) on the shales of the Nakpanduri scarp

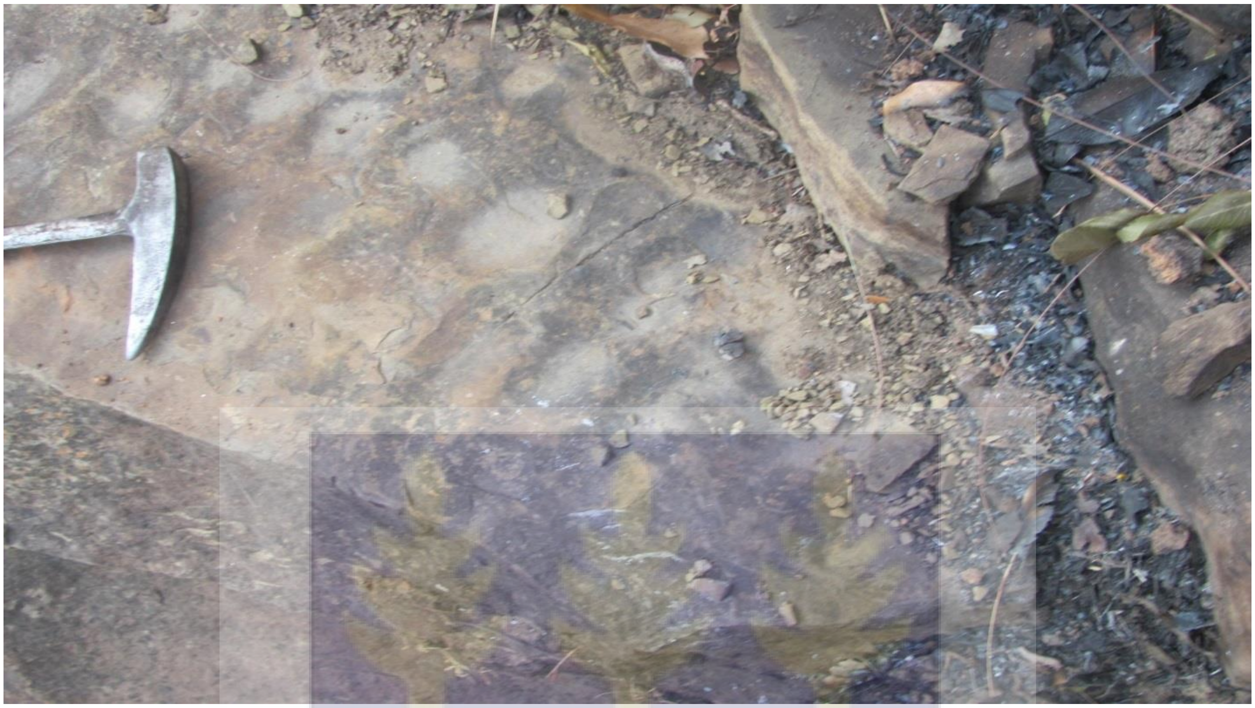


Figure 4.3: Poorly exposed ripple marks at the North of Natapsori scarp

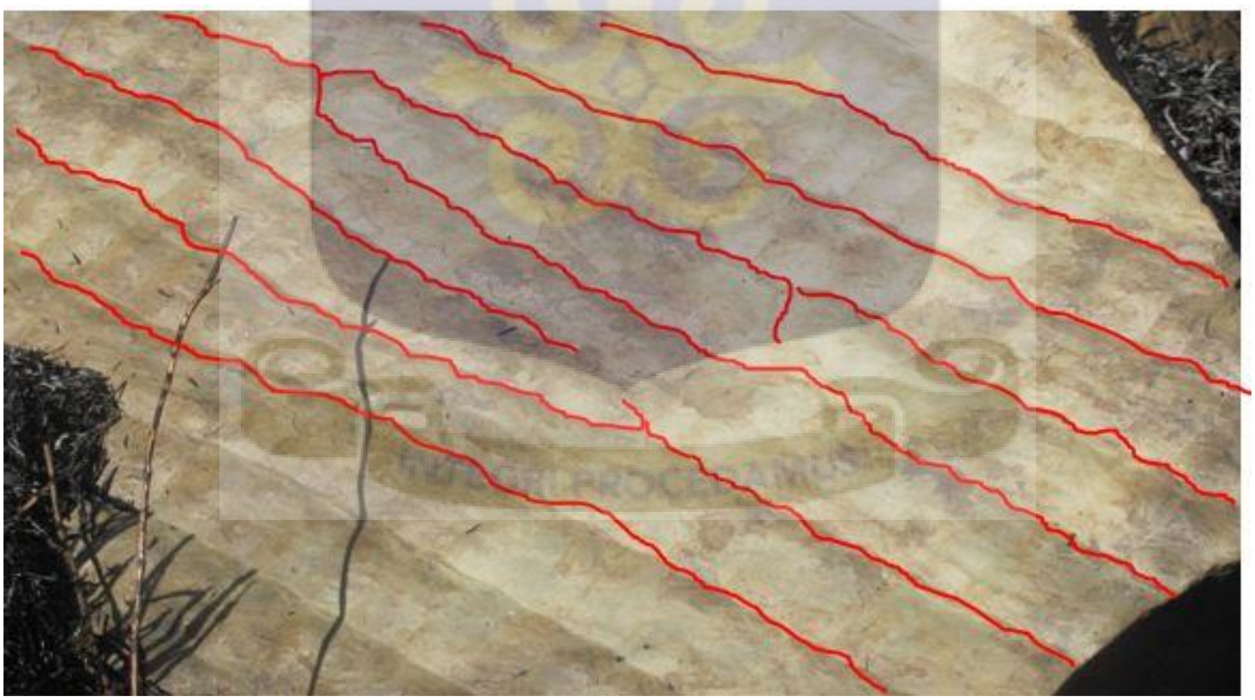


Figure 4.4: Bifurcated ripple marks (avg. RI=20.7) on the shales of the Nakpanduri scarp

Figure 4.5: Flute casts on the Nakpanduri scarp shales

Cross stratifications (Fig. 4.7,4.8,4.9) were observed within the sandy shales at the Nakpanduri and Gambaga parts of the scarp. Observable were flute casts (Fig. 4.5) and climbing ripple marks (Fig. 4.6) at the Nakpanduri area of the scarp. They have closely spaced partings – papery type fissility (Tucker, 2003) when hit with a hammer, and appear massive on outcrop scale

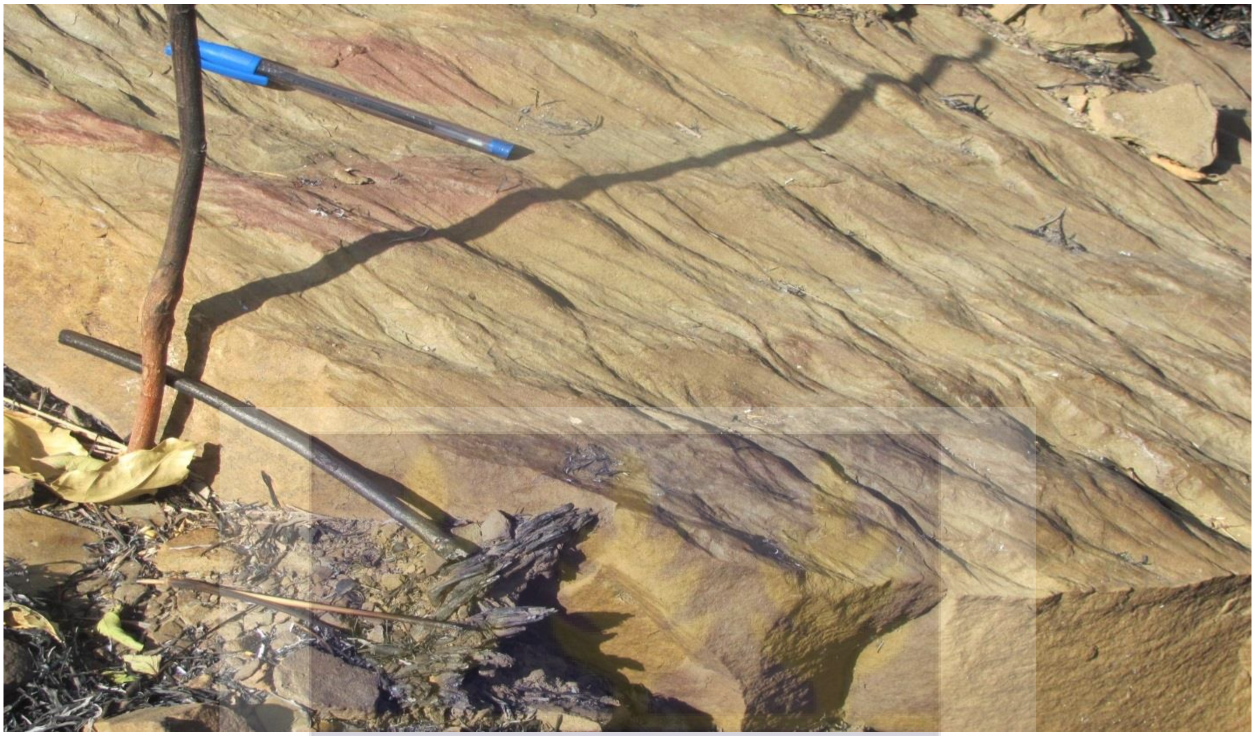


Figure 4.6: Climbing – ripples on the shales at Nakpanduri area

Figure 4.7: Cross – stratification on sandy shales at the Nakpanduri area

Figure 4.8: Trancated foresets of cross – stratification on the Nakpanduri sandy shales

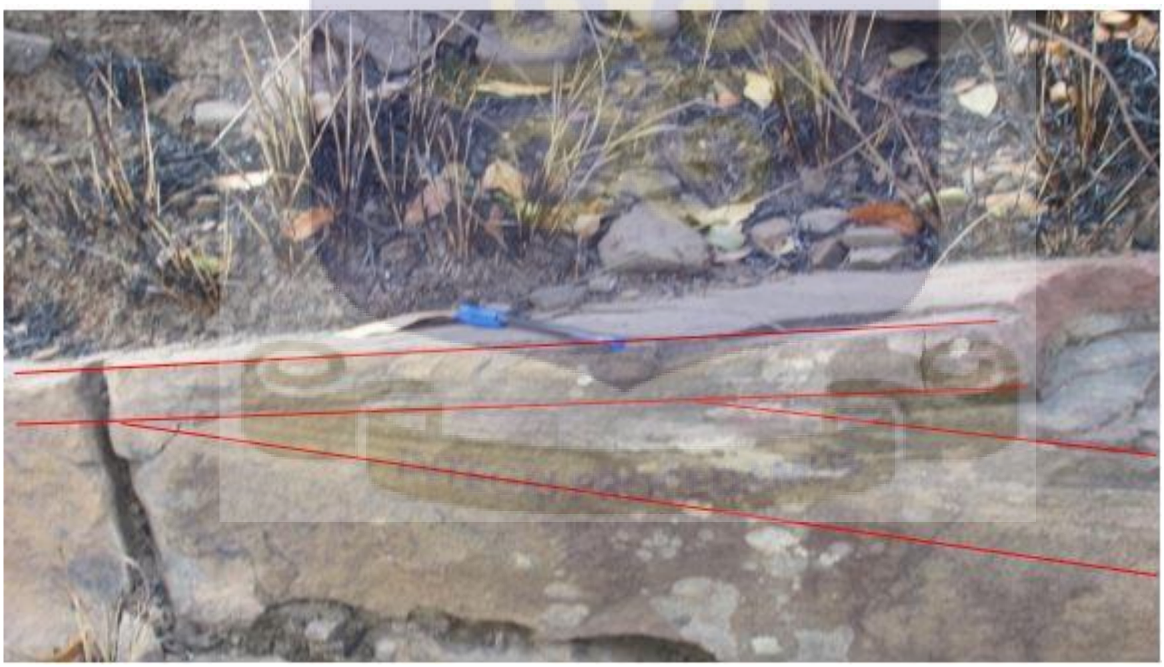


Figure 4.9: Trancated topset of cross – lamination of a shale at the Gambaga scarp

The shales are greenish – grey with quartz, biotite and muscovite and hence micaceous in hand specimen and in microscopic scale.

4.1.3 Sandstones

4.1.3.1 *Ripple Marks Sandstone*

Sandstone with ripple marks were observed in the northeastern most part of the study area within the Morago river which is at the base of the Nakpanduri scarp (Fig. 4.10). This was observed only within the Morago river, with the surface however, masked with mud. The sandstone is thinly bedded with bed thickness varying between 1.5cm – 3cm. The sandstones have stoss and lee sides dips of 11º NE and 15º SW respectively with wave length and height measuring 10cm and 1.5cm respectively. The ripple index calculated, thus,

RI = L/H

RI = 10cm/1.5cm = 6.7

RI = 6.7

(where R, I, L, and H means ripple, index, wave length and height respectively)

On mesoscopic scale, the sandstone is fine – medium grained, cream with quartz, feldspars and muscovite composition.

Figure 4.10: Ripple mark (RI=6.7) sandstone within the Moraga river

4.1.3.2 *Cross – bedded sandstone*

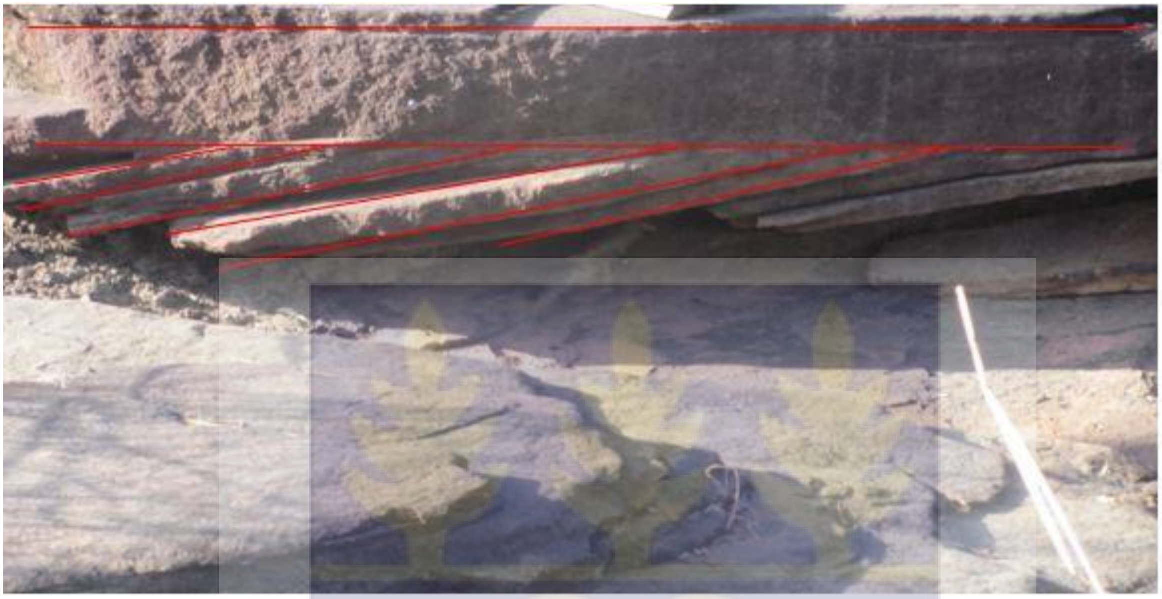


Figure 4.11: Thin bottom set cross – bedded sandstones at the Nakpanduri scarp.

4.1.3.3 *Feldspar rich sandstones (Arkose)*

Feldspar rich sandstones were recorded at Nusuan, Tambokurugu, Gulugu (south of Nakpanduri) and Sumniboma (south of Sakogu) areas in both field sheets. They contain feldspar, quartz and muscovite in mesoscopic scale, the feldspar and quartz occurs as alternating laminations. The feldspar rich sandstones at Nusuan are thinly – medium bedded with bed thickness ranging between 2cm – 4cm, with planar cross – bedding of tangential bottom contacts (Fig. 4.13), they also have over turned cross – bedding.

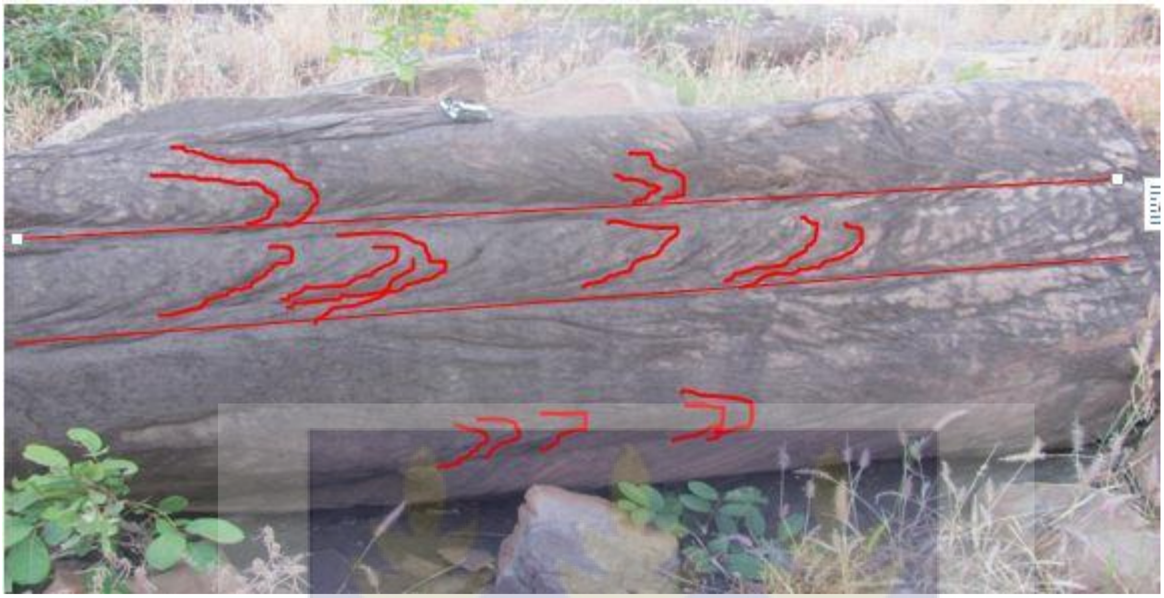


Figure 4.12: Cross and small scale over – turned cross bedded sandstone at the outskirt of Nusuam

Figure 4.13: Over turned – cross bedded sandstone at Nusuam

Figure 4.14: Wavy laminated sandstone at Nusuam

This sandstone has observable wavy lamination, (Viljeon et al., 2008) (Fig. 4.14) in all its area of exposure. This feldspar rich sandstone is fine – medium grained textured, poorly sorted and pinkish – grey colored. The sandstones have 'elephant skin' or pseudokarren – like weathering in outcrop scale. There is observable small scale ripples marks (Fig. 4.15) at Sumniboma No. 1 village center on the road to Soginvusi.

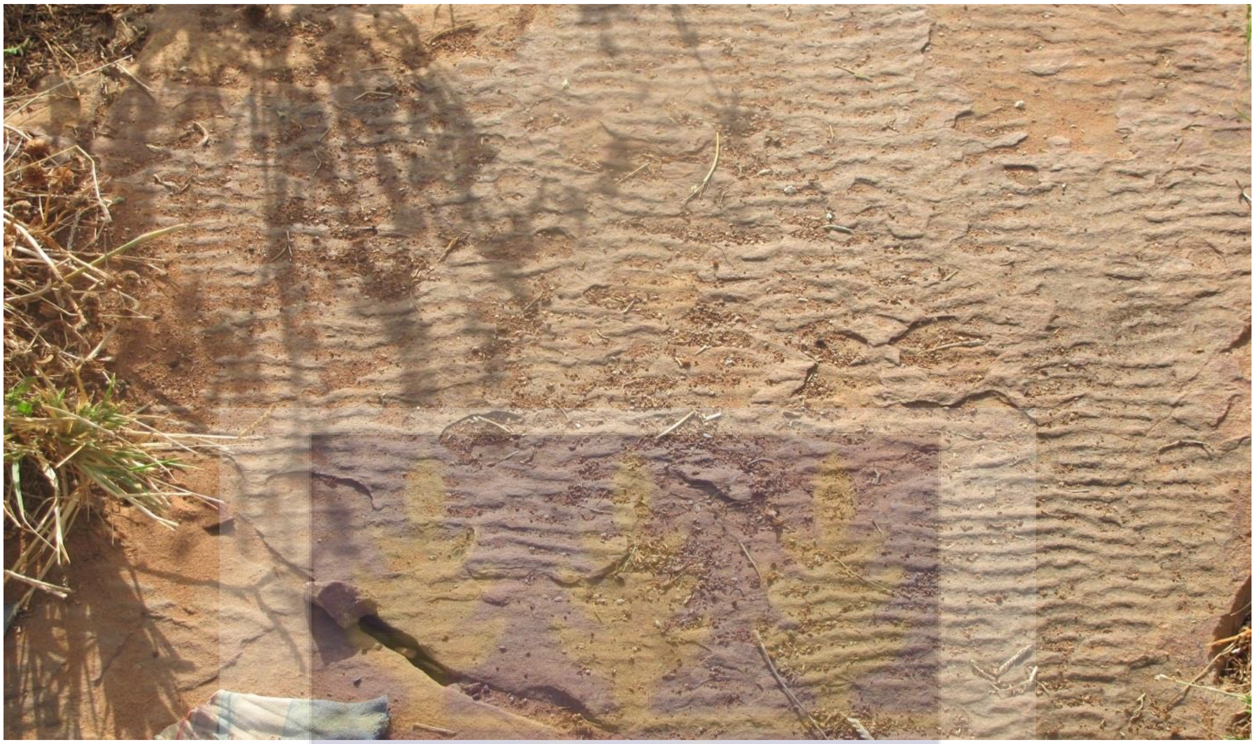


Figure 4.15: Wavy laminated Sandstone at Sumniboma No. 1.

4.1.3.4 *Quartz rich sandstone*

The sandstone in hand specimen contains quartz predominantly, feldspar and muscovite, it is medium – coarse grained and pale – brown colored. The sandstone is medium – thickly bedded in the Yipala – Tambona exposure near Sakogu (Fig. 4.17) and varies in bed thickness throughout its area of exposure in the southern half of the study area ranging from 1cm – 35cm.

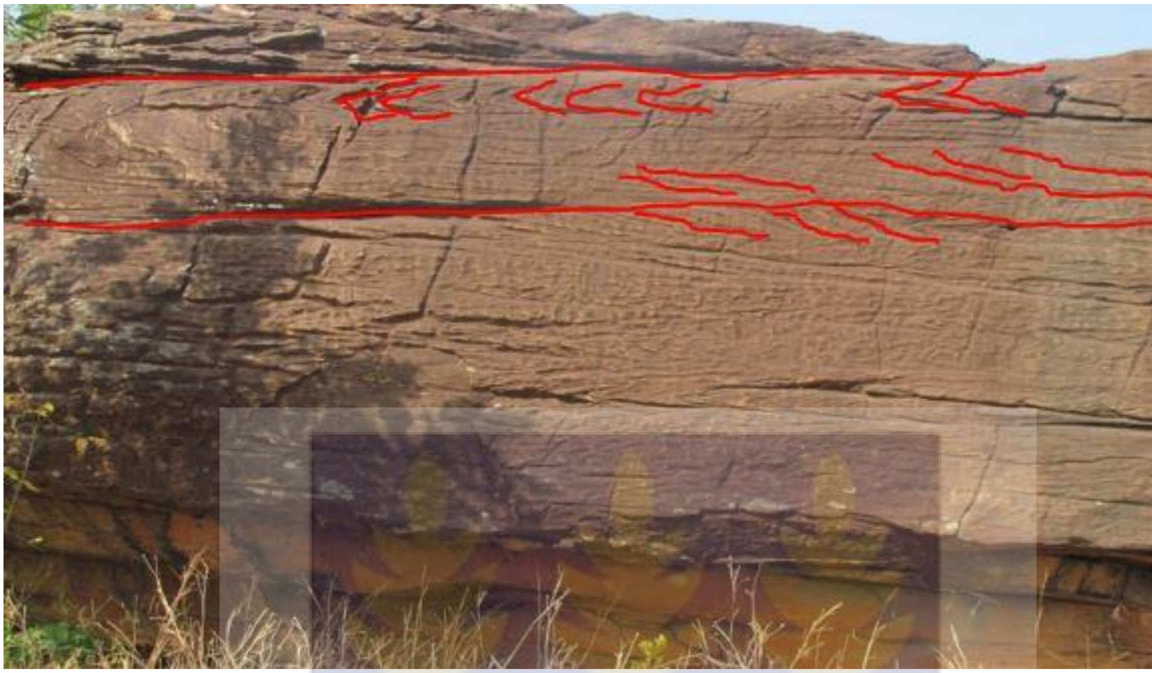


Figure 4.16: Medium – thickly cross bedded Sandstone at the outskirt of Natapsori towards the scarp

Figure 4.17: Medium – thickly cross bedded Sandstone between Tambona and Yipala near Sakogu.

Figure 4.18: Well developed cross - bedded/over turned – cross bedded sandstone at the outskirt of Sakogu towards Nakpanduri.

Figure 4.19: Well developed burrows in cross – section at the outskirt of Nakpazong

Figure 4.20: Well developed burrows (Skolithos) in plan view at Duklotku

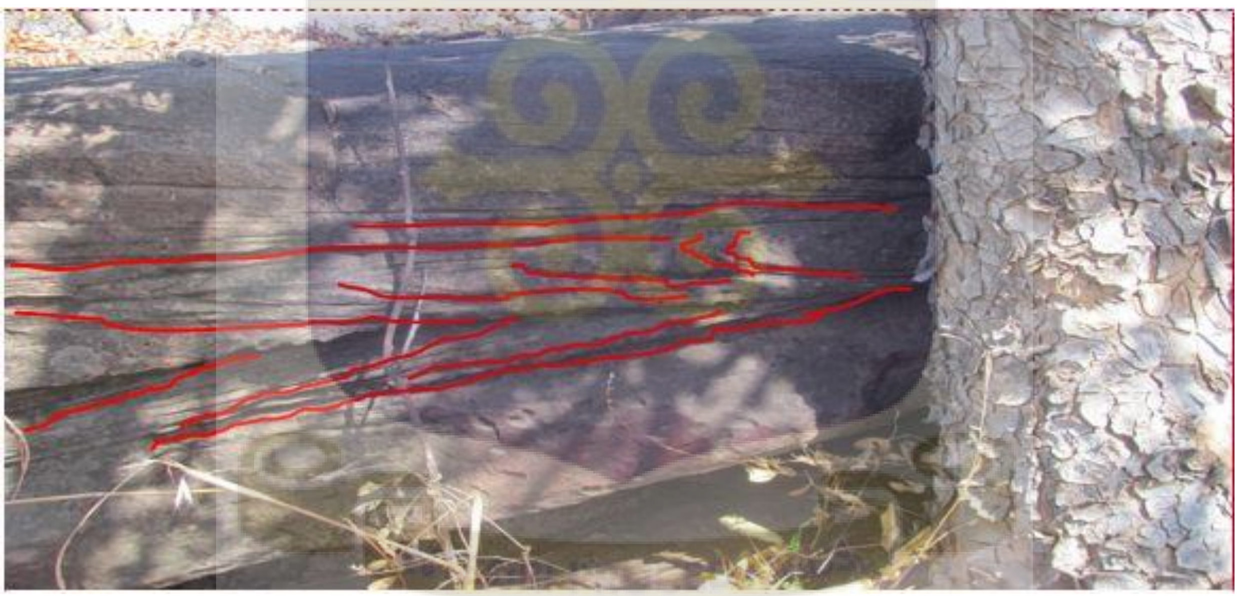


Figure 4.21: Herringbone cross – bedding at the outskirt of Duklotku towards Nakpanduri

The sandstone is characterized by cross – bedding (Fig. 4.16,4.17,4.18), herringbone cross – bedding (Fig. 4.21) at Duklotku, and with accompanying over turned cross – bedding in most areas of the southern part of the study area. The sandstone have well developed burrows (Fig. 4.19,4.20) with an average diameter of about 4cm.

4.2.1 Paleocurrent Analysis

The analysis of paleocurrent is useful in the complete description of lithofacies, (Tucker, 2004; Odumoso et al., 2013).

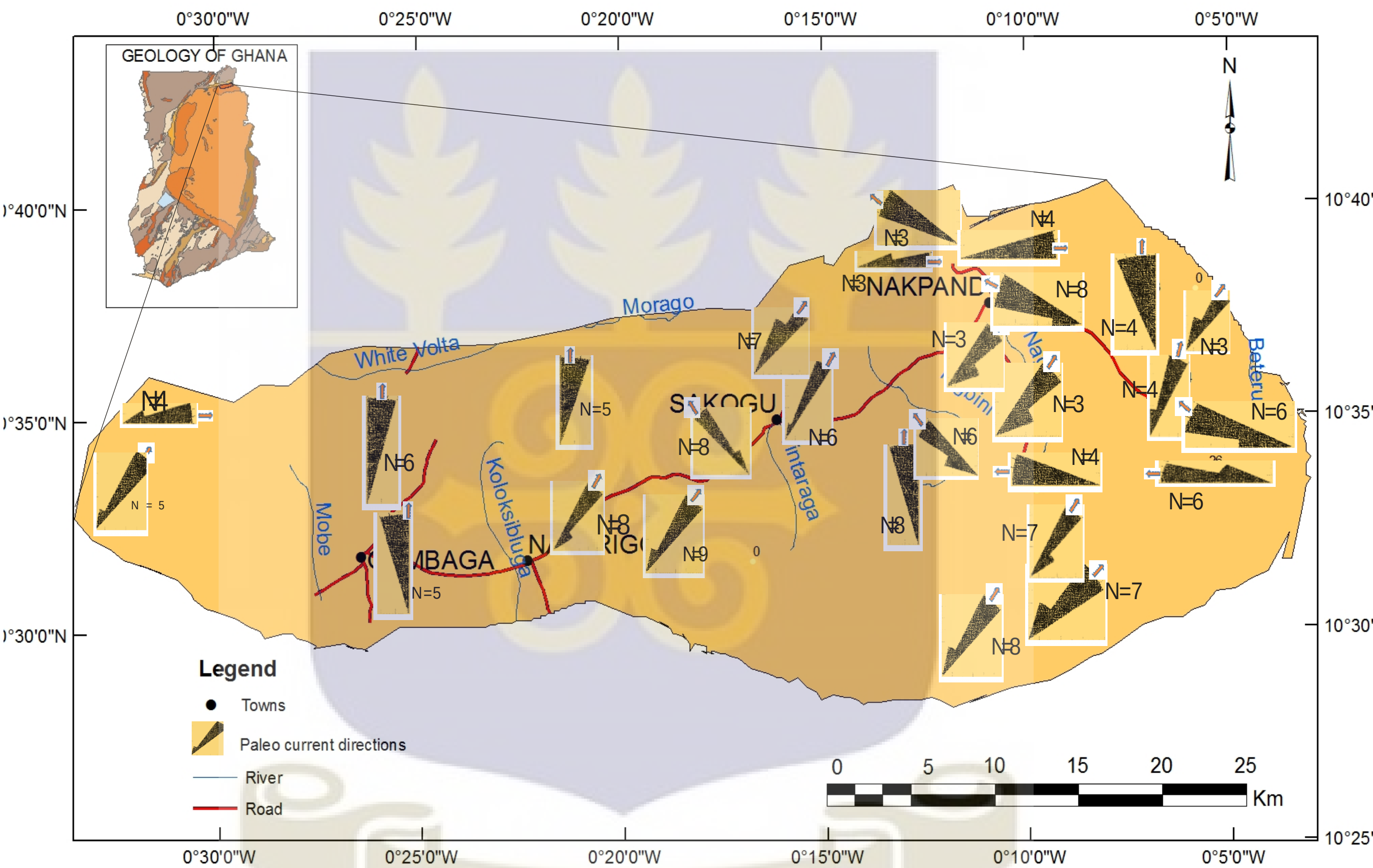


Figure 4.22: Map of the paleocurrent directions at the sample locations

Paleocurrent analysis is an important aspect in sedimentology, the measurements are useful in the indication of paleogeography, where the flow pattern of river(s) in the area is/are considered mostly together with the paleacurrent plots in the interpretation of the current direction (Fig.

4.23A,B,C,D),

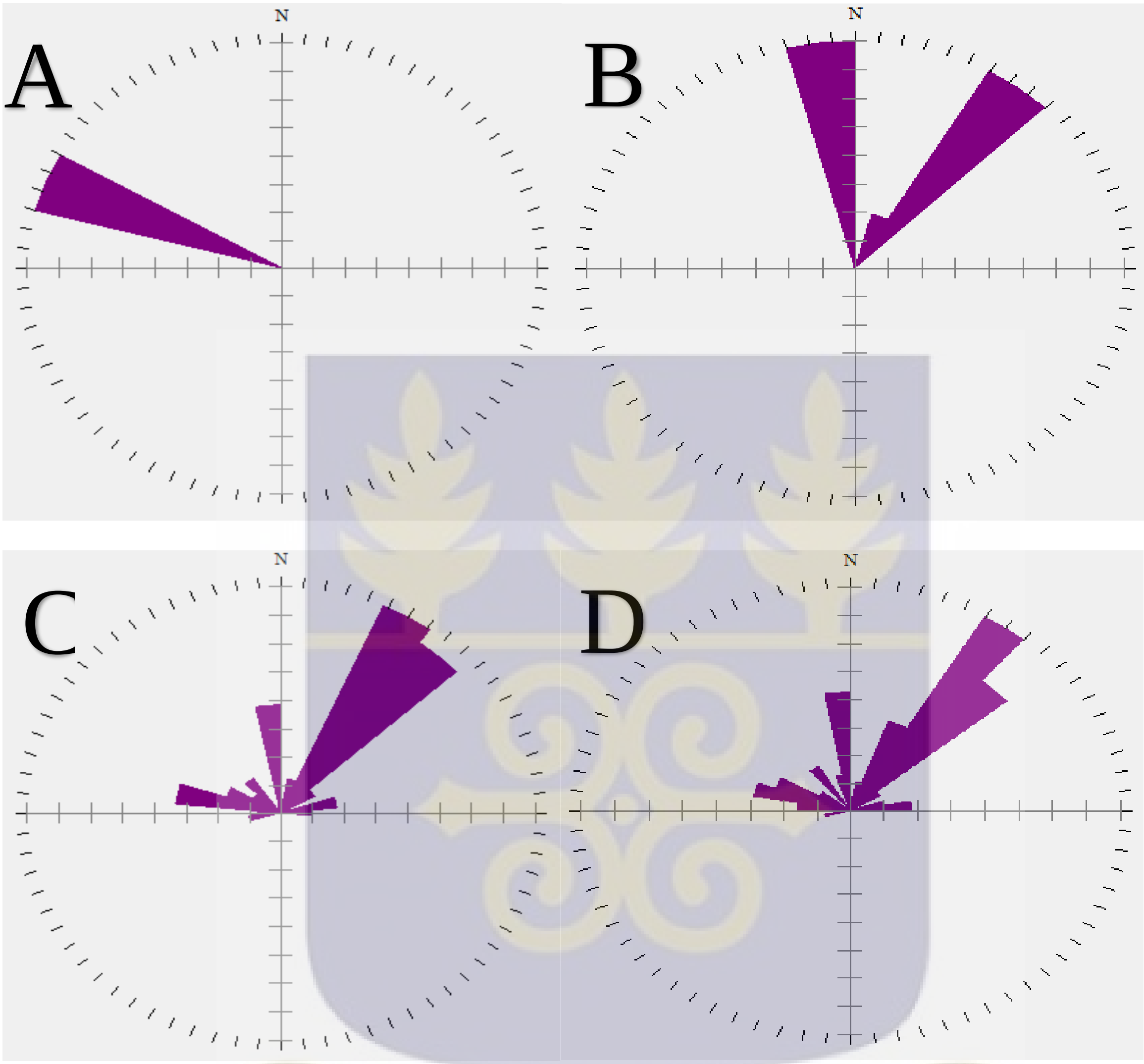


Figure 4.23: Paleocurrent direction of the lower ripple marks sandstone (local trend) - Tossiegou formation (A), (B) is the paleocurrent direction of the cross – stratified shales – Poubogou formation,(C) Feldspathic – quartzitic sandstone, - Panabako formation and (D) paleocurrent direction for the study area.

The paleocurrent measurements taken during the study was put together to generate a rose diagram to show the paleocurrent directions of the entire studied area (Fig. 4.23D).

The reconstruction of the direction in which sediments were moved by ancient current is possible by considering the azimuths of cross – bedding, cross – lamination, the azimuth of asymmetric ripple marks (lee – side indicates the flow direction current) (Tucker, 2004). The paleocurrent directions indicates that about 85% of the paleocurrent is in the NE – SW. This is indicative of the upper Panabako Formation as much of the measurements were taken from this formation (Fig. 4.23C). Minor N – S and NWW – SEE directions (Fig.4.22) of about 15%, represents the trend of the middle Poubogou and Lower Tossiegou formations (Fig. 4. 23B and 23A) respectively of the total paleocurrent directions. The paleocurrent plot of the ripple marked sandstone (Morago river) was generated considering the asymmetrical ripple marks on the sandstone exposed at the Morago river in the Nakpanduri area (Fig.4.23A). It shows a NW – SE unidirectional local flow direction of the current that deposited the ripple marked sandstone. The cross – stratifications observed on the sandy shales at the Gambaga (Fig. 4.23B) and the Nakpanduri areas of the scarp shows N – S and NE – SW flow patterns for the currents that deposited the shales/sandy shales of the Gambaga massif. The feldspathic sandstones and quartzic sandstone was largely characterized by cross – bedding, this was peculiar with the southern part of the study area. These cross – beds (Fig. 4.23C) shows a predominant NE – SW paleocurrent flow direction with a subordinate N – S and NWW – SEE flow directions of the current media/medium that deposited the sandstones of the southern part of the studied area of the massif. Putting the measurements together, the rose diagram (Fig. 4.23D) indicates a dominant NE – SW flow with minor N – S and NWW – SEE directions of the current media/medium that deposited the sediments of the Gambaga massif. The sediments of the studied area – Gambaga massif, possibly would have been largely deposited from the SW with minor input from the SEE and S.

4.2.2 Depositional Environment

The ripple marks of the sandstone of the Morago river as in (Fig. 4.10) are wave formed ripples with ripple index of 6.7, (Tucker, 2004). The sandstone is medium grained textured supported by shorter wave length of the ripples. The wavelength of ripple marks are controlled by the grain size and the depth of water, thus, larger wavelengths are produced from deeper depth and coarser sediments (Tucker, 2004). The depositional environment is a possible shallow marine environment, a beach environment is also possible (Kavoosi et al., 2009). Wave formed ripples are generally symmetrical ripples, however, the variable gentle stoss – side dip of 11ºNE and a steep lee – side dip of 15ºSW indicates an asymmetric wave ripples. This means the wave ripples were formed in an environment of variable strength of the waves in opposite directions, (Tucker, 2004).

The silty/argillaceous sediments – siltstone/sandy shales (Fig. 4.1) are possibly deposited in deep marine environment by a low/moderate energy transporting medium, a fluvial environment is also possible (Tucker, 2004; Dorrik, 2005). The ripple index of 20.9 indicates current formed ripples, however, straight – crested and bifurcated ripples (Fig. 4.4) of the shales of the scarp suggests the dominance of wave action over current (Tucker, 2004; Dorrik, 2005;Kavoosi et al., 2009) in a flood plain environment. The presence of flute casts (Fig. 4.5) indicates the action of eddies in a turbulent current over muddy sediments (Tucker, 2004), thus, supporting a high energy environment and the climbing - ripples (Fig. 4.6) also supports a very rapid deposition from a sediment – laden current in a shallow marine environment, (Tucker, 2004; Dorrik, 2005) by a low energy current. The observable flat crest ripples suggests a low energy marine environment. The poorly sorted nature of the fine grained, greenish - grey (sandy shale) and their alternation with siltstones supports a rapid deposition in shallow marine environment by a low energy current.

According to (Haruna et al., 2013) a fluvial condition is possible with the presence of ripples and cross – laminations on the shale (Fig. 4.8, 4.9). Flood plain environment is a possible environment (Zakir et al., 2002), with the presence of the parallel lamination of the shales of the study area.

Moderately – sorted (compositionally), medium – coarse grained quartz – rich sandstones (quartz arenites) (Fig. 4.25a,c) are dominant in the southern part of the study area. Large – scale cross – bedded sandstones (Fig. 4.17) with horizontal erosional surfaces in some places and relatively high dips of about 35º is typical of an aeolian depositional environment (Asiedu et al., 2005; Viljeon et al., 2008; Tucker, 2004; Kavoosi, et al., 2009). The bipolar cross – bedding (herringbone cross bedding) is as a result of reversal of tidal currents (Tucker, 2004), these sandstones would have been deposited in a tidal flat environment.

Trace fossils are useful in sedimentary studies (Tucker, 2004), the presence of burrows are evidence of trace fossils (ichnofacies), the intensely bioturbated sandstones reflects low sedimentation rates (Tucker, 2004; Kavoosi et al., 2009), moderate to high sediment supply is also reported by (Odumoso et al., 2013), burrowed surfaces shows a break in sedimentation and also reflecting the possible development of burrows on a hard ground as burrows are well developed without sediment fillings. This indicates a shoreface/foreshore environment of deposition by a high energy medium.

The relatively high feldspar content sandstones (arkose) with wavy lamination/bedding in some isolated areas with tangential bottom contact cross – bedding, is indicative of a possible continental shelf environment under turbulent current conditions (Odumoso et al., 2013). A possible tidal flat and delta front environment where the sediment supply is fluctuating or some level of current – wave activity is also possible (Viljeon et al., 2008), a rapid deposition in a fluvial environment is also possible (Anani et al., 2013). They are observed small scale ripple marks (Fig. 4.15). The ripple marks suggests a changing current direction and supports a possible shallow – marine wave environment. The studied area represents largely, a shallow marine environment with records of tidal flats, deltaic and Aeolian environments, this supports depositional environments reported by earlier workers in the northeastern Voltaian (Gambaga massifs) (Carney et al., 2010; Kalbeek et al., 2008; Viljeon et al., 2008; Ayite et al., 2008)

4.2.3 Sedimentary Facies

Depositional environment of sediments is usually characterized by certain sedimentary structure(s) and this defines the type of sedimentary facies (Tucker, 2004). The interpretation of facies can be by considering the depositional environments, processes and the prevailing conditions at the time of deposition. Sedimentary facies are the products of the environments in which they are found. Sedimentary structures provides much information on sediments depositional and textural properties (Tucker, 2004; Dorrik, 2005). Different energy levels of the depositional media could reflect variable sedimentary facies as the sedimentary structures will be different with a possible similar composition of the sediments. The grouping of the sediments into facies is principally based on the observed sedimentary structures – which reflects the depositional environments, conditions and processes, the composition and the texture of the sediments (Tucker, 2004; Kavoosi et al., 2009). The sediments has been grouped into six (6) facies (Table 4.1).

Table 4.1: The types of sedimentary facies and their characteristics

FACIES TYPES	CHARACTERISTIC FEATURES
Facies 1:	This class of facies is a sandstone observable within the Morago river at the Nakpanduri area, it is predominantly quartz, altered feldspars and

	some muscovites, it is medium grained. This has a dirty white color with wave (RI = 6.7) formed asymmetric ripple marks. This is thinly bedded with bed thickness between 1.5cm – 3cm.
Facies 2:	At the Nakpanduri area, the middle part of the scarp is largely of sandy shales. This has observable flute casts on the surfaces of floats (generated possibly from the frequent rock fall). These are greenish – grey and shiny dark – brown smooth surfaces, they are micaceous and fine grained.
Facies 3:	This facies type is peculiar with Nakpanduri area of the scarp, greenish – grey, micaceous and fine grained. They are with climbing ripples and bifurcated ripple marks, they are without observable laminations on outcrop scale. These sedimentary features are on silt/sandy shales.
Facies 4:	This group of facies characterizes the top parts of the Nakpanduri and Gambaga areas of the scarp. These are greenish – grey micaceous and are slightly altered, they appears massive on outcrop scale with a papery fissility (< 1mm partings) (Dorrik, 2005). They have parallel laminations as well as cross – stratifications, there are with foresets and topsets truncations on sandy shales in the Nakpanduri and Gambaga areas respectively. The truncation of the sets indicates the current directions.
Facies 5	This class of facies is to the northeast of Nakpanduri and close to Duklotku. This is almost quartz in mesoscopic scale, medium – coarse grained and white colored. It is characterized by herringbone cross – beds

	and over turned cross – beds with bed thickness between 2cm – 5cm, these features are observable on quartzitic sandstones.
Facies 6	This characterizes the southern parts of the study area. These are quartz rich, medium – coarse grained and whitish colored. They have planar cross – bedding and relatively large scale over turned cross – beds widely distributed in this part of the study area. The thickness of bedding range from 1.5cm – 5cm. These have height of the deposited sediments in the range of 25m – 30m in some areas. These also have well develop burrows which destroys the bedding of these group of sandstones and associated cross - bedding. The burrows are without sediments in – filling suggesting development in hardgrounds and are penetrative in cross – section indicating Skolithos. The bed thickness is between 1cm – 1.5cm.

4.2.4 Facies sequence

There was no observed parasequence boundaries except paleosol evidence marking the boundary between the lower Bombouaka/Gambaga massif and that of the middle Oti/Pendjari group. This is characterized by pseudokarren – like weathering observed in the Panabako Formation. The middle Poubogou Formation of the studied area has step – like topography towards the lower Tossiegou Formation. There is repetition of the lower sandstone component as an intercalation within the middle shale/silt/sandy shale formation of the studied area as in (Fig. 4.24) below. The transition of siltstone into shales and then to sandy shales and onto sand stones indicates a coarsening upwards parasequence. The parasequence of the studied area also supports an overall shallowing and coarsening upward sequence.

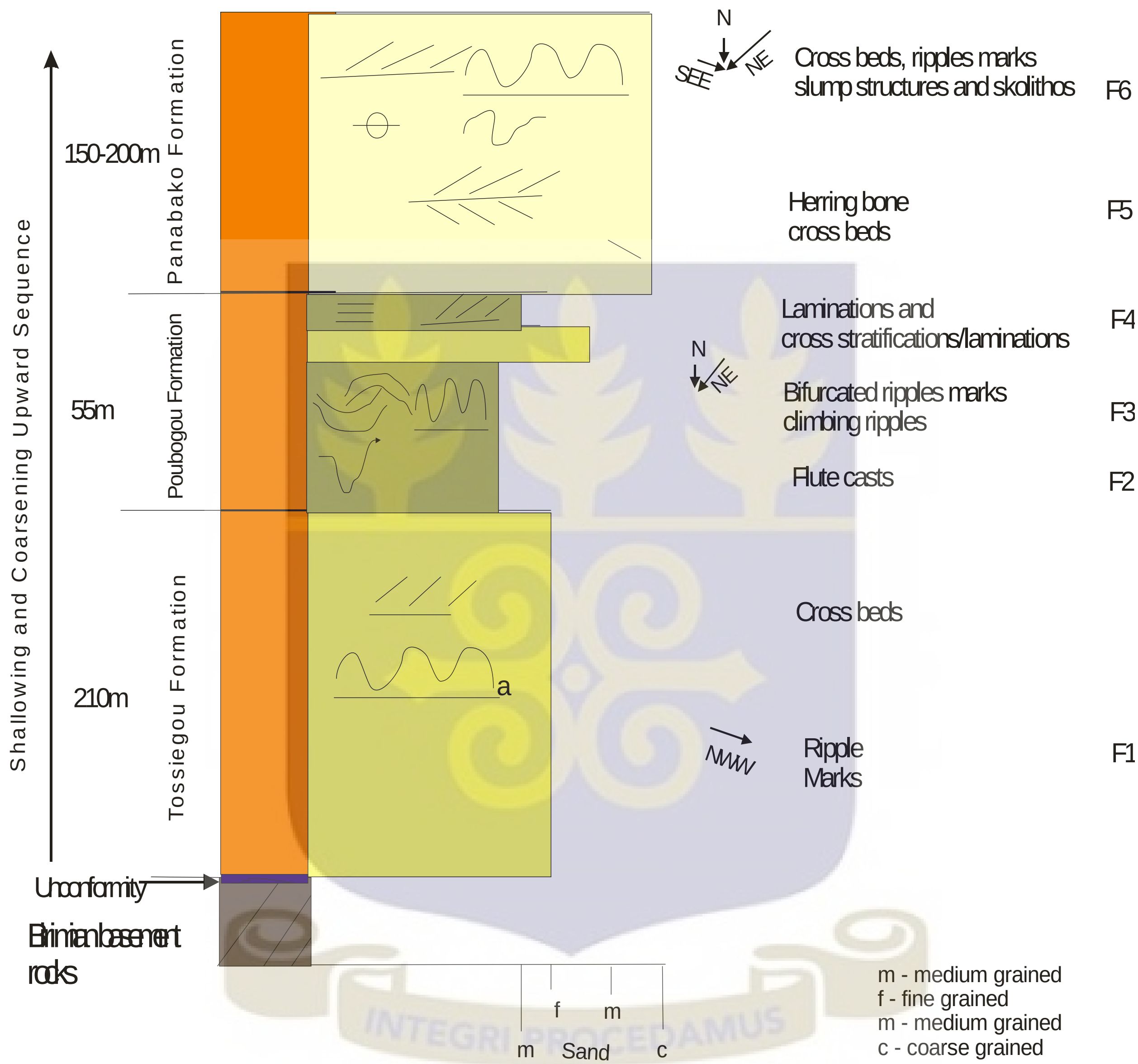


Figure 4.24 Stratigraphic/Facies sequence of the study area

CHAPTER FIVE: PROVENANCE

5.1 Petrography

Weathering and ancient conditions plays an initial control on the composition of the deposited sediments (Raymond, 1995; Pettijohn, 1957; Tucker, 2003). The composition of sandstones are properly revealed by petrographic study of thin sections prepared from samples (Tucker, 2003; Dorrik, 2005; Boggs, 2006). According to Dickinson, 1970, a vigorous study of sandstone petrography will reveal information that cannot be provided by any other method. Ingersoll et al., (1984); Dickinson, (1970, 1985); Dickinson and Suczek, (1979) recommended the use of petrographic study together with results of point counting techniques in the discussing of sediments provenance as well as their related tectonic settings. The mineralogical composition of clastic sediments reflects the geology of the source area (Dorrik, 2005; Ernest and Blatt, 1982; Boggs, 2006; Pettijohn, 1957). The composition and the properties of the minerals under a petrographic microscope gives information on the provenance (relief and elevation/topography, the possible variable source area as well as the paleo climatic conditions) including the tectonic setting under which the protolith was formed (Boggs, 2006; Ernest and Blatt, 1982; Tucker, 2003). The mineralogical properties of two principal sedimentary minerals, thus, quartz and feldspars (plagioclase and potassium) tends to reflect the tectonic setting of the parent rock which weathered to produce the available sediments (Bogg, 2006; Ernest and Blatt, 1982).

Sandstones

The composition of the sandstones observed in thin section (Fig.25) are monocrystalline quartz – with undulatory (strained) and nonundulatory extinction, polycrystalline quartz, minor feldspars with calsbad and albite twinning (K – feldspars and plagioclase respectively) and some muscovite with low order pink and blue interference colors.

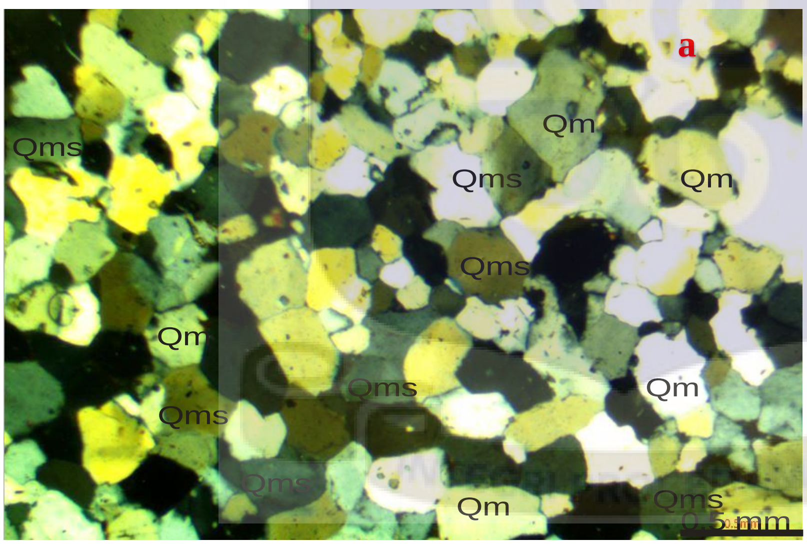
Arkose

These are composed of quartz, feldspars. The feldspars alters into sericites (sericites the products of hydrothermal alteration of the feldspars).

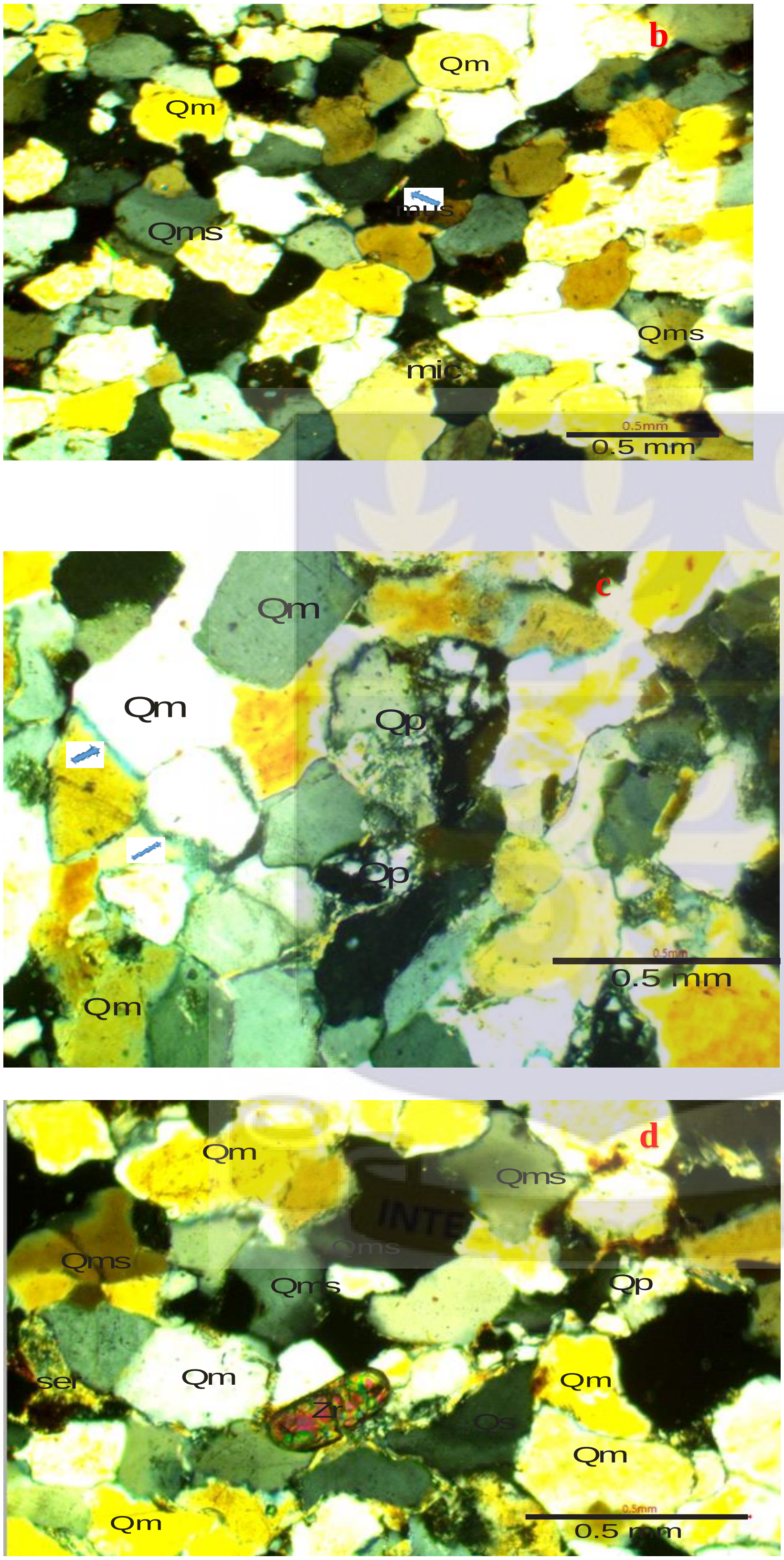
Sandy shales

Quart, biotite, muscovite and some amount of zircon grains are the mineralogical composition of these rocks.

Some heavy minerals (dominantly zircons) occurred as accessories, some of these were observable in 40X magnification and under cross hairs. The maturity (compositional and textural), sorting, recycled grains, grain alteration and overgrowth of quartz (Boggs, 2006), were the other properties of the minerals observed under the microscope.



Photomicrographs a, b, c and d are photomicrographs of sandstones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Qm
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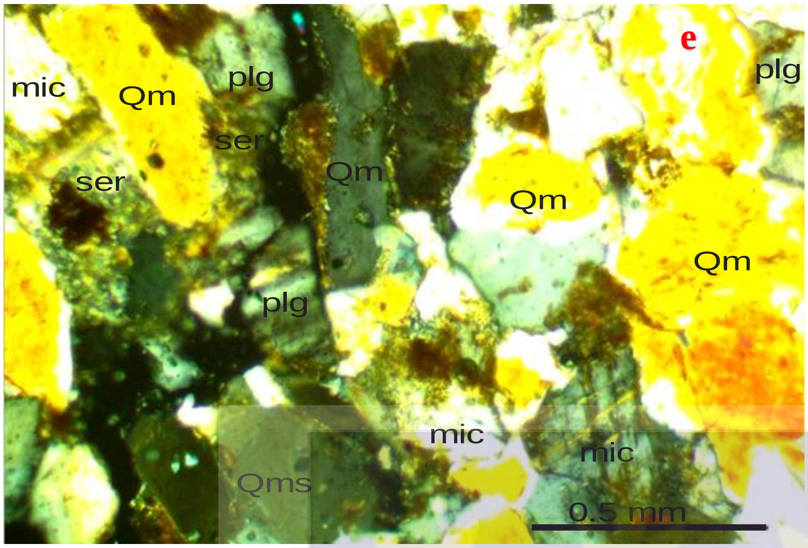
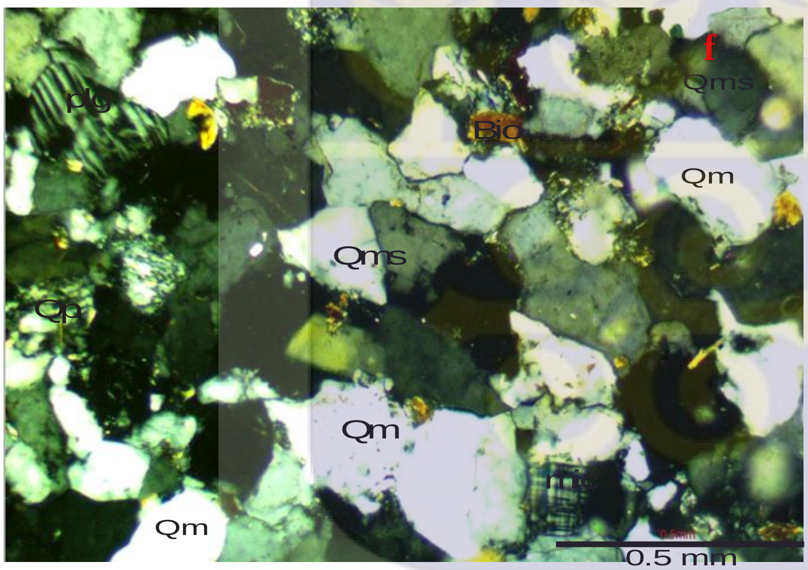
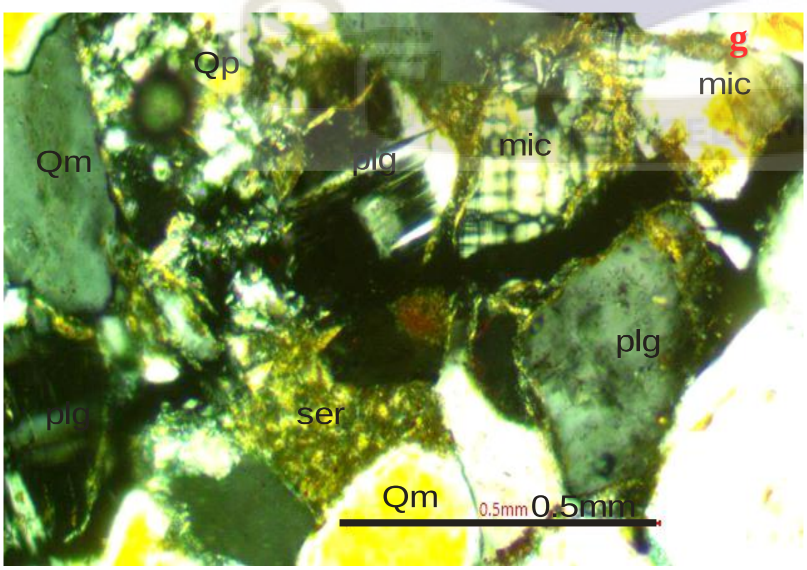
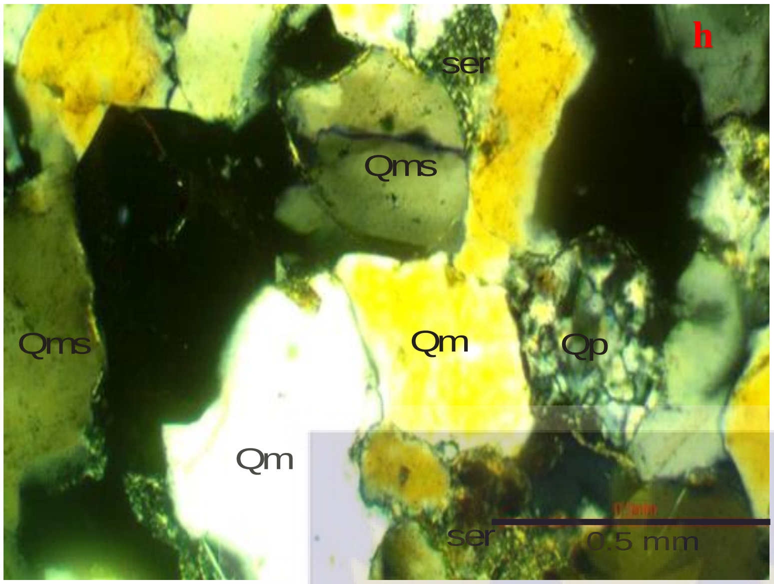
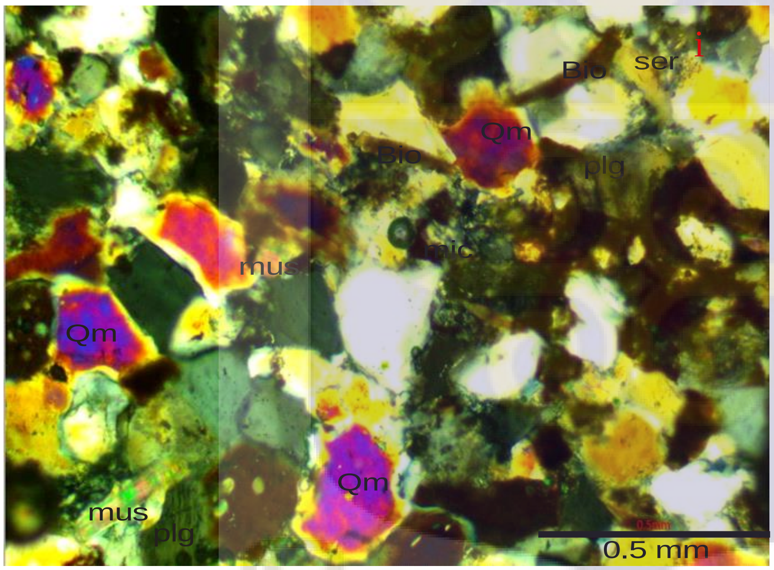


Photomicrographs e, f, g and h are photomicrographs of Arkoses









Photomicrograph of sandy shales

Figure 5.1: Photomicrographs of the studied samples showing the mineralogical compositions: Qms = monocrystalline strained quartz, qtz = quartz, Qp = polycrystalline quartz, Ser = sericite, Zr = zircon, Plg = plagioclase, Mic = microcline. Blue arrows show quartz overgrowth.

5.2 Petrographic Analysis

The mineralogical make up of sedimentary rocks can be obtained by two basic ways: petrographically (mineralogy and texture) or chemically (Hilmar et al., 2002). The petrographical study which is referred to as light – mineral analysis (Hilmar et al., 2002), is carried out by adopting the point – counter technique on the study of the thin sections to obtain the framework mineralogical constituents (Ingersoll et al., 984; Dickinson, 1970; Dickinson and Suczek, 1979) of which such data can be used to decipher the provenance as well as classify the petrofacies of the studied sediments (Tucker, 2004).

5.3 Weathering

The presence of feldspars and micas with some compositionally matured sediments indicates a moderate – highly weathered sediments. The feldspar (K – feldspars) present are highly weathered relative to the plagioclase feldspars, this suggests low relief, short travel distance of the sediments and a possible low sedimentation rate (Ogungbesan and Akaigbobi, 2011). The presence of the labile minerals (feldspars and biotite) in some of the samples (Zaid et al., 2015) studied, with angular – sub angular quartz grains coupled with the evidence of quartz overgrowth suggests an intermediate chemical weathering with the sediments experiencing some degree of recycling.

5.4 Maturity

Maturity is the measure of the approach of a clastic sediment to the stable type (Pettijohn, 1957). This is also the combine record of time through which such processes have operated and the intensity of their action. According to Pettijohn, (1957) the time and duration of action on sediments and the intensity is largely determine by relief. The mineralogical composition as evidenced by the petrographic work suggest a probably short time/duration of sediments transport before lithification with an accompanying moderate - high intensity of weathering of the sediments. This supports a possible flat/gentle relief of source area allowing sediments to be moved relatively slow and subsequently buried, thereby allowing moderate - high weathering to remove the relatively unstable minerals from the lithified sediments (Boggs, 2006; Raymond, 1995).

(Figure 5.1e,f) indicates a possible closer of sediments to source area, hence not allowing the removal of the labile minerals that still exist within the sediments. A sediment is said to be stable when it is composed of quartz minerals than there are other unstable minerals (Pettijohn, 1957; Boggs, 2006), a matured sediment is one which is not likely to undergo further processes due to the absence of unstable minerals (Pettijohn, 1957). The sediments/sedimentary rocks of the studied area are sub matured – matured compositionally (Fig. 5.1a,b). The sediments are on the hand not texturally matured as the compositionally matured sediments are with angular to sub – angular mineral (quartz) grains supporting the possible proximity of the sediments to their source.

5.5 Provenance

The mineralogical composition of sedimentary rocks has proven to be one of the possible methods of deducing the provenance of sediments (Ehlers and Blatt, 1982; Boggs, 2006). The composition of detrital sediments is controlled by provenance, transportation, depositional environmental conditions and diagenesis (Boggs, 2006; Ingersoll et al., 1984; Raymond, 1995). The provenance of sediments comprises of all aspects of the source area, including source rocks, climate, depositional environment and relief/elevation (Pettijohn et al., 1972; Dickinson and Suczek, 1979). In areas of intense tectonic/magmatism, source rocks controls to a large extent, the composition of the sediments than do relief and climate (Dickinson, 1970), however, where there is no evidence of tectonic/magmatic activities (Basu et al., 1975; Dickinson, 1985) as in the case of the Voltaian basin, relief and climate plays a major role on the composition of the sediments.

5.5.1 Relief/ Elevation

Relief/elevation has control on the composition of detritus sediments available (Boggs, 2006;

Raymond, 1995; Pettijohn, 1957). The minor presence of feldspars and micas within the lithified (Fig. 5.1e,f,i) sediments suggests a weathering in a relatively flat/gentle relief area(s), the erosion of sediments would have been relatively rapid and subsequently buried, this process did not allow complete weathering of the sediments of the study area which would have entirely remove the unstable minerals, this resulted in a moderate - highly weathered (Ernest and Blatt, 1982) sediments. A possible rapid deposition did not allow the decomposition of the most unstable minerals which are still observable within the constituents of the sediments (Arkose). Ogungbesan and Akaigbobi, (2011) also stated that, the presence of highly altered feldspars within sediments could be an indication of a low relief. The quartz rich samples could have come from a close granitic source as the quartz are mostly not texturally matured and are still angular to sub – angular, most likely from the adjacent Birimian granites and granitic gneisses.

5.5.2 Paleoclimate

Ancient climatic conditions plays a significant role in the composition of detrital sediments (Boggs, 2006) especially, where there is no tectonic activity/magmatism (Basu et al., 1975) like the studied area. High temperature regimes favors the brake down of mineral grains whiles reducing the decomposition (chemical alteration). Wet climatic conditions supports high decomposition whereas dry conditions reduces decomposition (Boggs, 2006; Raymond, 1995). Strong chemical weathering is associated with high temperature and humid climatic conditions, with arid conditions supporting relatively weak chemical weathering (Basu et al., 1975; Suttner et al. 1986). High rainfall will help remove the labile minerals e.g plagioclase feldspars and potassium feldspars. The presence of feldspars (Fig. 5.1f,g) indicates a possible high paleo temperature regimes of the sediments under semi humid – arid conditions (Boggs, 2006).

5.5.3 Sediments transport

The composition of detrital sediments tells the history of their travel distance from its weathered source to the current deposited environment. The most unstable components of detritus are the feldspars and micas (Dickinson, 1970; Dickinson and Velloni, 1984; Dickinson and Suczek, 1979). The presence of feldspars that are highly altered with some minor content of micas suggests a relatively moderate residence time of sediments as they are moved from source/a possible short distance of travel of sediments from source (Ogungbesan and Akaigbobi, 2011). The relative angular grains of sediments (Fig. 5.1a) and poorly sorted nature supports a short travel time, it is possible that sediments are closer to the source where initial weathering took place (Raymond, 1995). The compositionally matured sediments are most likely to be coming from a quartz rich source rock where with little distance of travel, the sediments will still have a similar/same composition as the source rock, a close granitic/granitic gneissic source is most likely.

5.5.4 Source

Mineralogical property together with the composition can be used to decipher the source of the sediments (Dickinson, 1970, 1985; Ingersoll et al., 1984; Boggs, 2006; Ernest and Blatt, 1995). The presence of quartz, feldspar, micas and accessory minerals (Ingersoll et al., 1984; Dickinson and Suczek, 1979) indicates a plutonic or metamorphic source, ie, granitic or gneissic source. The undulatory monocrystalline quartz grains suggests a metamorphic and igneous rocks according to Blatt and Cristie, (1963); Blatt et al., (1980); Dhiman et al.,(2006). According to Blatt et al., (1980); Dhiman et al., (2006), the nonundulatory monocrystalline quartz grains are indicative of sediments from fine-grained schist, phyllites and slates of volcanic rocks origin, hypabyssal igneous rocks as the protoliths. Micas, according to Pettijohn et al., (1987) is generally of schist and gneisses of plutonic igneous rocks and volcanic rock sources. Although feldspars are unstable, they are significant provenance indicator, the presence of microcline indicates slow cooling of magmatic material, hence characteristics of plutonic source rocks. Plagioclase indicates a volcanic or hypabyssal sources (Pittman, 1963; Dhiman et al., 2006). The heavy minerals, such as zircons points to a sedimentary, possibly the metasediments of the Birimian, an acid/intermediate sources of sediments (Faupl et al., 1998). The relative angularity of mineral grains supports the assertion that the sediments is most likely to be the weathering products of the adjacent Birimian rocks – granites and granitic gneisses which are very close to the study area (Gambaga massif). The polycrystalline quartz grains and undulatory extinction (sweeping pattern of extinction) of quartz minerals (Boggs, 2006), suggests that the quartz is derived from varied sources. This is supported by the variable paleocurrent pattern indicated by the rose diagram (Fig. 4. 23D). A possible plutonic source of the Kwahu massif which is the lateral equivalent of the Gambaga massif (Carney et al., 2010; Affaton et al., 2008) is reported by (Anani, 1999). The sediments of the Bombouaka Group are reported to have their source area at the western part of the WAC according to Carney et al., (2010); Affaton and Frei, (2009).

5.5.5 Tectonic setting

The tectonic setting of the detritus was inferred from the petrographic study of the collected samples of the study area of the Gambaga – Nakpanduri area. Quartz arenites (Ernest and Blatt, 1982; Boggs, 2006) are associated typically with rocks assemblages deposited in stable cratonic environments or tectonically quiescence, possibly, a passive margin tectonic setting.

5.6 Geochemistry

The mineralogical and chemical composition of clastic sediments is controlled by the composition of the source rock and aspects of the source area (Anani et al., 2013; Hilmar et al., 2015; Boggs, 2006; Adel et al., 2010; Elzien et al., 2014; Mclennan et al., 1999), ie, weathering, climatic conditions, relief transportation and to some extent, the depositional environment. The chemical composition of clastic sediments has been reported by several workers to be suitable indicators of the paleo weathering conditions, relief, source/provenance, tectonic setting and the paleo climatic conditions (Mclennan et al., 1983, 1985; Anani et al., 2012; Adel et al., 2010; Elzien et al., 2014; Floyd and Leveridge, 1987; Shao et al., 2012; Bhattia and Crook, 1988; Bracciali et al., 2007; Kroonenberg, 1994; Roser and Korsch, 1988; Nesbitt and Young, 1982,1984). Indices of geochemical parameters like CIA (Chemical Index of Alteration), CIW (Chemical Index of Weathering), PIA (Plagioclase Index of Alteration), ICV (Index of Compositional Variability) together with ratios and ternary diagrams, thus, K_2O/Na_2O, K_2O/Al_2O_3, Th/U, SiO_2 – $Al_2O_3+K_2O+Na_2O$, Al_2O_3 – $CaO+Na_2O$ – K_2O. Plots of these together with other geochemical parameters are suitable (Cullers, 1994; Cox et al., 1995; Nesbitt and Young, 1984; Elzien et al., 2014; Adel et al., 2010; Floyd and Leveridge, 1987) provenance, paleoclimatic conditions, sediment maturity, relief and intensity of weathering indicators. The estimation of the type of sandstone using geochemical data by (Herron, 1988) has been effectively done using the log of (Si_2O/Al_2O_3) and (Fe_2O_3/K_2O) parameters (Table. 4.2)

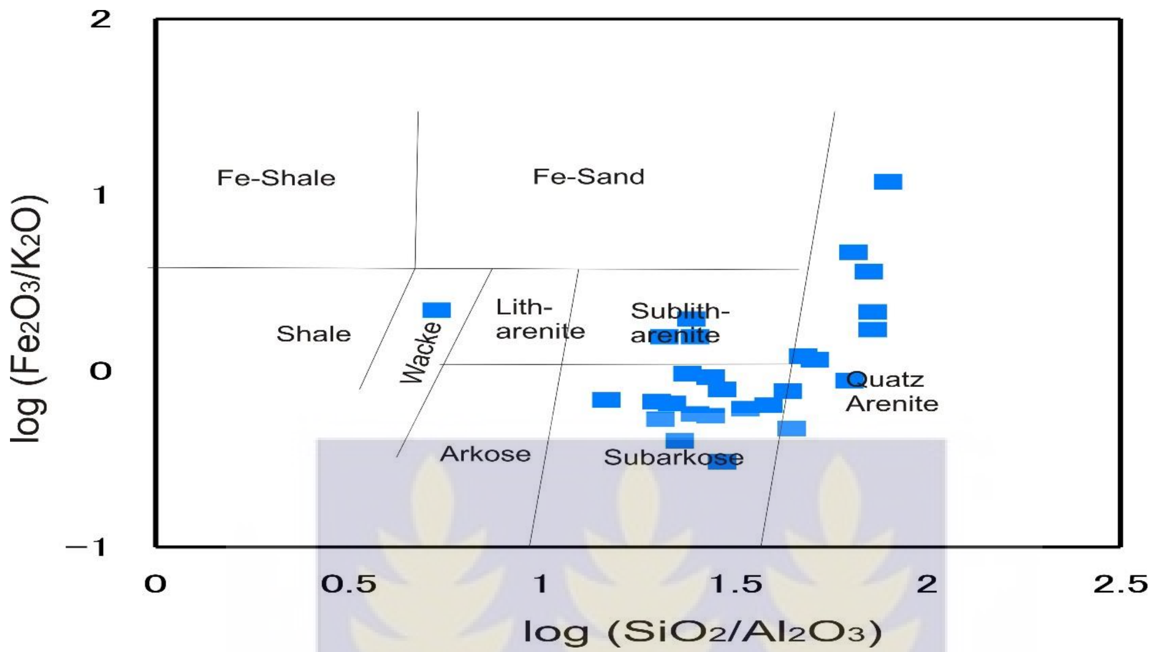


Figure 5.2: Geochemical classification of the Gambaga – Nakpanduri area sandstones. After Herron, (1988)

Major elements has been effectively used to discuss sediments maturity (Nesbitt and Young, 1984; Shao et al., 2012), Al_2O_3, $CaO+Na_2O$ and K_2O on a ternary diagram has been over time been used to decipher the weathering conditions of clastic sediments.

Table 5.1: Geochemical results of the Gambaga-Nakpanduri area of Northeastern voltaian

Sample Number	AM01	AM02	AM03	AM04	AM05	AM06	AM07	AM08	AM09	AM10	AM11	AM12	AM13	AM14	AM15	AM16	AM17	AM18	AM19	AM20	AM21	AM22	AM23	AM24	AM25	AM26	AM27	Aveg.
Major oxide (wt%)																												
SiO2	86.5	91.6	96.7	92.1	89.7	96.3	90.5	92.4	92.8	90.1	94.7	96.5	97.8	68.5	93.2	95.1	94.6	90.7	92.9	96.6	93.5	97.3	95.3	96.9	93.8	94.3	91	92.64
TiO2	0.25	0.23	0.2	0.15	0.17	0.07	0.36	0.08	0.25	0.27	0.14	0.17	0.08	0.7	0.15	0.15	0.21	0.07	0.12	0.04	0.26	0.1	0.09	0.04	0.08	0.11	0.08	0.17
Al2O3	5.87	4.64	2.04	3.66	4.34	1.22	4.17	3.11	3.74	3.76	2.41	1.34	1.89	12.85	2.75	1.46	2.18	4.42	3.18	1.33	3.42	1.37	2.14	1.55	3.77	3.44	3.94	3.33
Fe2O3	1.6	1.26	0.52	1.85	2.02	1.09	1.19	0.68	0.81	1.63	0.35	0.43	0.4	5.77	0.58	0.72	0.48	0.99	0.42	0.5	0.99	0.59	0.43	0.47	0.79	0.68	0.74	1.04
MgO	0.3	0.27	0.04	0.26	0.31	0.03	0.1	0.08	0.07	0.08	0.06	0.04	0.04	2.05	0.07	0.03	0.06	0.07	0.07	0.03	0.07	0.03	0.03	0.07	0.05	0.04	0.05	0.16
CaO	0.03	0.08	0.05	0.05	0.06	0.03	0.04	0.09	0.03	0.05	0.06	0.03	0.02	0.32	0.04	0.02	0.04	0.03	0.07	0.02	0.04	0.02	0.02	0.07	0.05	0.03	0.03	0.05
Na2O	0.06	0.11	0.03	0.26	0.21	0.01	0.04	0.02	0.01	0.04	0.01	0.01	0.01	1.28	0.03	0.01	0.01	0.05	0.03	0.01	0.01	0.01	0.02	0.02	0.05	0.05	0.06	0.09
K2O	2.29	1.86	0.42	1.18	1.27	0.09	1.81	0.86	0.41	1.65	0.54	0.25	0.34	2.55	0.93	0.15	0.62	1.84	1.37	0.23	1.05	0.16	0.89	0.53	1.37	1.21	1.83	1.03
P2O5	0.03	0.03	0.01	0.02	0.02	0.01	0.01	0.02	0.01	0.04	0.06	0.01	0.02	0.11	0.01	0.01	0.01	0.01	0.04	0.01	0.02	0.01	0.01	0.02	0.01	0.02	0.02	0.02
MnO	0.01	0.03	0.01	0.04	0.04	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.17	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02
SiO2/Al2O3	14.74	19.74	47.40	25.16	20.67	78.93	21.70	29.71	24.81	23.96	39.29	72.01	51.75	5.33	33.89	65.14	43.39	20.52	29.21	72.63	27.34	71.02	44.53	62.52	24.88	27.41	23.10	39.06
Fe2O3/K2O	0.70	0.68	1.24	1.57	1.59	12.11	0.66	0.79	1.98	0.99	0.65	1.72	1.18	2.26	0.62	4.80	0.77	0.54	0.31	2.17	0.94	3.69	0.48	0.89	0.58	0.56	0.40	1.66
K2O/Na2O	38.17	16.91	14.00	4.54	6.05	9.00	45.25	43.00	41.00	41.25	54.00	25.00	34.00	1.99	31.00	15.00	62.00	36.80	45.67	23.00	105.00	16.00	44.50	26.50	27.40	24.20	30.50	31.92
K20/Al2O3	0.39	0.40	0.21	0.32	0.29	0.07	0.43	0.28	0.11	0.44	0.22	0.19	0.18	0.20	0.34	0.10	0.28	0.42	0.43	0.17	0.31	0.12	0.42	0.34	0.36	0.35	0.46	0.29
CIA	71.15	69.36	80.31	71.07	73.81	90.37	68.81	76.23	89.26	68.36	79.80	82.21	83.63	75.59	73.33	89.02	76.49	69.72	68.39	83.65	75.66	87.82	69.71	71.43	71.95	72.73	67.24	76.19
CIW	98.49	96.07	96.23	92.19	94.14	96.83	98.12	96.58	98.94	97.66	97.18	97.10	98.44	88.93	97.52	97.99	97.76	98.22	96.95	97.79	98.56	97.86	98.17	94.51	97.42	97.73	97.77	96.86
ICV	0.76	0.80	0.61	0.96	0.89	1.08	0.84	0.58	0.42	0.98	0.48	0.69	0.47	0.90	0.65	0.74	0.65	0.68	0.65	0.63	0.71	0.66	0.69	0.77	0.62	0.60	0.70	0.70
LOI	1.91	1.47	0.95	1.42	1.69	0.75	1.1	1.3	1.55	1.02	0.95	0.57	0.76	4.42	0.86	0.77	0.94	1.25	1.01	0.61	1.18	0.73	0.73	0.71	1.19	1.01	1.07	
Total	98.9	101.63	100.98	101.02	99.86	99.6	99.36	98.67	99.67	98.68	99.32	99.36	101.38	98.78	98.65	98.41	99.16	99.48	99.26	99.4	100.57	100.32	99.68	100.4	101.2	100.91	98.86	
trace elements (ppm)																												
Sc	3	3	1	2	2	1	2	1	2	1	1	1	1	12	1	1	1	1	1	1	1	1	1	0.08	1	1	1	
Cr	20	20	30	20	20	20	60	10	30	20	20	20	10	70	30	30	20	10	20	10	40	10	20	20	10	10	10	
V	15	13	7	16	22	8	17	5	7	11	7	5	6	87	5	5	5	7	5	5	8	5	5	5	8	6	7	
Co	2	2	1	5	5	2	1	1	1	1	1	1	1	17	1	1	1	1	1	2	1	1	1	1	1	1	1	
Ni	9	6	1	9	11	2	1	1	1	2	1	1	1	34	1	1	1	1	1	1	2	1	1	1	1	1	1	
Cu	8	6	2	2	4	5	5	2	2	3	2	5	2	24	2	3	2	3	3	3	2	6	2	3	3	2	2	
Rb	76.3	58.8	13.8	37.1	42.5	5.2	69.5	32.8	15.6	63.4	18.3	9.7	12.6	127	35.7	6.6	24.6	74.3	49.1	9	42.3	8	30.6	20	50	42.7	66.8	
Sr	47	45.2	16	20	21.3	18	32.9	24.9	13.9	32.4	90.2	11.8	15.8	48.7	20.1	13	21.1	29	40.9	12.3	24.7	13.5	20.4	17.1	25.1	25.4	31.8	
Cs	1.21	1.03	0.35	0.6	0.74	0.2	1.12	0.74	0.6	0.85	0.4	0.27	0.3	5.47	0.56	0.18	0.51	1.15	0.82	0.3	0.84	0.56	0.53	0.52	0.87	0.67	0.95	
Ba	392	355	60.7	234	268	40	297	170	35.6	305	165.5	35.4	79.2	480	145	25.2	106.5	335	300	66.5	152.5	19.9	163	104.5	247	225	331	
Y	19.1	14.4	8.3	14.5	15.9	4.2	15	6.1	10.7	11.6	8.5	6.7	4.5	36	8	5.7	10.3	11.7	5.6	4.2	13.3	4.8	4.2	3.1	8.3	8.2	9	
Zr	239	312	342	108	110	191	732	81	425	196	231	266	105	189	278	247	396	81	140	43	489	157	137	59	78	114	104	
Hf	6.3	8.6	8.8	2.9	3	4.4	18.3	2.2	11.1	5	5.9	6.8	2.8	5.1	6.9	6.4	10.2	2.2	3.6	1.2	12.6	4.2	3.5	1.7	2.1	3.2	2.6	
Nb	4.6	4.6	3.6	3.1	3.5	1.2	6.7	2	4.6	5.8	2.5	3	1.5	12.2	2.9	2.7	3.7	1.8	2.3	0.8	4.7	1.7	1.9	1.3	1.8	2.5	1.9	
Ta	0.4	0.3	0.3	0.2	0.3	0.1	0.6	0.2	0.4	0.5	0.2	0.2	0.1	0.9	0.2	0.2	0.3	0.1	0.2	<0.1	0.4	0.1	0.1	0.1	0.1	0.2	0.2	
Th	6	6.25	5.12	3.42	3.65	1.08	8.26	2.5	6.16	5.34	3.48	3.7	1.57	8.79	2.86	3.9	3.91	2.6	2.67	1.09	6.24	1.49	2.25	3.63	3.12	4.38	3.73	
U	1.75	1.79	1.28	1.46	1.6	0.52	1.3	0.47	0.97	0.89	0.97	0.84	0.64	2.8	1.24	0.52	1.83	1.07	0.67	0.82	1.76	0.7	0.61	0.45	0.96	1.14	1.18	
La	25.3	17.3	10.3	13.7	14.7	11.3	16.7	14.3	20.4	17.8	28.1	8.7	10.2	24.8	10	8.5	12.4	12.2	10.5	15.7	13	10.8	7	7	11.1	13.5	13.8	
Ce	48.8	34.2	20	35.2	37.3	24.1	33.1	24.3	30.7	34.7	51.4	17.6	18.7	51.6	18.9	16.3	21.6	23	20.7	28.6	24.6	20.7	13.4	13.2	21.2	21.9	25.1	
Pr	5.85	3.83	2.21	3.91	4.04	2.22	3.59	2.6	3.7	3.82	5.46	1.76	2.1	6.79	1.96	1.65	2.37	3.03	2.13	3.13	2.71	2.19	1.49	1.37	2.5	2.85	3.4	
Nd	22.5	14.4	8.1	16	16.3	8.1	13.7	9.3	11.8	14.9	20.1	6.5	8.1	29.1	7.9	5.6	8.4	13.1	8.3	11	10.3	8.3	5.5	5.1	9.4	11	12.8	
Sm	3.35	2.63	1.54	3.06	3.16	1.12	2.77	1.57	1.93	2.77	3.39	1.09	1.55	7.12	1.41	0.82	1.52	2.79	1.6	1.64	1.86	1.35	0.83	0.87	1.91	1.87	2.21	
Eu	0.58	0.49	0.26	0.57	0.46	0.24	0.55	0.31	0.34	0.47	0.58	0.17	0.29	1.42	0.26	0.18	0.26	0.52	0.33	0.26	0.35	0.27	0.16	0.17	0.33	0.33	0.41	
Gd	2.94	2.2	1.37	2.82	2.49	1.04	2.64	1.26	1.73	2.01	2.38	0.87	1.21	7.02	1.29	0.73	1.35	2.31	1.28	0.93	1.63	1.15	0.63	0.73	1.36	1.34	1.6	
Tb	0.47	0.41	0.18	0.37	0.42	0.13	0.4	0.18	0.32	0.36	0.33	0.19	0.17	1.09	0.18	0.16	0.22	0.34	0.17	0.14	0.31	0.16	0.09	0.09	0.2	0.19	0.26	
Dy	3.11	2.52	1.31	2.37	2.78	0.83	2.73	1.18	1.76	2.35	1.74	1.14	0.94	6.79	1.25	0.9	1.56	2.48	1.08	0.86	2.11	0.85	0.85	0.6	1.38	1.43	1.64	
Ho	0.68	0.58	0.3	0.56	0.6	0.15	0.61	0.26	0.39	0.49	0.33	0.27	0.17	1.4	0.27	0.21	0.37	0.52	0.21	0.16	0.47	0.18	0.19	0.12	0.28	0.3	0.37	
Er	2.08	1.59	0.95	1.51	1.66	0.45	1.74	0.72	1.23	1.3	0.92	0.78	0.53	3.91	1.01	0.7	1.27	1.71	0.58	0.51	1.53	0.57	0.47	0.37	0.87	0.96	1.03	
Tm	0.31	0.25	0.14	0.23	0.25	0.06	0.3	0.08	0.18	0.2	0.12	0.11	0.08	0.51	0.14	0.1	0.19	0.29	0.11	0.07	0.21	0.08	0.07	0.04	0.15	0.15	0.16	
Yb	1.97	1.69	1.1	1.57	1.89	0.55	2.01	0.77	1.51	1.58	1.09	0.89	0.56	3.34	1.1	0.75	1.27	1.72	0.79	0.4	1.48	0.68	0.56	0.36	1.04	0.97	1.13	
Lu	0.3	0.26	0.16	0.23	0.3	0.08	0.35	0.1	0.23	0.23	0.14	0.13	0.08	0.49	0.17	0.12	0.21	0.27	0.12	0.08	0.25	0.13	0.08	0.06	0.13	0.15	0.16	
Th/U	3.429	3.492	4.000	2.342	2.281	2.077	6.354	5.319	6.351	6.000	3.588	4.405	2.453	3.139	2.306	7.500	2.137	2.430	3.985	1.329	3.545	2.129	3.689	8.067	3.250	3.842	3.161	3.800
Th/Sc	2	2.08	5.12	1.71	1.825	1.08	4.13	2.5	3.08	5.34	3.48	3.7	1.57	0.7325	2.86	3.9	3.91	2.6	2.67	1.09	6.24	1.49	2.25	45.375	3.12	4.38	3.73	4.52
Cr/Th	3.33	3.20	5.86	5.85	5.48	18.52	7.26	4.00	4.87	3.75	5.75	5.41	6.37	7.96	10.49	7.69	5.12	3.85	7.49	9.17	6.41	6.71	8.89	5.51	3.21	2.28	2.68	6.19

La/Sc	8.43	5.77	10.30	6.85	7.35	11.30	8.35	14.30	10.20	17.80	28.10	8.70	10.20	2.07	10.00	8.50	12.40	12.20	10.50	15.70	13.00	10.80	7.00	87.50	11.10	13.50	13.80	13.92
La/Co	12.65	8.65	10.30	2.74	2.94	5.65	16.70	14.30	20.40	17.80	28.10	8.70	10.20	1.46	10.00	8.50	12.40	12.20	10.50	7.85	13.00	10.80	7.00	7.00	11.10	13.50	13.80	11.05
Th/Cr	0.30	0.31	0.17	0.17	0.18	0.05	0.14	0.25	0.21	0.27	0.17	0.19	0.16	0.13	0.10	0.13	0.20	0.26	0.13	0.11	0.16	0.15	0.11	0.18	0.31	0.44	0.37	0.20
Th/Co	3.00	3.13	5.12	0.68	0.73	0.54	8.26	2.50	6.16	5.34	3.48	3.70	1.57	0.52	2.86	3.90	3.91	2.60	2.67	0.55	6.24	1.49	2.25	3.63	3.12	4.38	3.73	3.19
(La/Lu)N	8.76	6.92	6.69	6.19	5.09	14.70	4.96	15.06	9.22	8.04	20.84	6.95	13.27	5.26	6.11	7.35	6.13	4.69	9.08	20.42	5.40	8.62	9.10	12.14	8.86	9.35	8.96	9.19
Eu/Eu*	0.57	0.62	0.55	0.59	0.50	0.68	0.62	0.67	0.57	0.61	0.62	0.53	0.63	0.61	0.59	0.71	0.55	0.63	0.71	0.64	0.61	0.66	0.68	0.65	0.63	0.64	0.67	0.62
∑REE	118.24	82.35	47.92	82.10	86.35	50.37	81.19	56.93	76.22	82.98	116.08	40.20	44.68	145.38	45.84	36.72	52.99	64.28	47.90	63.48	60.81	47.41	31.32	30.08	51.85	56.94	64.07	65.36

ICV = $(Fe_2O_3+K_2O+CaO+MgO+MnO+TiO_2)/Al_2O_3$, CIA= $[Al_2O_3/(Al_2O_3+CaO+Na_2O+K_2O)*100]$ and CIW = $[Al_2O_3/(Al_2O_3+CaO+Na_2O)*100$

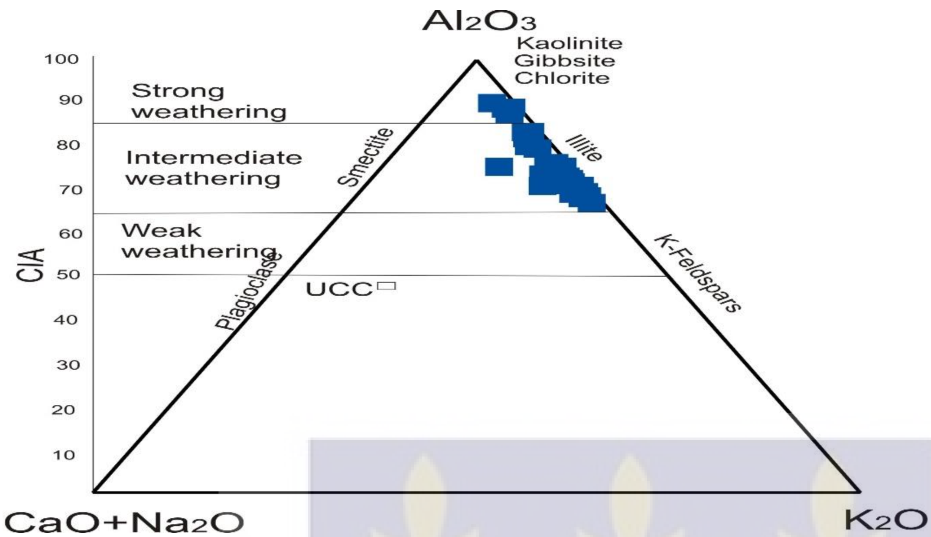


Figure 5.3: A-CN-K ternary diagram showing the weathering conditions of the sandstones of the studied area. After (Shao et al., 2007)

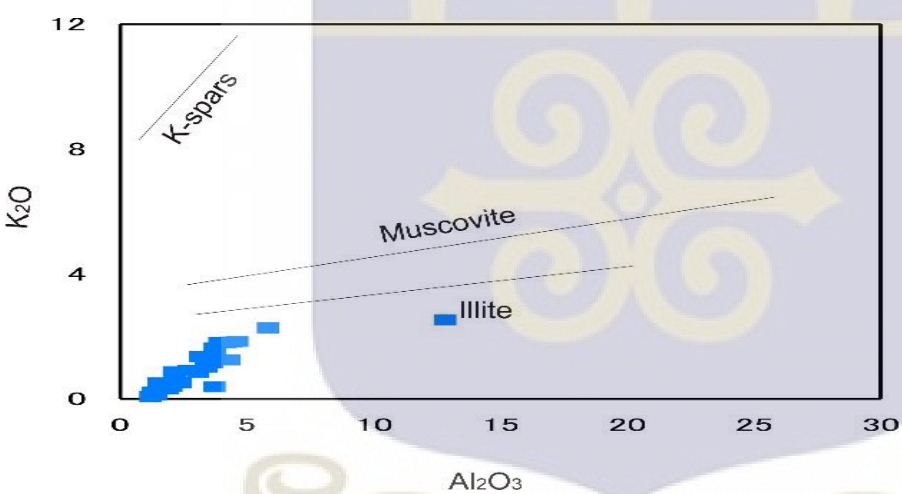


Figure 5.4: K_2O versus Al_2O_3 ratio diagram showing the alteration of potassium feldspars into illite. After (Cox et al., 1995)

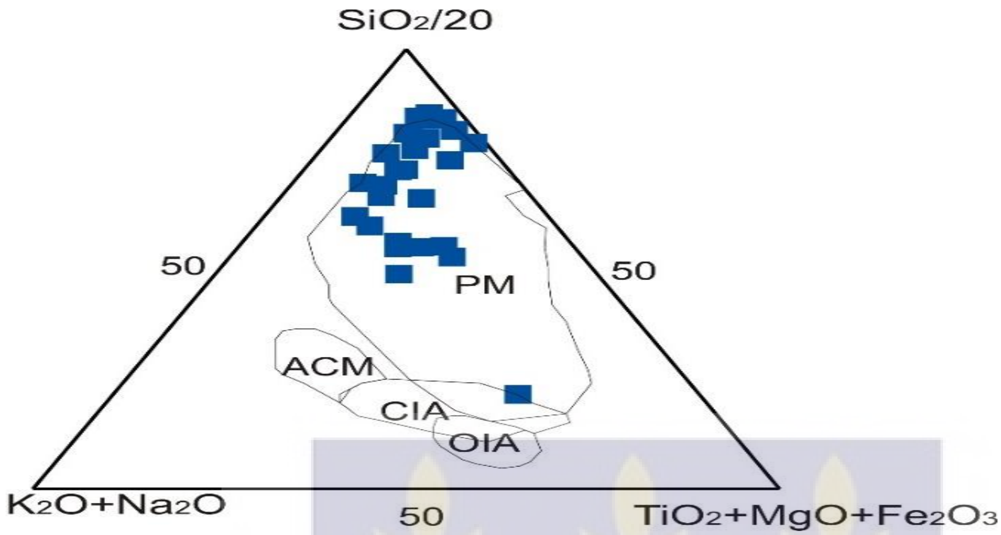


Figure 5.5: The tectonic setting of the sediments. After (Kroonenberg, 1994).

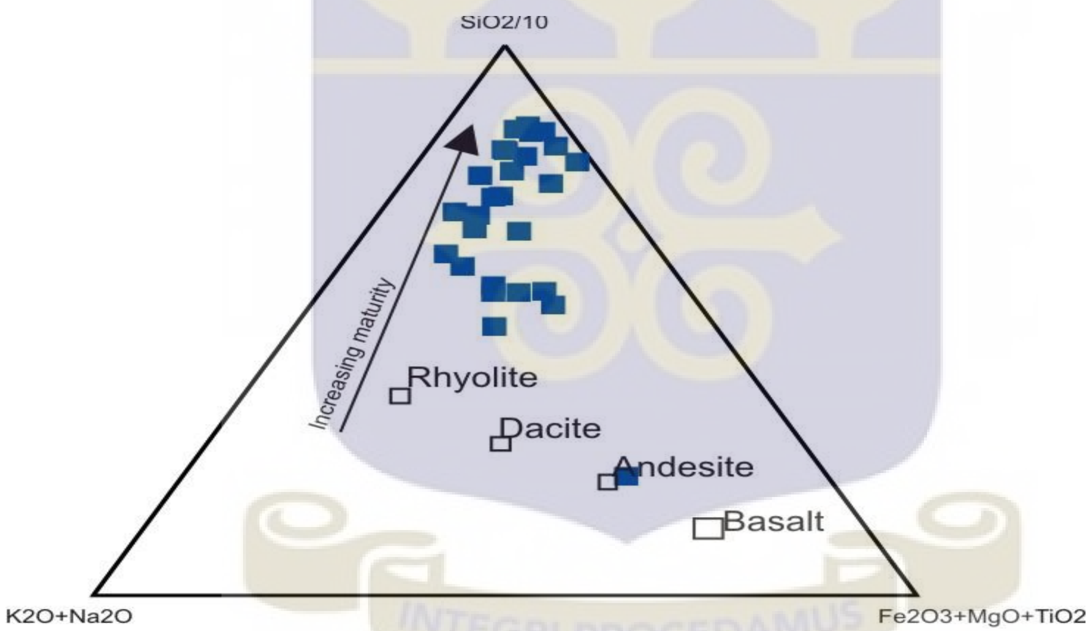


Figure 5.6: Silica – alkali – mafic sediments source indication diagram. After (Roser and Korsch, 1988)

The ratios of compatible and incompatible elements has been used by (Mclennan et al., 1993) to decipher the recycling of sediments as well as the enrichment of zircon

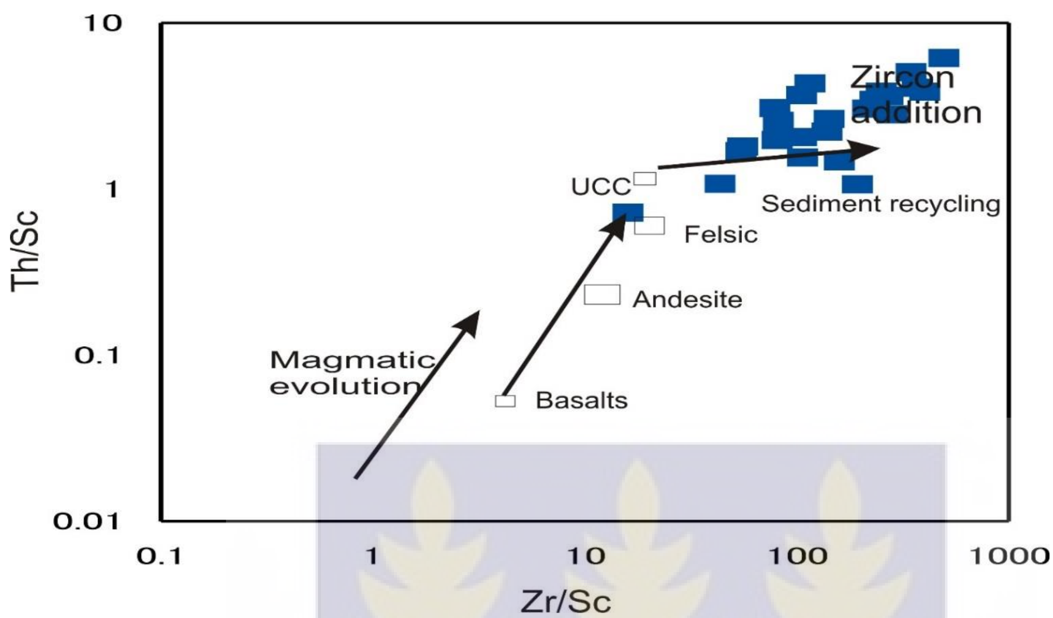


Figure 5.7: Plot of Th/Sc versus Zr/Sc source and recycling discrimination diagram. After (Taylor and Mclennan, 1993)

Major elements (SiO_2, Al_2O_3, K_2O and Na_2O) of sediments has been used to infer the paleoclimatic conditions as a function of the sediments maturity (Suttner and Dutta, 1986; Elzien et al., 2014)

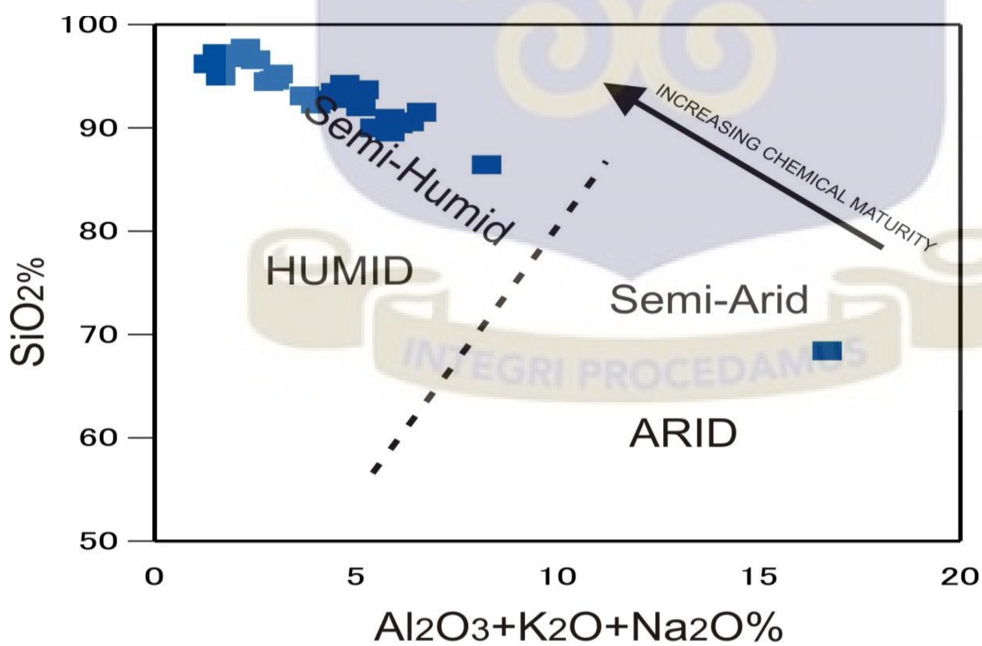


Figure 5.8: Climatic condition of the studied area with implication on sediments maturity diagram. After (Suttna and Dutta, 1986)

Floyd and Leveridge (1987) have used K_2O and Rb to distinguish between sediments coming from acid/intermediate source from those with mafic source. Using SiO_2 – K_2O+Na_2O – $Fe_2O_3+MgO+TiO_2$ parameters on a ternary diagram (Roser and Korsch, 1988) (Figure 5.6), the source rock that weathered to produce the sediments can be deciphered. Trace elements are not affected by sediments alteration processes thereby reflecting the chemistry of the source, as such they are extensively used to infer the source of sediments. Th/Sc versus Zr/Sc plot has been used (Floyd and Leveridge, 1987) to discuss the source of sediments. Th/Sc is a good indicator of igneous chemical differentiation process with Zr/Sc suitably reflecting sediment recycling and zircon enrichment. A ternary plot using V, Ni and Th*10 parameters (Bracciali et al., 2007) reflects the source rock type of the sediments. Using La/Th and Hf as the input parameters, the parent rock(s) that weathered into the sediments/sedimentary rock(s) can be deduced by plotting La/Th versus Hf (Leveridge and Floyd, 1987).

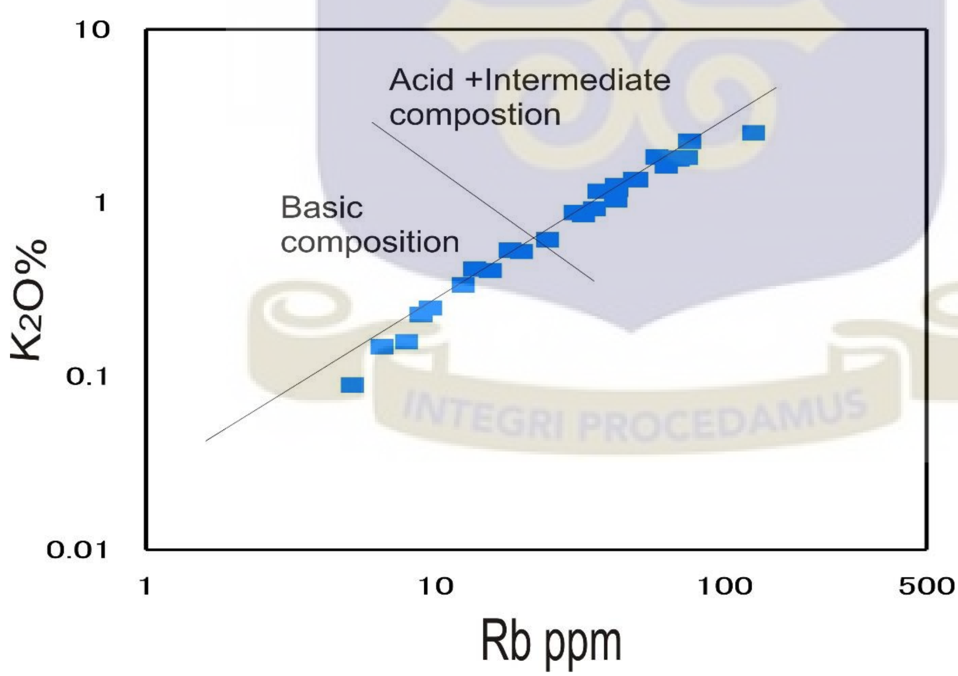


Figure 5.9: K_2O versus Rb plot relative to K_2O-Rb ratio of 230 (main trend after Shaw, 1968) modified after (Floyd and Leveridge, 1987)

Th/Sc versus Zr/Sc plots has been a suitable sediments source indicator. This differentiates between sediments of mantle source from those with crustal source, the binary plot of Th/Sc versus Zr/Sc (Fig. 5.7) implicates the recycling factor of the sediments from these two possible sources.

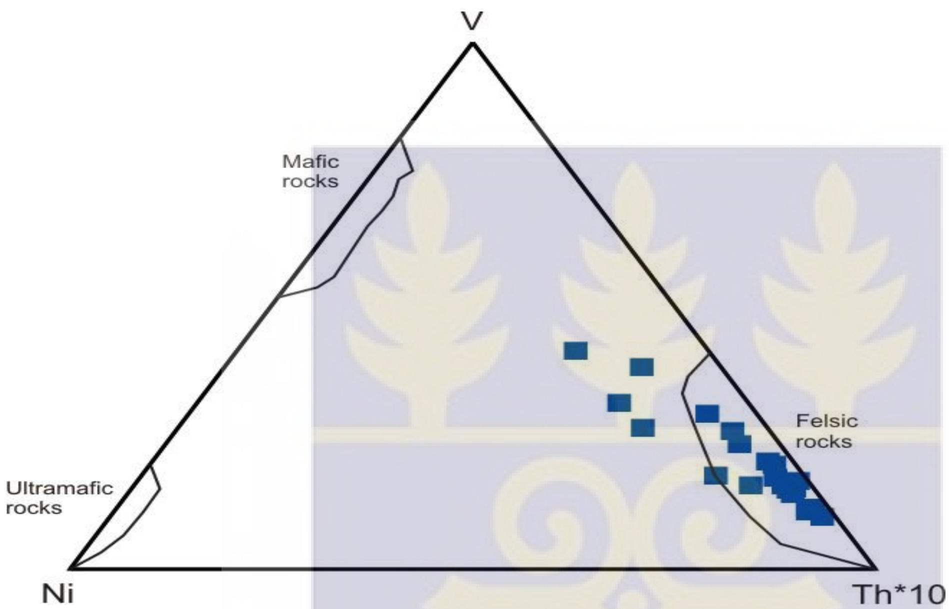


Figure 5.10: Source rock V – Ni – Th*10 discrimination diagram modified after (Bracciali et al., 2007)

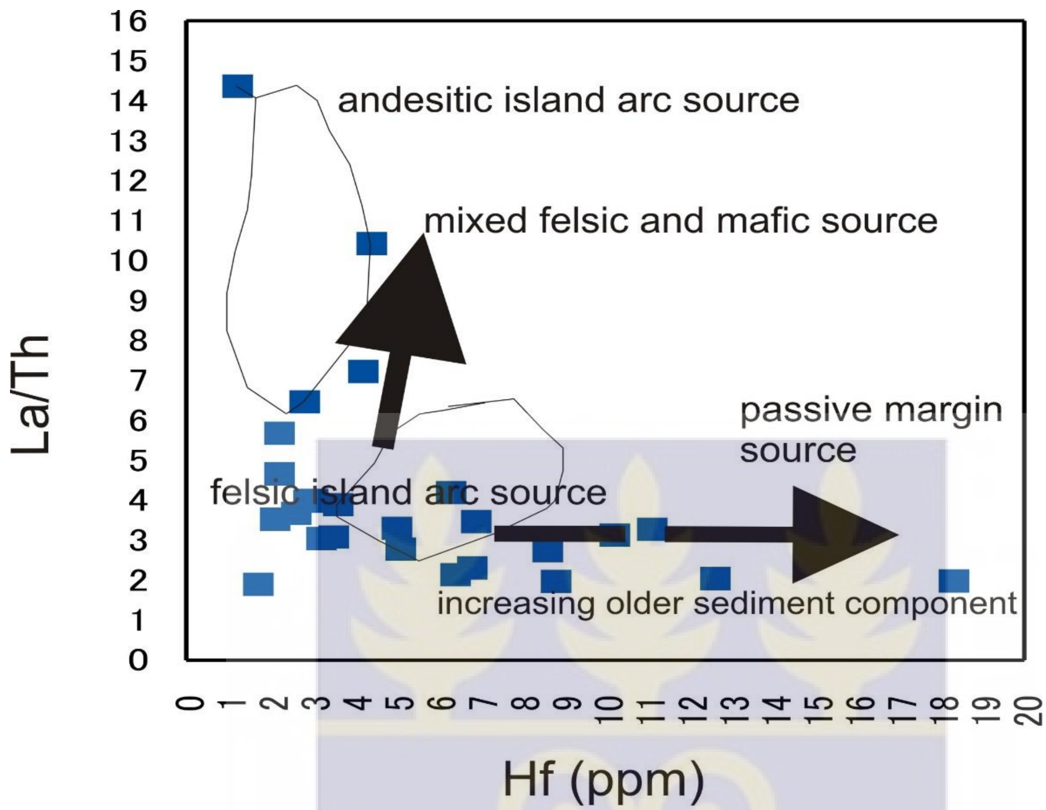


Figure 5.11: La/Th versus Hf source rock discrimination diagram of the studied area modified after (Floyd and Leveridge, 1987).

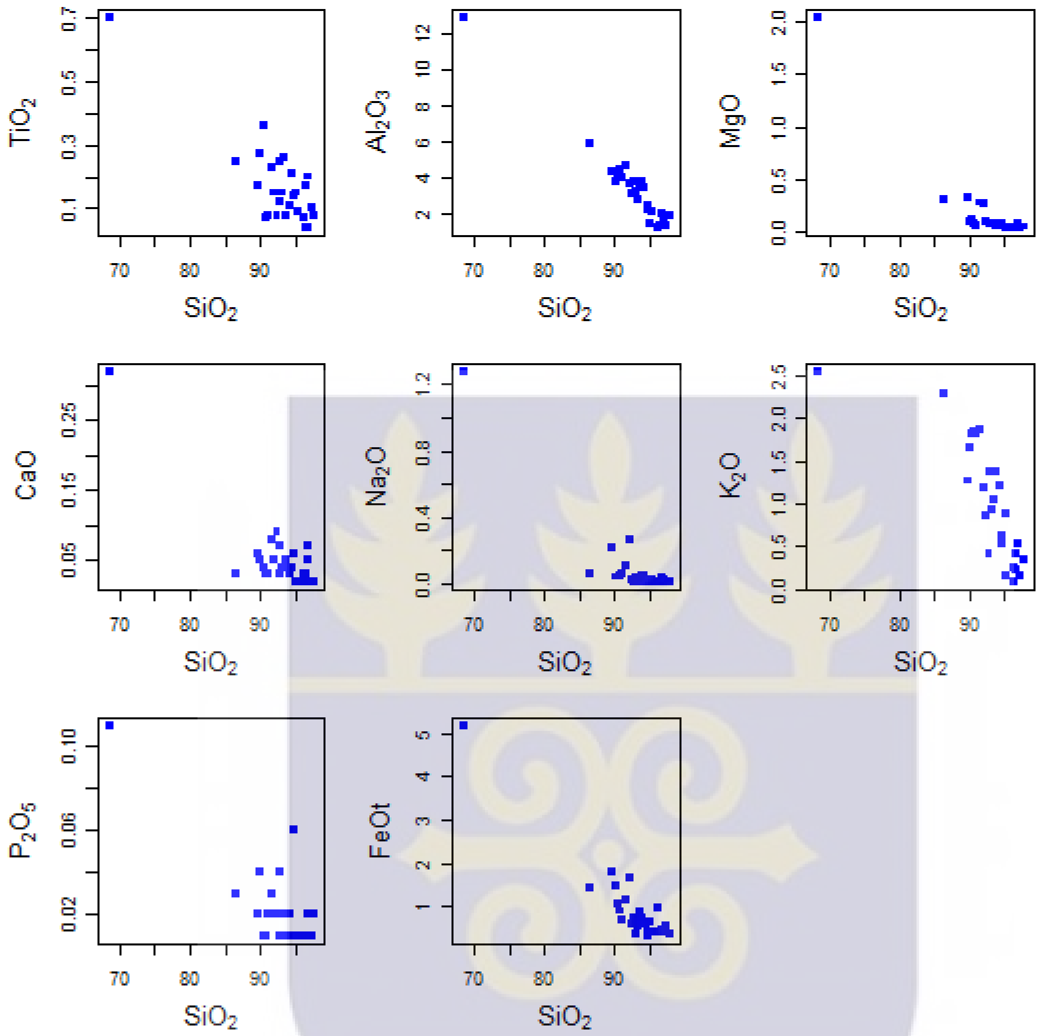


Figure 5.12: Binary plots (Harker diagrams) of the major elements against SiO_2 of studied sandstones of the Gambaga – Nakpanduri area.

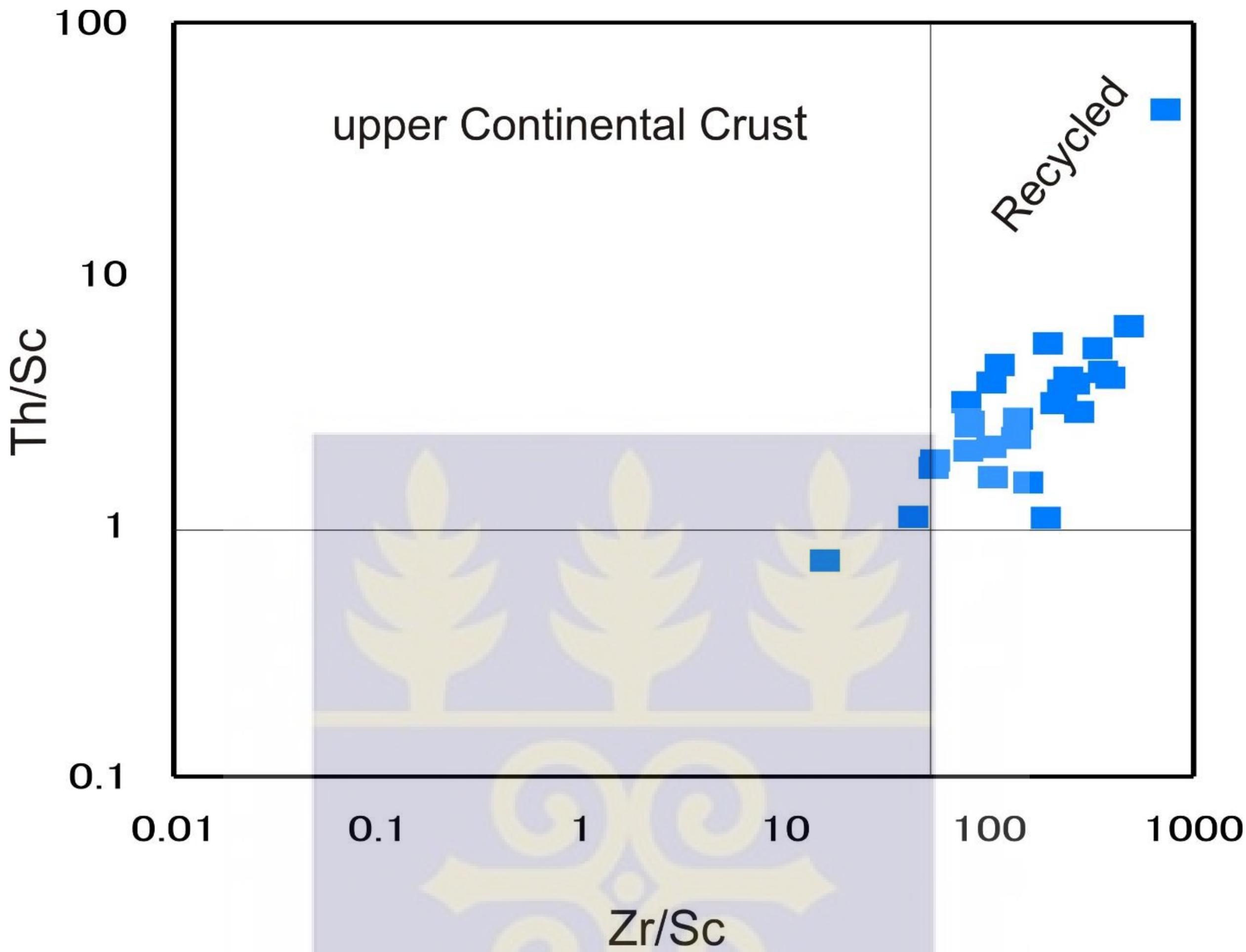


Figure 5.13: Th/Sc – Zr/Sc variation diagram of the Gambaga – Nakpanduri sandstone. After (Mclennan et al., 1993).

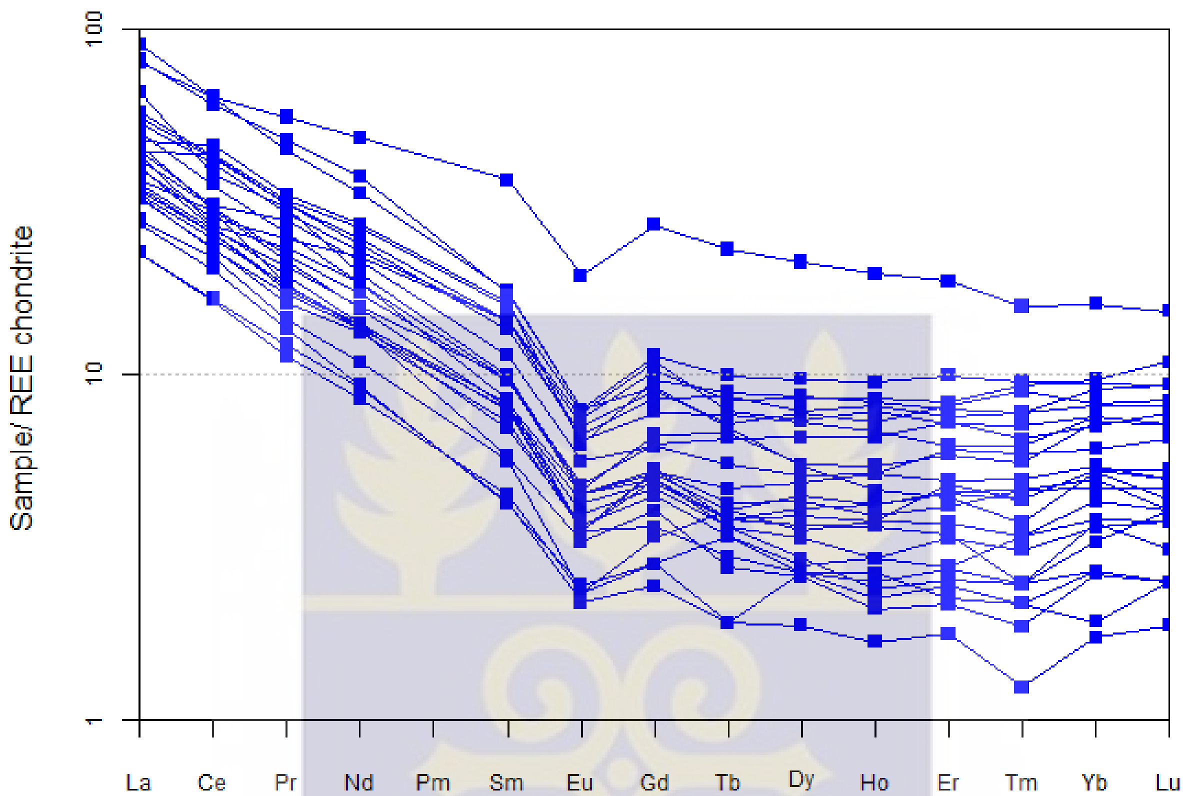


Figure 5.14: Chondrite – Normalized REE pattern of the sandstones of the Gambaga – Nakpanduri areas. Normalized values of Chondrite (Boyton, 1984).

Table 5.2: Range of elemental ratios compared to sediments of the Gambaga – Nakpanduri areas after (Cullers, 2000; Cullers et al., 1988; Taylor and Mclennan, 1985; Adel et al., 2010; Zaid et al., 2015).

Element Ratio	UCC	PAAS	Felsic Source	Mafic Source	Gambaga-Nakpanduri Area
Th/U	3.5/4		≥ 4	< 4	3.80
Th/Sc	0.79		0.84-20.5	0.05-0.20	4.54

Cr/Th	7.76	6.85	4.00-15.0	25-500	6.19
La/Sc	2.21		2.50-16.3	0.43-0.86	13.92
Th/Cr	0.13	0.15	0.13-2.70	0.02-0.05	0.20
Th/Co	0.63	0.73	0.67-19.4	0.04-1.40	3.19
La/Co	1.76	1.91	1.80-13.8	0.14-0.38	11.05
Eu/Eu*	0.59		0.46-0.94	0.71-0.95	1.39
(La/Lu)N	7.21		3.00-27.00	1.10-7.00	1.52

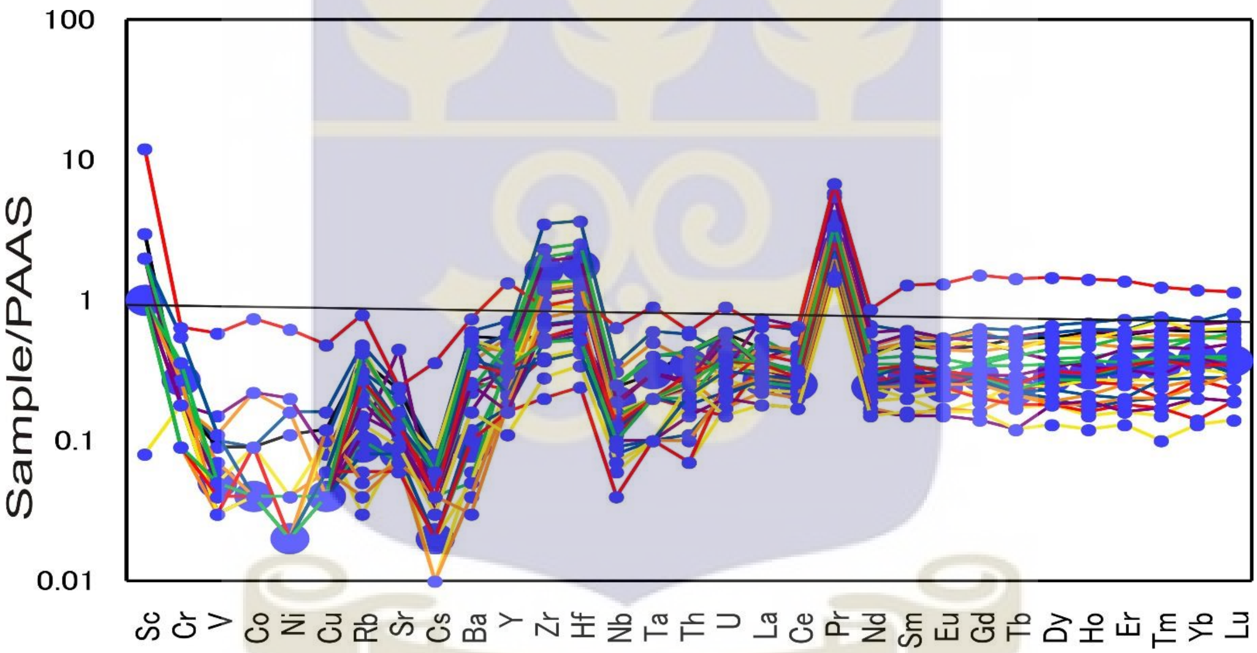


Figure 5.15: Multi – element diagram of the studied samples composition compared to PAAS. Normalized values (Taylor and Mclennan, 1985).

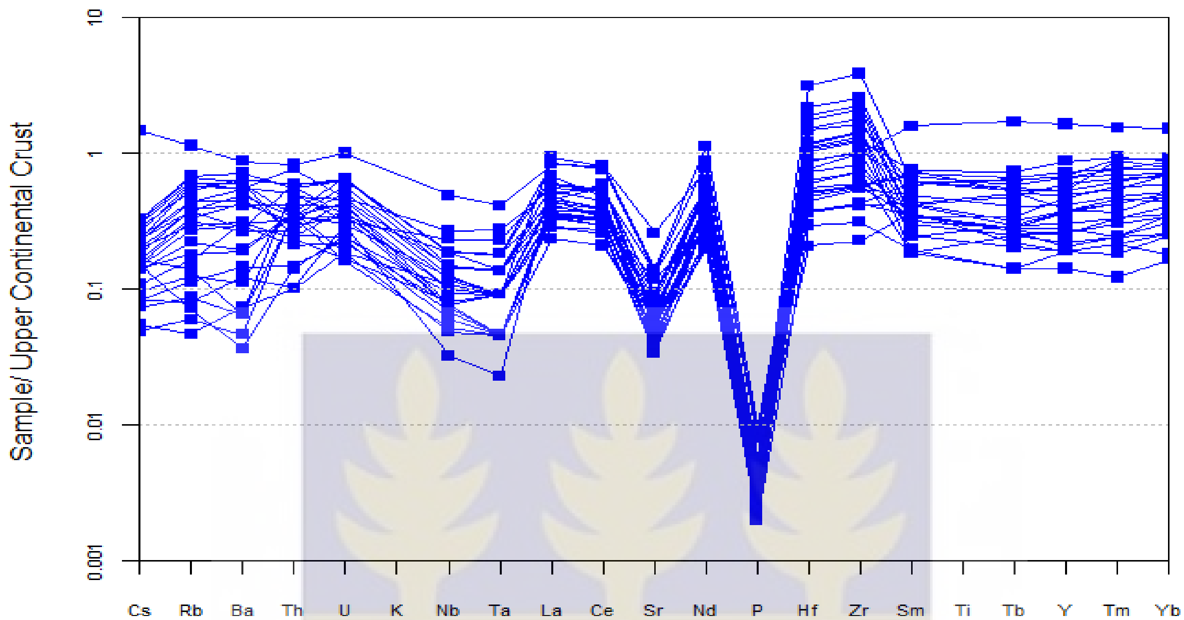


Figure 5.16: multi-element diagram of the studied Gambaga - Nakpanduri sandstones. Normalized values (Taylor and Mclennan, 1985).

Th/U ratio versus Th composition within weathered materials is a suitable discriminant factor between sediments input from depleted mantle source and those with crustal contribution (Mclennen et al., 1993).

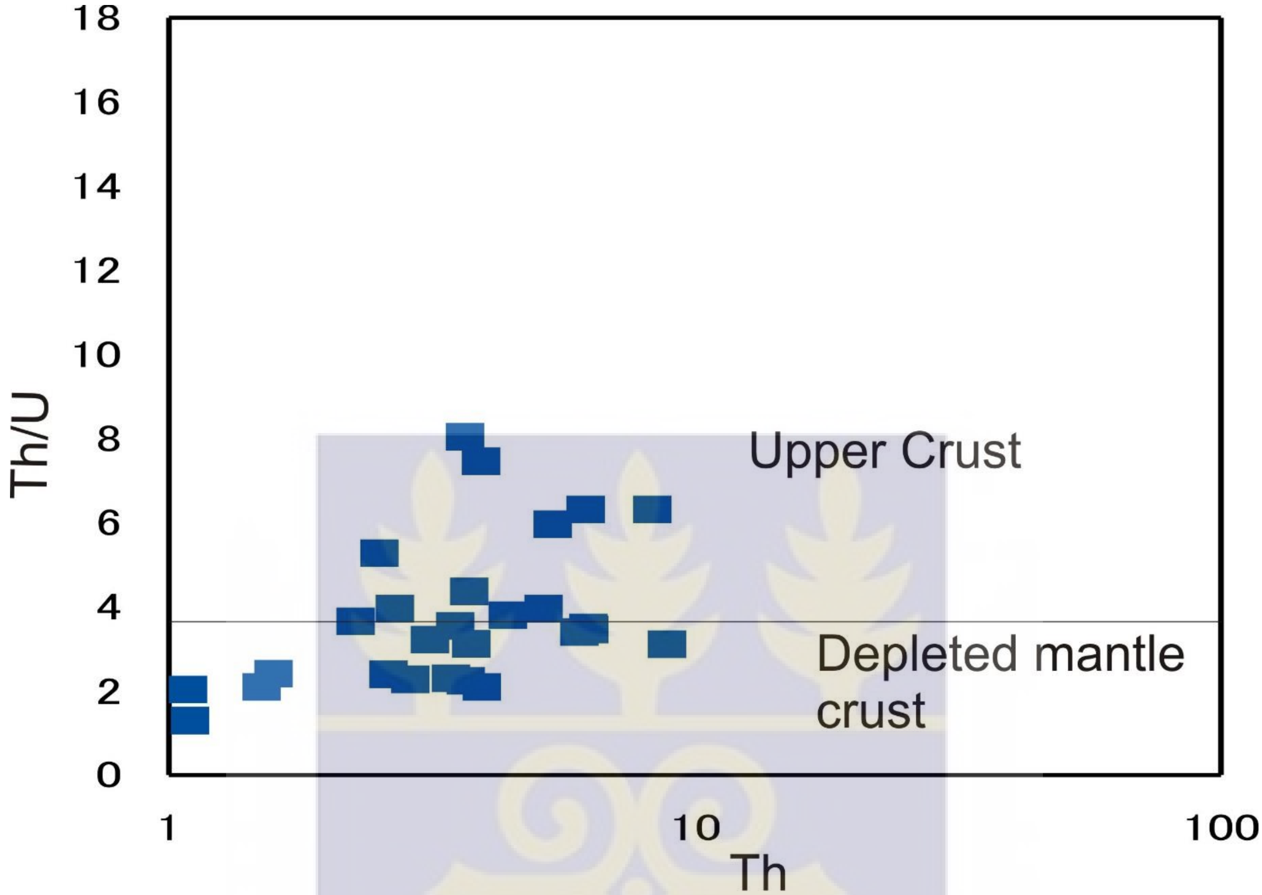


Figure 5.17: Th/U versus Th Source discrimination diagram after (Mclennan et al., 1993)

The major elemental composition as well as most significantly, the trace elemental composition of the sediments, trace elements are not affected by sediments alteration processes (Adel et al., 2010; Bhatia and Crook, 1986; Elzien et al., 2014), they have for this reason been used over the years to effectively associate sediments with the various tectonic settings.

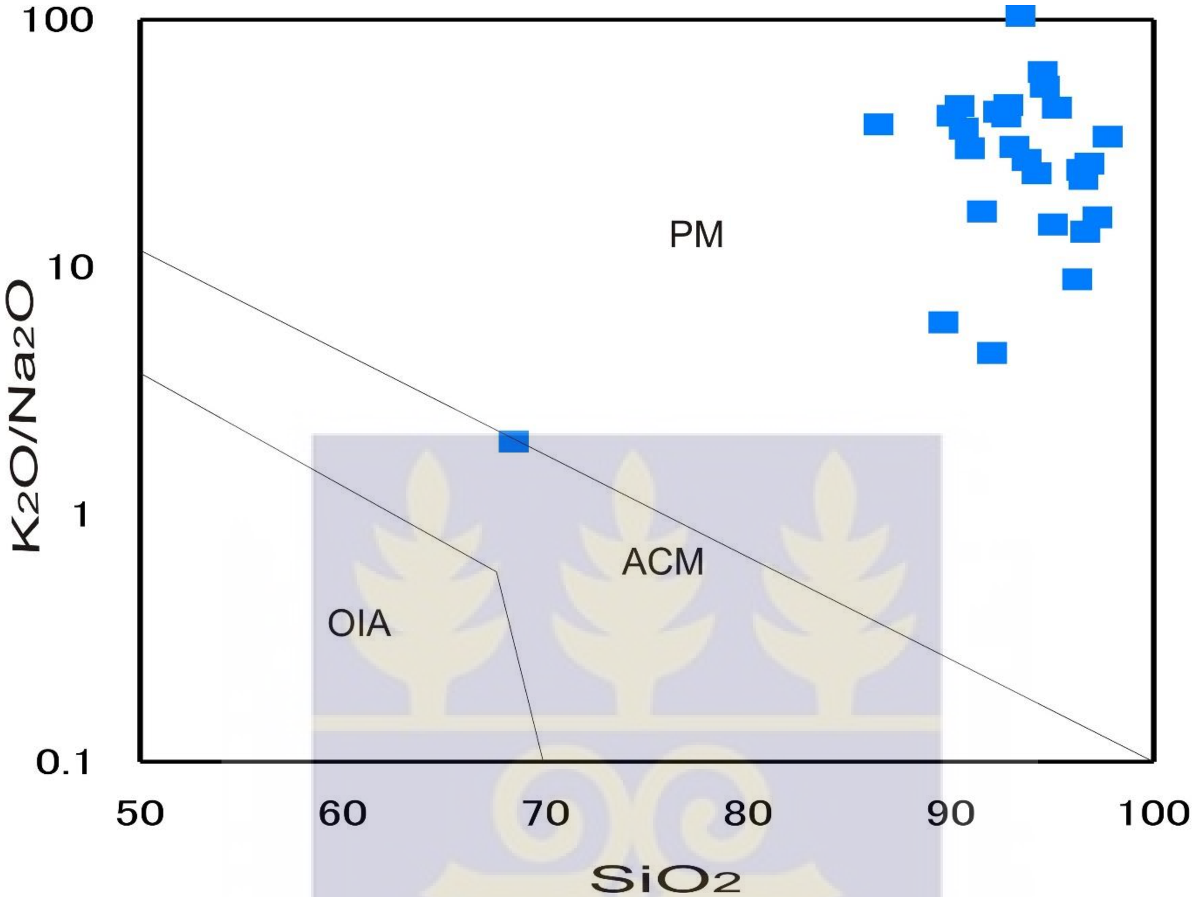


Figure 5.18: Tectonic discrimination diagram of the studied sediments after (Roser and Korsch, 1986)

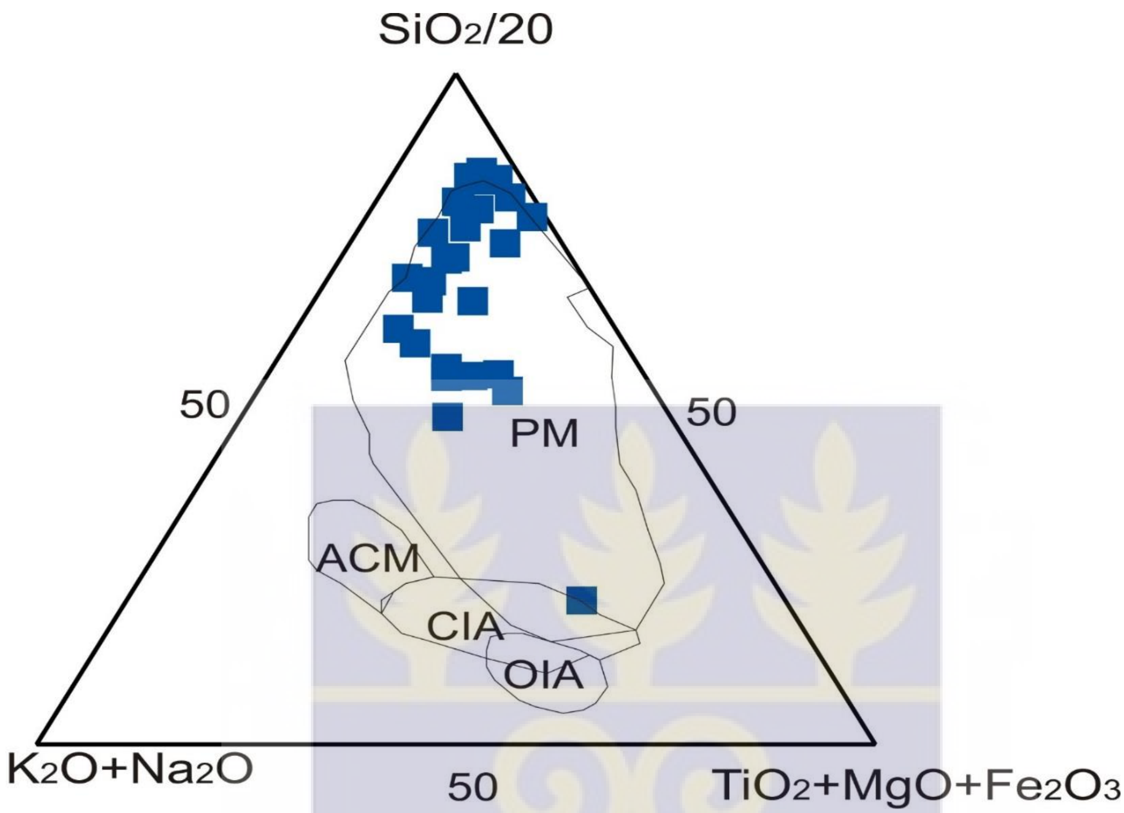


Figure 5.19: Silica-Alkali-Mafic major element tectonic discrimination diagram. After (Kroonenberg, 1994)

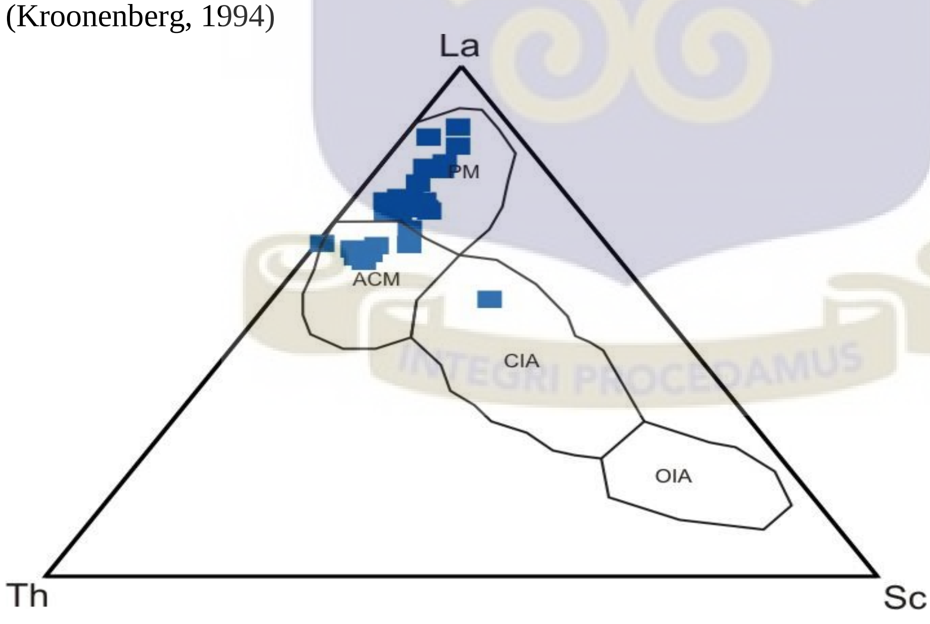


Figure 5.20: La-Th-Sc tectonic discrimination diagram of the studied area. Fields after (Bhatia and Crook, 1986)

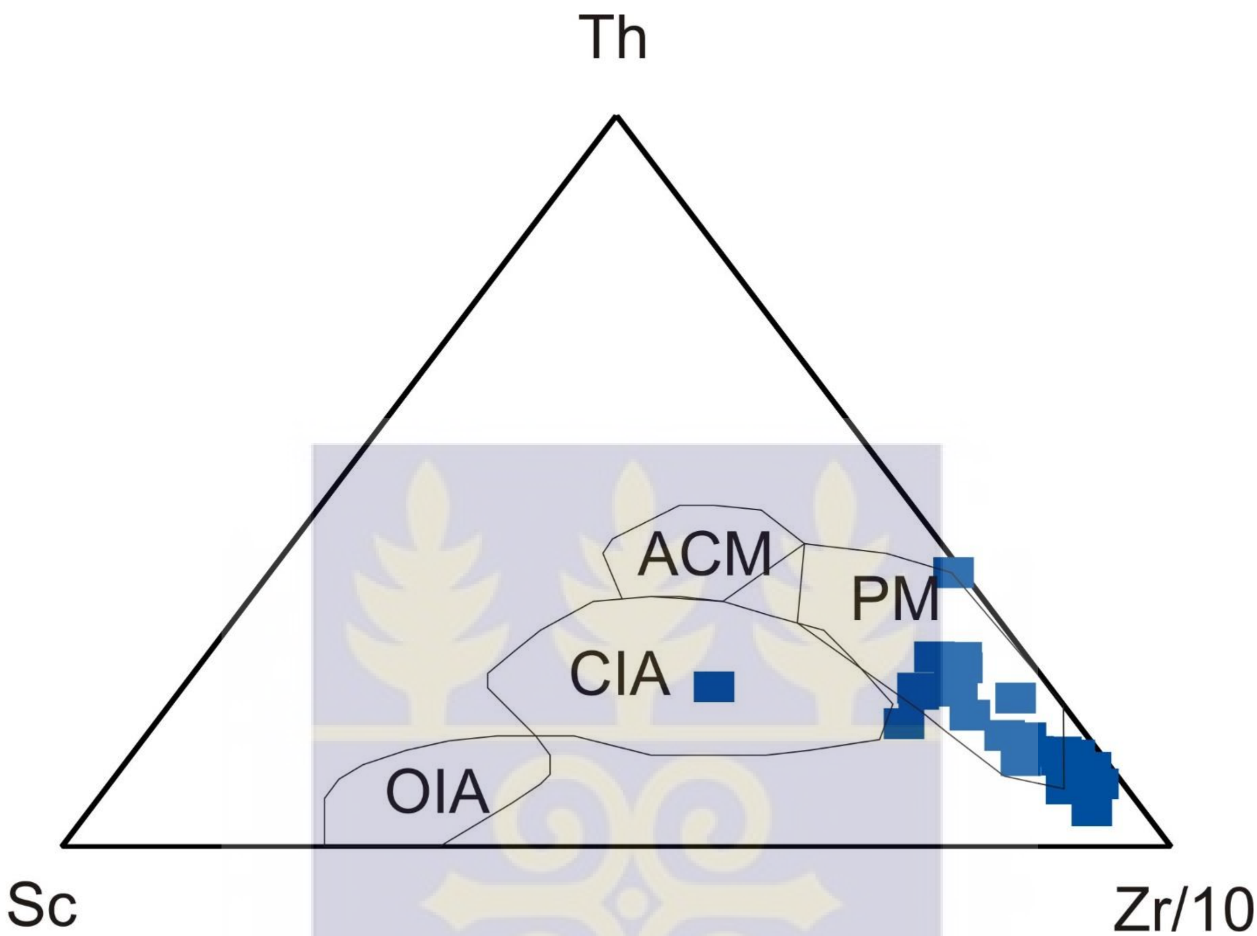


Figure 5.21: Th-Sc-Zr/10 tectonic discrimination ternary diagram. Fields after (Bhatia and Crook, 1986)

5.7 Discussions

5.7.1 Geochemistry

The geochemical composition of the sediments supports high amount of silica (Tab.5.1) relative to the other oxides (Fig.5.12) with an average of 92.64, due to the high content of quartz minerals. Quartz rich/chemically matured sediments have also been reported by Viljeon et al., (2008) from at the southern part of the current study (Gambaga – Nakpanduri area). The alteration of CaO, Na_2O and K_2O rich minerals, ie, anorthite, albite and microcline to clay minerals, e.g, illites, smectites etc, reduces the percentages of their oxides and subsequently increases the composition of the Al_2O_3 as seen in (Table.5.1) according to Holail et al., (1998). The relative composition of K – Feldspars (microcline) to plagioclase feldspars (albite) indicates the dominance of K – feldspars over plagioclase from the ratio of K_2O/Na_2O (aveg. 31.92). The presence of iron rich minerals like biotites although in small amount, is evidence by a Fe_2O_3 average composition of 1.04. SiO_2/Al_2O_3 has been a good indicator of sediment maturity (Pettijohn et al., 1972) with Fe_2O_3/K_2O ratio separating lithic fragments from the potassium feldspar composition of the sandstons (Herron, 1988; McLennan et al., 1993). The presence of iron rich and magnessian rich minerals will give rise to high Fe_2O_3/K_2O ratios, the average Fe_2O_3/K_2O ratio of 1.66 of the studied samples supports a minor amount of unstable mineralogical component within the studied samples (Herron, 1988). There is a positive correlation between K – Rb, and which may suggests that the K – bearing clay minerals like illite, are responsible for the abundance of Rb, Ba and K (Table 5.1) (Holail et al., 1998; McLennan et al., 1993). There is no correlation between K and Sr. The major contribution to the abundance of Sr is plagioclase, the composition of K (potassium feldspars) is high in the source area relative to plagioclase evidenced by an average 31.92 value of K_2O/Na_2O (Holail et al., 1998). The ferromagnesian trace elements exhibits similar behavior in magmatic processes, ie, Co, V, Cr and Ni (Holail et al., 1998), and are rich in mafic source. The relative high composition of Cr and V suggests a contribution of a mafic source rock of the studied samples (Table, 5.1). According to Bhattia and Crook, (1986); McLennan et al., (1993) and Holail et al., (1998), incompatible elements such as Zr, Nb and Y are mostly enriched in felsic igneous rocks relative to mafic igneous rocks and are not affected during igneous processes. The relative high amount of Zr and Y (Table.5.1) points to a felsic source of the sediments. On the SandClass diagram (Fig. 5.2), the samples can be grouped into a minor proportion of sublithic arenite and a dominant subarkose and quartz arenites with one sample plotting as a wacke. The major elements are not having any relation with SiO_2 as in (Fig. 5.12) except for Al_2O_3 and K_2O. Increasing weathering conditions will reflect high SiO_2 and Al_2O_3 (Holail et al., 1998), the negative correlation of Al_2O_3 and K_2O against SiO_2, is likely due to the removal of K_2O bearing minerals from the material during the sediments alteration processes. The negative correlation could also be that, K_2O and Al_2O_3 do not contribute SiO_2 to the sandstones studied (Ogungbesun and Okaigbobi, 2011).

5.7.2 Sediments Maturity and Recycling

The ratio of SiO_2/Al_2O_3 is used to indicate the degree of sediment recycling and maturity (Mclennan et al., 1999; Ahmad et al., 2014; Roser and Korsch, 1988). The ratio of SiO_2/Al_2O_3 is widely varied ranging between 14.74 – 78.93. The average SiO_2/Al_2O_3 of 39.06) supports high quartz content, which is indicative of a chemically matured sediments (Table. 5.1). Sample AM14, which is a sandy shale sample however, have low ratio of 5.33 supports low recycling and sediment immaturity. This is possibly due to the relative high amount of clay minerals in the sample. The maturity and recycling of sandstones/shale (Cox et al., 1995; Ahmad et al., 2014), can be inferred from the ICV (Index of Compositional Variability) where major elements (oxides) are used in the computation. The ICV of the Gambaga - Nakpanduri sandstone samples studied ranges between 0.42 – 0.90 (aveg. 0.70) and 1.17 for the Morago river ripple marked sandstone. ICV > 1 is indicative of immatured sediments with a possible first cycle whereas ICV < 1 indicates matured sediment that has been recycled (Cox et al., 1995). All the samples except sample AM06 – Morago river sandstone, have ICV < 1 (Table. 5.1) which suggests that the sediments are matured and has been recycled in a tectonically stable or cratonic environment (Fig. 5.13). Recycled sediments of the adjacent southern part of the area has been reported by (Viljoen et al., 2008) with high ratios

Th/Sc and Zr/Sc. The sample AM06 however, with an ICV > 1, indicates an immatured sample with a probable first cycle (Cox et al., 1995; Ahmad et al., 2014). The low composition of C, N and K (Table. 5.1) supports the maturity of the studied samples. These are present in the labile elements (muscovite, plagioclase and microcline/orthoclase), their low amount supports the removal of these minerals during recycling processes/weathering. The A – CN – K ternary diagram (Fig.5.3) (Nesbitt and Young, 1984; Shao et al., 2007) and the silica (SiO_2/20) – alkali (K_2O + Na_2O) – mafic (Fe_2O_3 + MgO + TiO_2) of (Roser and Korsch, 1988) (Fig.5.6) indicates matured sediments through recycling in a tectonically quiescent (Passive margin) or cratonic environment where the unstable/labile minerals had enough time to weather out leaving the stable SiO_2 component. Th/Sc is a suitable indicator of igneous chemical fractionation processes (Cullers, 1990) whereas Zr/Sc indicates sediments recycling and zircon enrichment processes (Cullers, 1990; McLennan et al., 1993). Th/Sc and Zr/Sc ratios of 4.52 and 196.31 respectively, suggests the removal of Sc through sediments alteration processes. The degree of sediments recycling is high in the studied samples and there has been zircon enrichment (Fig. 5.7) according to Mclennan et al., (1993); Zelilidis and Maravelis, (2009). High Th/Sc and Zr/Sc are reported in an area adjacent to the current study area by Viljeon et al., (2008).

5.7.3 Paleoweathering

Weathering controls to a large extent the composition of silicate rocks. During chemical weathering Rb, Sr cations remains in the weathered residue whiles Ca, Na and K are preferentially leached (Nesbitt and Young, 1980; Holail et al., 1998) due to their removal from the feldspars during weathering (Elzien et al., 2014). The proposed CIA (Chemical Index of Alteration) by Nesbitt and Young, (1982) has been extensively used in the discussion of the source weathering conditions of sediments. A fresh unweathered igneous rocks and feldspars have CIA values of 40 – 50. CIA values of highly weathered approaches 100 (Nesbitt and Young, 1982). Values of CIA in the range of 70 – 75 are reported for PAAS (Post Archean Australian Shale) representing low to moderately weathered sediments. Values of fresh unweathered plagioclase and K – feldspars is about 50 whereas the completely weathered plagioclase and K- feldspars giving rise to clay minerals (Kaolinite, gibbsite, goethite) have CIA values of 100 (Fedo et al., 1995). The CIA values of the studied samples ranges between 67.34 – 90.37 (aveg. 76.19). On the basis of the CIA, the samples are moderately weathered as that of PAAS. There is the possibility of remobilization of K onto the weathered residue during weathering or metamorphism (K – metasomatism) (Fedo et al., 1995; Ahmad et al., 2014). The plotting of samples on the A – K line of A – CN – K diagram (Fig. 5.3) is typical of K – metasomatism (Elzien et al., 2014), thus, there has been the remobilization of potassium feldspars onto the weathered residue in the Gambaga area. The K – feldspars within the studied area, have altered into illite and muscovite (Fig. 5.4) (Zaid et al., 2015), this is supported by the low K_2O/Al_2O_3 with average ratio of 0.29 (Tab. 5.1). The index of alteration of plagioclase (PIA) and to avoid the influence of the likely remobilized K onto the weathered residue, the CIW (Chemical Index of Weathering) was proposed (Harnois, 1988; Fedo et al., 1995) and this has been mostly considered in the inference of the paleo weathering conditions. The CIW values (calculated without K_2O) of the samples are closely varied from 88.93 – 98.94 (aveg. 96.87) (Table. 5.1), these values suggests highly weathered samples. U (uranium) resides in the labile minerals, and weathering processes leads to the removal of U from the sediments with subsequent elevation in Th (Cullers, 1990;Adel et al., 2010), Th/U can be related to the weathering history of the source. High Th/U values in the excess of 4 is indicative of intense weathering in the source area of the sediments (Mclennan et al.,1993). The Th/U values of the upper continental crust (UCC) is in the range of 3.5 and 4, the samples with average Th/U value of 3.80 (Table. 5.1) suggests an intermediate weathering of the sediments which is comparable to the weathering conditions of the UCC. The paleo weathering of the study area/terrain has not been looked at by earlier workers.

5.7.4 Paleoclimate

Plotting SiO_2 versus Al_2O_3+K_2O+Na_2O, the samples fall within a semi – humid with one sample plotting in the semi – arid paleoclimate terrain of (Suttna and Dutta, 1986) diagram (Fig. 5.8) with chemically matured sediments.

5.7.5 Source of Sediments

Ternary diagrams of major elements can reflect the source of sediments. Plotting SiO_2/20 – K_2O+CaO – Fe_2O_3+MgO+TiO_2 (silica – alkali – mafic) ternary diagram, the sediments of the studied area can be said to be the weathered products of magmatic rocks with high composition in silica, thus, dacites and andesites (Fig. 5.6), (Roser and Korsch, 1988). The sediments of the Gambaga massifs are possibly coming from a suit of magmatic rocks of both basic and acid/intermediate (Fig. 5.9) composition (Shaw, 1968). A ternary diagram of (Bracciali et al., 2007) using V – Ni – Th*10 parameters (Fig. 5.11), suggests a felsic source of the sediments. The source of the sediments of the southern part of the Gambaga – Nakpanduri area could not be inferred (Viljeon et al., 2008) for the reason that the sediments are compositional matured and hence making it impossible to decipher the source. The sediments are the weathering products of a mixed felsic and mafic source rocks dominantly with felsic island arc rocks and an older sediment component contribution to the sediments of the Gambaga areas is indicated by the La/Th versus

Hf plot in (Fig. 5.11) (Floyd and Leveridge, 1987). Th/Sc versus Zr/Sc (Mclennan et al., 1993) has been used to discriminate between sediments with crustal imprints from those with mantle signatures. The studied samples of the Gambaga – Nakpanduri areas all fall on the recycled zone. The sediments are recycled crustal materials (Fig. 5.13) with only one sample indicating a mantle source.

The REE pattern and size of Eu anomaly has been an important source rock discrimination factors (Amstrong-Altrin et al., 2004; Cullers et al., 1979; Amstrong-Altrin et al., 2015). The REE pattern of felsic rocks like rhyolite and dacites are usually with a negative europium anomaly (Amstrong-Altrin et al., 2015), the normalized chondrite REE values (Fig. 5.14) of the studied samples are with rhyolitic and dacitic signatures. The samples studied are all enriched in the LREEs with a flat HREEs patterns, however one of the samples has an enriched HREEs pattern suggesting a possible mafic source (Fig. 5.14), all the samples displays an Eu anomaly with Eu/Eu* value less than 1 (Eu/Eu* <1). The Europium depletion may be explained by sedimentary processes like weathering and recycling (Zalilidis and Maravelis, 2009). Plagioclase is slightly removed from the sediments through reworking processes (McLennan, 1989), this suggests that the plagioclase concentration was affected by intracrustal differentiation processes, this could also be explained that plagioclase fractionation (Mclennan et al., 1990) was of significant importance. The Eu negative anomalies supports sediments coming from a felsic magmatic rocks (Bhattia, 1985). The trace elements of the studied samples of the Gambaga – Nakpanduri areas are depleted relative to the Post Australian Archean Shale (PAAS), however, scantium (Sc), zirconium (Zr), hafnium (Hf) and praseodymium (Pr) are enriched relative to PAAS. The Sc enrichment can be attributed to mafic source of the sediments (Zelilidis and Maravelis, 2009). Hf is associated with Zr, their enrichment is indicative of acid/intermediate (felsic) source of the studied sediments (Fig. 5.15). The Zr-Hf enrichment could also be due to the introduction of weathered materials from a matured sedimentary source. Sediment recycling during sediment transfer/reworking is also suggested (Adel et al., 2010; Zelilidis and Maravelis, 2009). The Zr enrichment suggests a relatively much recycled sediments of the studied area relative to PAAS. Pr is strongly enriched in the crust relative to oceanic environments (Fig. 5.15), its enrichment compared to that of PAAS suggests a possible crustal source of the sediments. In (Fig. 5.16), most of the elements are comparable to the Upper Continental Crust (UCC) composition. Some few samples however, are depleted in Rb, Ba, Nb, Ta with almost all of the samples depleted in Sr. P composition of all the studied samples are depleted relative to that of UCC. Rb – Ba depletions in some of the samples is possibly due to the low amount/removal of Rb – Ba rich minerals during sediments reworking, thus, potassium feldspars, Nb – Ta depletion in some of the samples are typical of upper continental crustal source of sediments (McLennan et al., 1993) and the Sr and P negative anomalies is due to sediments input from a felsic source (Zelilidis and Maravelis, 2009). Th/U ratio is a suitable weathering indicator, this has also been considered to be an efficient source indicator. A Th/U ratio ≥ 4 and < 4 indicates an upper crustal source and a mantle source of sediments respectively (Roddaz et al., 2006). Many island arc magmatic materials have Th/U value below 3.8 (McLennan et al., 1990). The Th/U ratio of the sediments of the Gambaga massifs are with widely varied Th/U ratios of 1.33 – 7.50 (Table. 5.2) with average value of 3.80, this suggest sediments input from upper crustal source since the Th/U ratio value is not below 3.80 (McLennan et al., 1990). The plot of Th/U versus Th on (McLennan et al., 1993) diagram (Fig. 5.17) supports a contribution of sediments from both the depleted mantle as well as from the upper crust. Trace elements are not affected by weathering and sediments recycling processes. They are as such transferred as particulate material onto the deposited environment reflecting the chemical composition of the source (Cullers, 2000;

Taylor and McLennan, 1985). The range of their ratios has been used to discriminate between sediments from felsic source relative to sediments from mafic origin (Adel et al., 2010; Zaid et al., 2015). The ratios of the trace elements in the comparative table in (Table 5.2), suggests that the sediments from the Gambaga – Nakpanduri areas are weathering products of a felsic source rock.

5.7.6 Tectonic setting

Major elements as well as trace elements diagrams has been proposed for the discrimination of the tectonic setting of clastic sediments (Elzien et al., 2014). The binary tectonic discrimination diagram of K_20/Na_2O versus SiO_2 plots of the studied sediments on (Roser and Korsch, 1986) diagram (Fig. 5.18), indicates a passive margin setting (PM) for the sediments of the Gambaga – Nakpanduri area of the northeastern Voltaian. Passive margin setting is also reported by Viljeon et al., (2008) for the southern adjoining field sheet of the current study. The major elements ternary diagram of (Kroonenberg, 1994), where Silica (SiO_2) – Alkali ($K_2O + Na_2O$) – Mafic (TiO_2 + FeO + MgO) are the parameters used in (Fig. 4.19), the sediments of the studied area plots within the passive margin setting. Trace elements has been over the years used to discriminate effectively between ocean island arc (OIA), continental island arc (CIA), active continental margin (ACM) and passive margin (PM). On the Th-La-Sc ternary diagram of (Bhatia and Crook, 1986) in (Fig.5. 20) above, the sediment plots within an active and passive margin settings. The studied sediments of the Gambaga – Nakpanduri areas plots within a passive margin settings in (Fig. 5.21) of (Bhatia and Crook, 1988), Th-Sc-Zr/10 tectonic discrimination diagram. The quartz rich composition of the sediments agrees with tectonic setting where the sediments are generated from an active – passive margin setting onto a cratonic environment/tectonic quiescence environment thereby allowing deposited sediments enough time to undergo reworking/alteration processes.

CHAPTER SIX: PROSPOSED STRATIGRAPHY OF THE GAMBAGA GROUP

6.1 lithostratigraphy

The lithostratigraphy of the study area is discussed based principally on the field observations made on outcrop scale (sedimentary structures) and mesoscopic scale (composition, texture). The studied area correlates with the earlier grouping of Tossiegou, Poubogou and Panabako formations. There are however observed sedimentary features missing in these above formations of the earlier workers in the area.

6.1.1 *Lower Formation*

This is made of medium – fine grained, dirty white colored quartz rich sandstone, altered feldspars and some muscovite. At the Morago river, this was with asymmetric wave formed ripples indicating the activity of variable wave strength in opposite direction. These have a steep lee – side dip of 15° NW which is indicative of the wave direction during sedimentation. This is supposed to be overlying the lower Paleoproterozoic aged Birimian rocks, this was not however seen to be underlying this ripple marked sandstone during this study. The formation according (Affaton et al., 1980; Carney et al., 2010) supports a fluvial environment. The low energy asymmetric ripple marks of this study suggest a shallow marine shelf environment.

6.1.2 *Middle Formation*

This is greenish – grey micaceous shales/sandy shales and highly – moderately weathered (Natapsori area) in – situ siltstone, the siltstones are pinkish – brown colored. This formation, to the west of the Nakpanduri – Morago river road at the Nakpanduri area of the scarp, grades more into sandstones than of shales and at the Natapsori and Gambaga areas of the scarp, the shales/ siltstone unit is less with sandstones dominating. The shales are cross – stratified, parallel laminated, there are with flute casts, climbing ripples suggesting a rapid deposition from a sediment – laden current in a low energy environment (Tucker, 2004). Ripple marks were recorded in all the three areas where the scarp was exposed enough for observation, these ripples are with bifurcations suggesting the predominance of wave activity over current, (Kavoosi et al., 2009; Tucker, 2004). The formation is suggested to have been a high energy environment with the presence of flute casts and slump structures (Ayite et al., 2008). The current study shows the presence of flute casts, bifurcated ripple marks, climbing ripples and cross stratifications, these points to both low and high energy environments.

6.1.3 *Upper Formation*

This is observable at the southern part of the study area, this is characterized by quartz arenites and sub-feldspathic/feldspathic arenites. These sandstones are whitish – pinkish grey colored, medium – coarse grained textured. These have large scale cross – beds of a possible, shallow marine or Aeolian depositional environment (Tucker, 2004; Kavoosi et al., 2009). Wavy laminations, herringbone – cross beds typical of tidal environments, small scale ripple marks, suggesting a possible low energy wave depositional environment (Viljeon et al., 2008). These are with widely distributed soft sediment deformational structures, thus, over turn cross – beds. This grouping was compared to some few earlier classifications as shown below (table 4.4). The Gambaga – Nakpanduri area is likely to have been deposited mostly in a low energy shallow marine environments with tidal and wave activities.

Table 6.1: Table of lithostratigraphic comparison of the Gambaga – Nakpanduri area

Carney et al., 2010	**Viljeon et al., 2008**	**Saunders, 1970**	**Abu …….(this work)**
Panabako (quartz arenites moderately feldspathic, cross beds with locally syn – sedimentary folding)	Panabako (Quartzitic (matured – supermatured sandstones, with symmetric marks, crenulate/wavy lamination, syn – sedimentary structure ie slump folds and over cross – bedding)	Thin bedded quartzose sandstone, basal arkose and shale locally	Upper Formation (Predominantly Quartz arenites and subarkose with cross – beds, over turned cross – beds, crenulate/wavy lamination and small scale ripple marks)
Poubogou (greenish – grey, micaceous with papery fissility)	Not observed	Shale	Middle Formation (greenish – grey micaceous shales with papery fissility, weathered in – situ siltstones with medium grained quartz rich

			sandstones. Bifurcated ripple marks, flute casts, parallel and cross – laminated.
Tossiegou (ripple marks coarse grained sandstones)	Not observed	Orthoquartzites	Lower Formation (sandstones with ripple marks, medium – fine grained, quartzitic, altered feldspars)

CHAPTER SEVEN: CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The sedimentology of the Gambaga – Nakpanduri areas has revealed new information about the Gambaga massifs and as such the Voltaian basin as a whole. Considering the depositional environments, depositional conditions and processes, six (6) sedimentary facies can be identified within a variable depositional environments of dominant shallow marine environments for the studied area. Deltaic, Aeolian and tidal environments are the subordinate environments from the study. Both low and high energy media are responsible for the deposition of the sediments reflected in the sedimentary facies of the area. Low sedimentation rate in a shoreface/foreshore marine environment is as well indicated by the burrows identified to be Skolithos as they are penetrative in cross section.

There is no observed boundaries between the formations of the Bombouaka/Gambaga group during the study except for paleosol evidence which indicates the boundary between the Bombouaka/Gambaga group and that of the overlying Oti/Pendjari group. The facies sequence represents an overall shallowing and thickening upward sequence.

The paleocurrent direction from the rose diagrams suggests that about 85% of the sediments trends to NE – SW with N – S and NWW – SEE subordinate trends. The asymmetric ripple marks indicates a NWW – SEE local directions, the cross – stratified shales shows a N – S and a NE – SW. The paleocurrents suggests that the source area of the sediments is somewhere in the SEE, S and SW parts of the area, most likely coming from the Birimian rocks.

The detrital material of the northeastern Voltaian from petrography, is composed of monocrystalline quartz grains of both undulatory and non – undulatory extinction dominating and minor polycrystalline grains, feldspars, thus, microcline and plagioclase, micas – muscovites and biotites, zircons, sericites as the matrix and other accessory minerals. The mineralogical composition of the sediments indicates a moderate – highly weathered sediments in a relatively gentle to flat terrain. With the composition of the labile minerals – feldspars and the micas together with the presence of matrix, the sediments have experienced a possible short travel distance from source, this is supported by the angularity and poorly sorted compositionally matured studied samples. A relatively high temperatures with dry conditions together with cold or semi – humid climatic conditions coupled with low rainfall can be inferred with the presence of some labile elements. The sediments are the weathered products of granitic and granitic gneisses with contribution of metasediments/a possible sedimentary source (presence of well-rounded zircon grains) most probably of the adjacent Birimian Supergroup origin.

The geochemical composition of the studied area supports the dominance of SiO_2 over the other oxides. The oxides do not have any relation with SiO_2 on a Harker diagram except for Al_2O_3 and K_2O which have a negative correlation with SiO_2, supporting the removal of potassium bearing minerals (during sediments reworking processes). The geochemical classification of the studied sediments of the Gambaga – Nakpanduri areas from the bivariate plot of Log (Fe_2O_3/K_2O) and Log (SiO_2/Al_2O_3), indicates a sublithic, subarkose and quartz arenites type of sediments. The studied samples are intermediate – strongly weathered on the A – CN – K weathering ternary diagram with implication on sediments maturity. The diagram also implicates illite enrichment. This is supported by a bivariate plot of K_2O versus Al_2O_3 which suggests that the illite presence is as a result of the alteration of potassium feldspars. The weathering indices, CIA, CIW, ICV and Th/U, supports moderate – highly weathered sediments and compositionally matured studied samples. The source area of the studied samples has experienced semi – humid climatic conditions with implication for sediments maturity on SiO_2 versus Na_2O+K_2O+CaO bivariate diagram. The sandstones of Gambaga – Nakpanduri areas of the Voltaian Basin are the weathered products of andesitic and dacitic rocks with indications from silica – alkali – mafic ternary diagram. A mafic – acid/intermediate source of the sediments is reflected in K_2O versus Rb plot. The positive correlation between K and Rb suggests that the K – bearing clay minerals are contributing to the relatively high values of Ba and Rb. Depleted mantle and upper crustal source for the studied area is supported by a Th/U versus Th plot. A mixed felsic and mafic source, a felsic island arc source with input from an older sedimentary source of the sediments is indicated in Th/La versus Hf plot. Recycled sediments of upper continental crustal source of the sediments and a felsic source is indicated from Th/Sc versus Zr/Sc bivariate and V-Ni-Th*10 ternary diagrams respectively. Ratios of selected trace elements indicates a felsic source of the studied area. The studied samples of the Gambaga – Nakpanduri area are the weathered products of a dominant felsic source with a minor mafic and an older sedimentary source input. A passive margin and an active margin tectonic setting of the studied area is supported by both the tectonic plots of the major and trace elements, thus, K_2O/Na_2O versus SiO_2, silica-alkali-mafic, La-Th-Sc and Th-Sc-Zr/10 bivariate and ternary tectonic diagrams. The normalized chondrite values are enriched in LREEs with flat HREEs pattern. The sediments are enriched in Sc, Zr, Hf and Pr and depleted in the other trace elements relative to PAAS. Sr and P are depleted and enriched in Zr and Hf relative to UCC.

The studied area of Gambaga – Nakpanduri areas can be grouped on the basis of lithology and the accompanying sedimentary features into three formations of Lower, Middle and Upper formations. The Lower formation is of sandstones that is compositionally made up of quartz with some muscovite and potassium feldspars. Its medium grained with ripple marks and cross beds. The middle formation is characterized by sandy shales/shales, silt stones and some sandstones. They are micaceous with biotite, muscovite, quartz and some zircon grains. They are fine grained with a papery fissility and cross stratification, flute casts, bifurcated ripple marks and climbing ripple marks. The siltstones are highly to completely weathered and the sandstones are composed of quartz, muscovite and K – feldspars with some zircon grains. They are medium grained with no observable sedimentary structures. The upper formation is of both quartz rich and feldspar rich sandstones that are medium to coarse grained. They are characterized by cross beds, over turned cross beds, herringbone – cross beds, small scale ripple marks and penetrative burrows (Skolithos).

7.2 RECOMMENDATIONS

A complete geological picture of the Gambaga massif can be seen by looking at the remaining southern part of the study area with similar objectives adopting the same methods of this study. With the paucity of exposures of the southeastern Voltaian Basin. Looking at the basin from the northern half of Ghana where there is enough exposures with scarce vegetation coupled with the annual bushfires which will allow easy field mapping, is necessary to help the academic community make a conclusive description and classification/grouping of the Voltaian basin from Ghanaian perspective. Studying the sedimentology of the Damango Sandstones is important so as to enable a clear correlation with the Gambaga massif, placing that Damango formation between the Poubogou and Panabako formations of the Gambaga group by (Carney et al., 2010) needs to be investigated via detail work.

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