AN OVERVIEW OF THE VOLTAIAN BASIN OF GHANA AND ITS HYDROCARBON PROSPECTS

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Abstract

The Voltaian Basin (VB) is an onshore sedimentary basin in Ghana that covers most central parts of Ghana. Unlike other Neoproterozoic sedimentary basins, a comprehensive sedimentology, tectonic evolution, economic prospects, and paleontological evidence of the VB are either inconclusive or unknown. The stratigraphic sequence of the basin from drill core is also still unknown. Hence, the review highlights the general sedimentology and other elements of a petroleum system of the basin and how that can be leveraged in the assessments of the hydrocarbon prospects of the basin. This review adds to the general ongoing discussion on the basin's, with a special emphasis on its hydrocarbon prospecting and generation potential. Records of fieldwork show a thick unit of reddish argillaceous facies intercalated with thin lenses of greenish shales in the Ejura area and black shales together with phyllites in the Mpraeso area. The Kodjari Formation has well-exposed carbonates and cherts. Greenish and grey shale units are also exposed in the Sabari area with indications of phytoclasts and palynomorphs assemblage. Features of tectonic impact on the basin are reflected as microfolds, fractures, and faults. The organic geochemical indications from outcrop samples are suggestive of the presence of hydrocarbons, although very low. The hydrocarbon signatures observed from organic geochemical analysis of outcrop samples will require further investigations to ensure a comprehensive understanding of the basin evolution and the hydrocarbon prospects. Hence, the study recommends drill core samples should be used in the characterization of the petroleum system of the VB.

Keywords
Overview, sedimentology, paleontology, hydrocarbon prospects, Voltaian Basin, Ghana

Introduction

The Voltaian Basin is the largest geological province in Ghana and one of the supracrustal units of the West African Craton (WAC) (Abu et al., 2022). Leveraging extensive works on the smaller extension of the basin in Togo, Burkina Faso, and Benin (Affaton et al., 1980; Amard, 1992; Kalsbeek et al., 2008), coupled with some works in Ghana, it has largely been accepted to be of three main groups: Kwahu-Bombouaka, Oti-Pendjari, and Tamale-Obosum (Abu, 2018; Abu et al., 2022, 2020; Anani, 1999; Anani et al., 2017; Carney et al., 2010). These groups have subdivisions and formations. For instance, the Kwahu-Bombouaka Group is marked by three formations: Tossiegou, Poubogou, and Panabako (Anani, 1999; Carney et al., 2010). Kodjari and Pendjari formations define the Oti-Pendjari Group (Abu et al., 2022; Nédélec et al., 2007). The Tamale-Obosum Group is the only group without clear subdivisions (Deynoux et al., 2006).

The provenance of the detrital materials of the basin: the southeastern parts of the Kwahu-Bombouaka Group have been studied by Anani (1999) and Anani et al. (2013) from field sedimentological relations and geochemistry. Also, the northeastern fringe (Gambaga-Nakpanduri areas) of the same group has been studied by Anani et al. (2017) and Abu et al. (2020) with a focus on the provenance of those clastic sediments. These earlier works on the Kwahu-Bombouaka Group of the basin concluded that the sediments were of Birimian origin. The Oti-Pendjari Group, until recently (Abu et al., 2023a), has not been studied. However, Amedjoe et al. (2018) worked on the shales from the Oti-Pendjari Group and compared them with the shales of the Kwahu-Bombouaka Group using their geochemical proxies and mixing calculations, and concluded that the Oti-Pendjari Group shales were different from the shales of the Kwahu-Bombouaka Group based on their geochemical signatures. Also, Abu et al. (2023a) worked on the Oti-Pendjari Group using the geochemistry of the shales to characterize their provenance and concluded that they were likely sourced from the felsic igneous rocks of the Dahomeyides of the Pan-African orogenic belt.

The sedimentology of the Voltaian Basin has been studied to some extent from its francophone extension and to a lesser extent, in Ghana, detailing the sedimentological composition of the basin from field mapping exercises coupled with geophysical investigations in some cases by Abu (2018); Abu et al. (2020); Affaton et al. (1980); Carney et al. (2010). The sedimentology of the Voltaian Basin as a whole was again reviewed by Carney et al. (2010) using findings from reconnaissance survey field expeditions across the basin, remotely sensed data, and literature review. The study concluded that the depositional environments of the sediments of the basin were nearshore, shallow marine, littoral, and terrestrial depositional environments. Also, an earlier study by Anani (1999) on the sedimentology of the southeastern fringe of the basin (Kwahu-Bombouaka Group) concluded that the depositional environment in that part of the basin is a shallow marine setting. The sedimentology of the northeastern parts (Gambaga-Nakpanduri areas) (Figure 1) was also evaluated by

Abu (2018); Abu et al. (2020); Ayite et al. (2008). These workers in this part of the basin concluded that the sediments were largely of shallow marine and fluvial environments. However, there are still some sedimentary facies that are unaccounted for within the VB. This is an indication of the need for further work on the sedimentology of the basin, notwithstanding the extent of work on that aspect of the basin.

Unlike the extensively investigated hydrocarbon prospects of other Neoproterozoic basins, e.g., Tauodeni Basin by Craig et al. (2012), the Sichuan Basin of China by Zhang et al. (2006) and Ma et al. (2008), the Neoproterozoic Baykit High region of Siberia by Kelly et al. (2011), and the South Oman Salt Basin by Konert et al. (2001), the hydrocarbon potential of the VB until recently (Abu et al., 2021, 2023a,b, 2022), requires a much extensive study. These recent studies on the basin's hydrocarbon prospects were carried out using outcrop samples of shales and carbonates from the Kwahu-Bombouaka Group and the Oti-Pendjari Group following an earlier review of the basin's hydrocarbon prospects (Abu et al., 2021). From inorganic geochemical proxies, the depositional conditions appear suitable for organic matter production, although preservation conditions seem less favorable (Abu et al., 2022). In addition, Abu et al. (2023a) reported a poor organic matter content in outcrop samples (TOC < 0.5 wt%) and very mature organic matter in the Kwahu-Bombouaka Group and mature organic matter in the Oti-Pendjari Group shales (Abu et al., 2023a). Furthermore, a recent review of the Voltaian Basin with a focus on elucidating its hydrocarbon prospects by Zobah et al. (2022) concluded that the depositional conditions and environments are suitable for organic matter generation. The study also indicated there are favorable sedimentological conditions for hydrocarbon generation. The study recommended the need for further studies on the basin with a focus on ascertaining whether the VB of Ghana has complete elements of a petroleum system.

The VB of Ghana, until recently (Abu et al., 2023b), does not have records of paleontological evidence, however, its extension in Benin and Togo has been studied by Amard (1992). His study concluded that there are Acritarch, Conodonts, and some Amorphous Organic Matter (AOM) in shales believed to be of the Pendjari Formation. The shales of the VB also indicate the presence of some phytoclasts (Abu et al., 2023b), however, further works are required.

With the findings of work done so far on the basin, it is clear that there is a need for further work on the basin to provide a comprehensive understanding of the basin's depositional processes, sedimentary facies assemblages, lithostratigraphic sequence, tectonics/basin analysis, palynological facies, and hydrocarbon potential. The depositional processes and environments, and facies assemblages are among the primary assessment priorities of a sedimentary basin whose hydrocarbon prospects are of interest (Abu et al., 2022). They are key requirements in the source and reservoir identification and characterization. For instance, argillaceous sediments, which are source rocks due to the organic carbon content, are associated with low-energy depositional environments, while coarse sediments, which are potential reservoir rocks, are suggestive of high-energy environments. Hence, these aspects of a sedimentary basin control and determine where the source rock(s), reservoir rocks, stratigraphic traps, and seals can be located within a basin. The lithostratigraphic sequence helps provide details on the facies sequence and helps in the understanding of the petroleum system. The tectonics helps in elucidating the sedimentation history and highlights the availability or otherwise of structural traps, which is key in the assessment of the elements of a petroleum system of every sedimentary basin. Despite the absence of drill cores to resolve some of these aforementioned gaps in the basin, a systematic sedimentological field mapping of the basin can generate data that can be resorted to for further analysis and assessment, and provide answers to most of the discrepancies, if not all. Hence, the main aim of this review is to serve as a guide for further investigations and to indicate aspects of the basin that need further studies. The objectives of the study are to: (1) highlight some unreported sedimentary facies within the lithostratigraphic sequence of the basin, (2) highlight some organic matter indications, (3) show some evidence of deformations within the basin, and the hydrocarbon shows. Aside from this study contributing to the ongoing discussion on the VB, it will serve as a guide for future research works to the academic and research community, as well as relevant industry players, on the basin.

With the quest to increase the country's hydrocarbon resource reserves, the VB, as the only onshore basin, is a Neoproterozoic basin with a geological architecture similar to oil and gas producing Neoproterozoic sedimentary basins, e.g., Illizy basin (Libya), South Oman Salt Basin (Oman), and Sichuan basin (China). Hence, a comprehensive study of the basin to enhance the understanding of its hydrocarbon generation potential, with a focus on identifying the presence of the various elements of a petroleum system, holds the key to the country's chance of adding to its hydrocarbon reserves.

Materials and Methods

Geological summary of the VB of Ghana

Subsidence in the southeastern, northern, and central parts of the West African Craton (WAC) around 1.9 – 1.0 Ga resulted in the formation of the Voltaian, Tindouf, and Tauodeni Basins, respectively (Goodwin, 1996). These three basins form the main supracrustals of the WAC and are comparable (Craig et al., 2010). The VB covers most central parts of Ghana, representing a total land area of about 115,000 km^2 and about 40% of Ghana's total land mass (Carney et al., 2010) (Figure 1). The Voltaian Basin and the Pan African orogenic belt (Dahomeyides) define the Neoproterozoic geological terrains of Ghana (Deynoux et al., 2006).

The VB is made up of three major groups: Tamale-Obosum, Oti-Pendjari, and Kwahu-Bombouaka Groups. The Tamale-Obosum Group is the uppermost unit with distinctively reddish sandstones together with conglomerates, and other argilla-

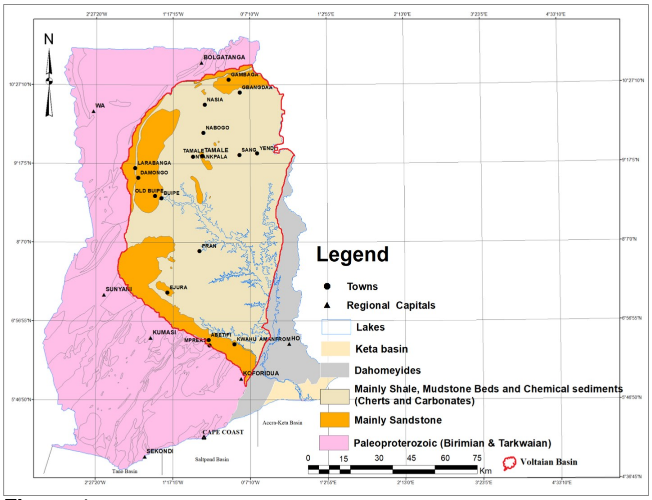

Figure 1. Outline of the geology of the Voltaian Basin relative to the Geological setting of Ghana.

ceous sedimentary facies (Affaton et al., 1991; Carney et al., 2010; Junner and Hirdes, 1946). This is less studied relative to the other groups, and hence, no formally accepted formations are known for the group. The Oti-Pendjari Group is the middle unit of the basin and is characterized by carbonates, cherts, sandstones, and argillaceous facies of mudstone and shale textures. This group has been divided into Kodjari and Pendjari formations, with the Kodjari Formation underlying the Pendjari Formation and uncomfortably on the Panabako Formation of the Kwahu-Bombouaka Group (Abu et al., 2023a; Carney et al., 2010; Deynoux et al., 2006; Nédélec et al., 2007). The Kwahu-Bombouaka Group has three formations and is generally composed of sandstones of both quartzitic and feldspathic facies, shales, sandy shales, and mudstones (Abu, 2018; Abu et al., 2020; Ayite et al., 2008; Carney et al., 2010; Viljeon et al., 2008).

Data Collection

In this study, fieldwork results used include results of fieldwork conducted across the basin in the period between 2015 and 2021 (Abu et al., 2023a,b, 2022, 2020; Anani et al., 2017), some of which are presented here for the first time, and the majority of which are presented from published works. Fieldwork was also conducted by making observations in the Kwahu-Bombouaka Group in its Northeastern parts (Nakpanduri-Gambaga areas) (Abu, 2018), Ejura areas in the central-southern parts of the basin, and at the Abetifi-Mpraeso environs, which define the southeastern parts of the Kwahu-Bombouaka Group (Abu et al., 2023a,b, 2022). The fieldwork within the Oti-Pendjari Group was conducted in the Yendi, Sabari, Salaga, and Buipe areas (Figure 1). In these areas, sandstone, shales, and carbonate exposures were observed. These areas within the basin were targeted because they are the formations with the presence of shale and carbonate units. apart from the thickness, these units are potential source rocks for hydrocarbons. During the fieldwork in these areas, sedimentological observations and recordings were made on the observable sedimentary features and other depositional structures (Abu et al., 2023b). The measurements on exposed units within the local lithological sequence in areas where the litho-sequence was exposed were taken. Information and field data from the Gambaga-Nakpanduri areas are modifications made to field images by Abu (2018) and Abu et al. (2020). The fieldwork results were augmented with accessible literature: conference proceedings and published international peer-reviewed papers on the basin on both its Francophone and Ghana extensions. This accessible literature, although generally scanty, was sorted based on its relevance to the subject of this paper and thoroughly reviewed, e.g., papers on groundwater studies on the basin were not considered.

Results and Discussion

The Kwahu-Bombouaka Group

In the Gambaga-Nakpanduri areas of the Kwahu-Bombouaka Group of the basin, there are well-exposed facies of shales, some mudstones/siltstones, quartzitic and feldspathic sandstone facies. These are well documented in Abu (2018) and Abu et al. (2020). Additional information on the sedimentary facies of the area is also available in Ayite et al. (2008).

The Damongo Formation is reported to be the equivalent of the "Lower Kintampo Sandstone Member" according to Kalvig (2008). This suggests and affirms that it belongs to the larger Kwahu-Bombouaka Group (Carney et al., 2010). The field observations conducted at the Damongo massifs reveal the presence of cross bedding (Figure 2a and c), wavy laminations (Figure 2b), parallel bedded algal mats (Figure 2d), and medium to thick parallel beds together with paleosol features such as pseudo-Karren weathering or 'elephant skin' structures (polygonal shapes on the surfaces of sandstones), within the formation (Figure 2e and f). These sedimentary facies were found to be ubiquitous in the Panabako Formation in the Gambaga-Nakpanduri areas of the Kwahu-Bombouaka Group (Abu, 2018; Abu et al., 2020).

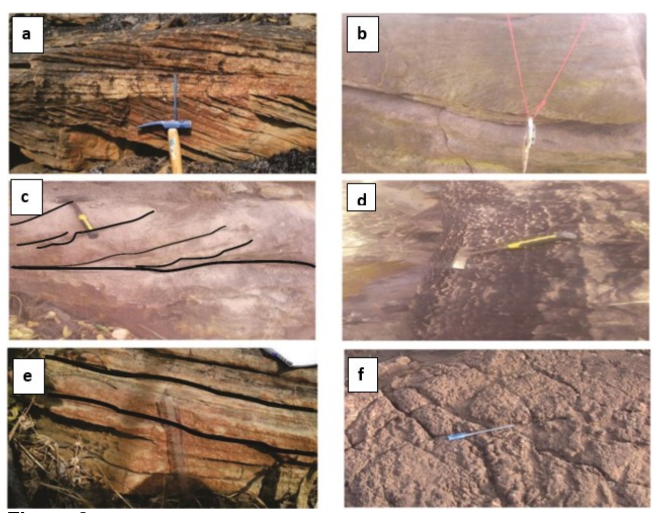

Figure 2. Field images from the Damongo areas of the Voltaian Basin: a & c, Cross-bedding, b, wavy lamination, d, algal mats, e, parallel bedding, and f, pseudo-Karren weathering or 'elephant skin' (polygonal shapes).

Figure 3. Red shale unit of the Kwahu-Bombouaka Group exposed at the outskirts of Ejura township off – Kumasi road (yellow lines showing thinly intercalated green shales).

From the field observations, the Damongo unit of the basin is similar to the Panabako Formation of the Kwahu-Bombouaka Group, with the same depositional process and environment, thus, a shallow marine environment of low-energy setting. This depositional environment has been reported for the Panabako Formation in the southeastern and northeastern parts of the Group (Abu, 2018; Abu et al., 2020; Anani, 1999; Ayite et al., 2008; Carney et al., 2010).

In the central southern part of the Group, thus, the Ejura areas, there are observable sandy shales on top of the Group in this area, with red shales that are intercalated with thin lenses of greenish shale facies (within yellow lines of Figure 3). The intercalated shale has ripple marks observable on floats. The sandy shales are parallel-bedded and laminated with no observable sedimentary features on the red shales (Figure 3).

The Ejura member of the group is most likely to have been deposited in a shallow marine environment under wave conditions. The Kwahu-Mpraeso member of the Kwahu-Bombouaka Group has been relatively studied compared to the other parts of the group, e.g., the Kimtampo, Ejura, and Damongo parts of the group. There are reports of shales and sandstones in the area by Anani (1999) and Carney et al. (2010). The depositional environment of these sedimentary facies is largely that of a shallow marine setting. Abu et al. (2023a,b, 2022) reported the presence of black shales underlying phyllites, with sandstones of both feldspathic and quartzitic facies, for the first time, in the Ebetifi-Mpraeso areas (Figure 4) of the southeastern parts of the group.

These observations (Figure 4 and Figure 3) have been reported for the first time in this study, on the sedimentology of the southeastern fringe of the basin. These are exposed from a road cutting in the area, and the spatial extent of these sedimentary facies in the area is unknown.

From the study, the sedimentological observations in the Damongo areas correlate with the observations made in the upper parts of the Gambaga-Nakpanduri parts (Abu et al., 2020) of the Kwahu-Bombouaka Group. The argillaceous lower member in the Gambaga-Nakpanduri area, which is characterized

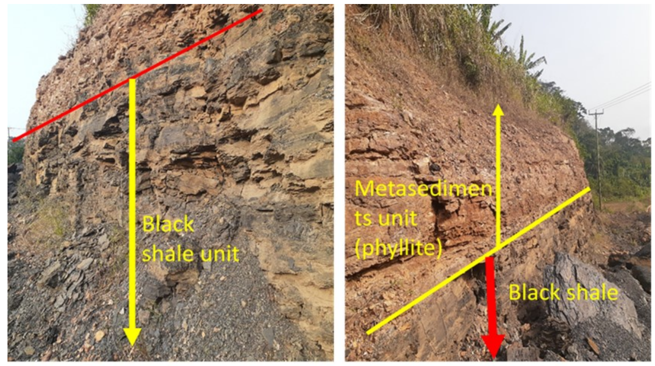

Figure 4. Metasediments (phyllite) and black shales of the Ebetifi-Mpraeso areas of the Kwahu-Bombouaka Group in the southeastern parts of the basin, modified after (Abu et al., 2023a).

by sandy shales, shales, and silty-mud clastic sediments, was not seen in the Damongo member. The upper members of all the areas Kwahu-Bombouaka Group appear to be well defined by sandstone in all these areas where the group is exposed. However, the lower argillaceous unit of the Gambaga-Nakpanduri member is different from that in the Ejura area, as well as that in the Ebetifi-Mpraeso areas. The Gambaga-Nakpanduri areas of the group have sandy shales, shales, and silty-mud detrital materials (Abu et al., 2020; Ayite et al., 2008). Whereas the lower unit of the Ejura area of the group has a thick (? m) unit of red shales with thin greenish shales intercalations (Figure 3), while the lower unit of the Ebetifi-Mpraeso areas of the group is defined by phyllites and black shales (Figure 4). The Kwahu-Bombouaka Group generally overlies the Paleoproterozoic Birimian in all these areas where it is exposed, however, aside from these observed sedimentological differences from field data, the thickness of these varied units in the Gambaga-Nakpanduri, Damongo, Ejura, and Ebetifi-Mpraeso areas is not known.

The Oti-Pendjari Group

The Oti-Pendjari Group is defined by two main formations; the Pendjari formation and Kodjari formation (Affaton et al., 1980). The Yendi areas in Ghana are believed to be the representation of the Pendjari formation with dominant argillaceous sediments (Carney et al., 2010; Deynoux et al., 2006). In this study, the Yendi-Sabare areas have indications of sandstones (Figure 5a), greenish-grey shales, and grey shales (Figure 5). These sedimentary facies have observable sedimentological features like; parallel laminations (Figure 5b and c), parallel laminations (Figure 5d), disrupted laminations and climbing ripples (Figure 5e), and ripple marks (Figure 5f).

The sedimentology characteristic of the formation in the area is that of rapid deposition of sediments from sediment-laden currents (disrupted laminations) (Abu, 2018). The presence of laminations is suggestive of a low-energy water medium, most probably, a floodplain environment, although fluvial environments cannot be precluded (Abu et al., 2023b). Ripple marks are indications of a wave-dominated depositional environment (Abu et al., 2020), which is typical of shallow marine environments. The depositional process and environment

Figure 5. Field images of the Pendjari Formation in the Yendi-Sabare areas: a, sandstones in the Sabari community, b, greenish-grey shale within a tributary of the Oti River, c, a thick unit of the grey shales exposed in the Oti River, d, cross-laminated sandy shale, e, disrupted laminations together with climbing ripples in Yendi township, and f, ripple marks on shales at Yendi, modified after Abu et al. (2023b).

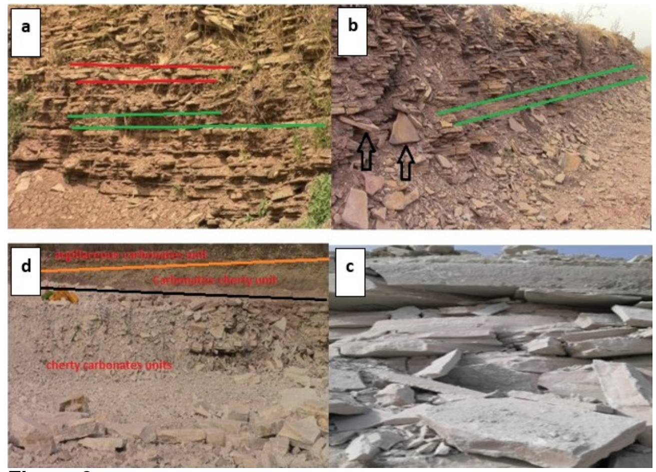

Figure 6. Field images of the Buipe areas from the carbonates/limestone mining site of Savana cement company a, laminated – thinly bedded clay (in greens lines)– carbonates facies (in red lines), b, laminated cherty (in blue lines) – carbonate facies (black arrows), c, bedded carbonates facies, and d, the main facies sequence of the Buipe area – a section showing all the facies of the area.

of the Pendjari Formation can be said to be that of a rapid sediment deposition process where sediments from sediment-laden currents were rapidly deposited into a shallow marine environment, which later evolved under wave action through marine transgression and regression conditions.

The Kodjari Formation of the Oti-Pendjari Group is composed of carbonates, cherts (silixites), and argillaceous sedimentary facies (Figure 6) that are dominantly clay/mudstone in texture (Abu et al., 2022; Affaton et al., 1980; Kalsbeek and Frei, 2010; Nédélec et al., 2007). As part of this study, the field expedition in the Buipe areas of the Voltaian Basin indicates an exposed (by the Savana Cement factory) sequence of argillaceous sediments with carbonate intercalations underlain by cherty-carbonates (Figure 6d). Below the cherty-carbonate unit is a carbonate-cherty unit, which also overlies a carbonate unit. From the quarry exposed section, all three 3 units above the carbonate unit at the bottom range between 0.5 m and 6 m in the Buipe areas (Figure 6). The thickness of the carbonates below is, however, unknown.

The carbonates of Neoproterozoic basins are reported to be associated with transgression and regression depositional environments as well as glaciation (Craig et al., 2009). The sequence of the deposition and the facies transition of the Kodjari as observed in the Buipe area can be said to be marine to shallow marine environments with regression and transgression events. This process most probably did not allow abrupt facies change between the cherts and carbonates. This observation appears to correlate with carbonate-bearing units of other Neoproterozoic basins (Craig et al., 2010), although further studies are required.

Paleontology/Biogeology

The paleontology study of shales of the Pendjari Formation and the Kwahu-Bombouaka Group of the VB of Ghana revealed the presence of some fossils (Figure 7). These are herein classified as phytoclasts and palynomorphs (Abu et al., 2023b), which are suggestive of the presence of flora and fauna paleontological evidence in the basin (**?**). The Pendjari Formation has indications of both palynomorphs and phytoclasts, whereas only palynomorphs were recorded in the black shales of the southeastern part of the Kwahu-Bombouaka Group (Figure 7).

The phytoclasts' organic matter, according to **?** and **?**, is indicative of organic matter (OM) of terrestrial source, whereas palynomorphs are indications of marine sourced OM (**??**). In the studied samples, the observed palynomorphs dominate those of the phytoclasts. This implies that although generally sparse in the outcrop samples studied, marine-sourced OM presence in the Voltaian Basin is likely more than that of terrestrial OM content. The presence of Acritarch dominated by acanthomorphs Tanarium conoideum and Variomargosphaeridium litoschum, as reported by **?**, observable in the greenish–grey shales of the Pendjari Formation, is comparable to similar observations in other Neoproterozoic basins, e.g., Australia (Amadeus Basin) and South China (Sichuan Basin). This observation, thus, the observed phytoclasts (Chuaria circularis) in greenish shales of the Pendjari Formation correlates with an earlier observation reported in the Francophone extension of the basin in Burkina Faso and Benin by Amard (1992).

Tectonic Deformations in the Basin

The Voltaian Basin is largely considered to be undeformed except for some minor deformations where it is in contact with the Dahomeyides in its southeastern fringe (Anani, 1999; Anani et al., 2017; Carney et al., 2010; **?**). Geophysical data, however, suggest the presence of brittle deformations, e.g., NS and EW faults within the Oti-Pendjari Group and at the basin's contact with the Birimian (Kalvig, 2008). Also, this study has evidence of both brittle (Figure 8a and b) and ductile

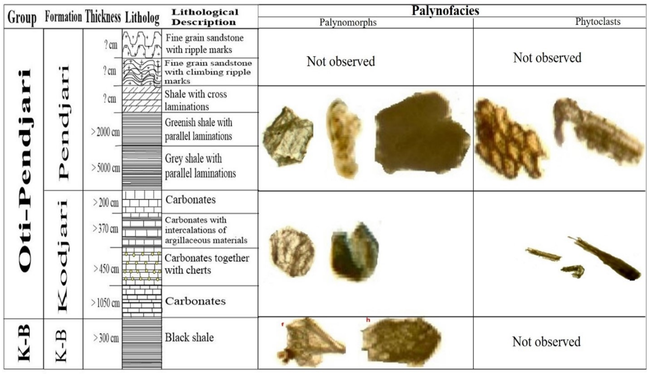

Figure 7. Paleontological results of outcrop samples of the Kwahu-Bombouaka and Oti-Pendjari Groups of the Voltaian basin of Ghana, after Abu et al. (2023b).

(Figure 8c and d) deformations in both the Oti-Pendjari Formation and the Kwahu-Bombouaka Group (Figure 8). A fault can be inferred with the presence of metasedimentary units (phyllite) overlying black shales (Figure 4) in the Mpraeso areas. The inferred faults on the metasediments at the Mpraeso area are in direct contact with the Dahomeyides to the immediate east (Figure 1). The Dahomeyides are characterized by multiple episodes of tectonic events evidenced by faults, fractures, joints, and folds (**?**). The VB basin to the immediate left of the Dahomeyides has most likely experienced some level of deformation, as indicated in the Mpraeso parts of the VB. These are plausible events that could generate structural traps in the VB capable of trapping any generated hydrocarbon, given suitable geological conditions. These observations, however, confirm the geophysical indications of the deformations on the Oti-Pendjari Group by Kalvig (2008).
These deformational structures are both in contact with the basin with the Birimian (Figure 8a and b) and at the central parts of the basin, where it is not in contact with the Birimian (Figure 8c and d). The structures are indicative of both extensional and compressional tectonic events. Although further studies on the basin's tectonic evolution are required, these observations (Figure 8) disagree with the earlier assertion that the basin has not been deformed except for minor deformations at its contact with the Dahomeyides.

Hydrocarbon investigation in the basin

Systematic efforts towards unraveling the hydrocarbon prospects of the Voltaian Basin are currently underway by the Ghana National Petroleum Corporation (GNPC), hence, there is no available literature on the basin's hydrocarbon potential. Recently, the hydrocarbon prospects of the basin were investigated (Abu et al., 2022) using outcrop samples. From this, the primary organic matter production, the climatic conditions, and the depositional conditions appear to have supported organic matter productivity in the basin. The organic matter preservation conditions, however, appear not to have favored the preservation of the produced organic matter. The poor organic matter content, poor preservation conditions could be better evaluated from drill core samples since outcrop samples and their organic matter content are exposed to surficial processes and alteration processes.

Figure 8. Deformations observed in the Voltaian Basin of Ghana; a, is a fracture (red circle) observed in sandstone at the outskirt of Ejura, b, a fractured black shale at the Mpraeso areas, c and d, folds on the Kodjari Formation at the Buipe areas.

Organic geochemistry

The organic geochemistry of the outcrop samples suggested very low total organic carbon (TOC) content (< 0.5 wt%), with Tmax values suggestive of mature to over-mature organic matter according to Abu et al. (2023a). The poor TOC content can be attributed to alteration processes that the outcrop samples might have experienced. Also, poor OM accumulation conditions in the basin due to its paleogeographic location cannot be precluded as a possible reason for the low OM content observed in the samples evaluated.
From the indications of this investigation of the basin's hydrocarbon prospects, the sedimentological evidence suggests that the shales in the Sabari areas (around the Oti River) and the black shales in the Mpraeso-Ebetifi areas could be the probable source rock location in the basin. However, better organic geochemical indications can be obtained from fresh (drill core) rock samples.

Conclusion and Recommendations

From the study, the following conclusions can be drawn;

- **Well-exposed outcrops:** The Voltaian Basin has well-exposed outcrops to support a systematic mapping and sedimentary facies assessment of the entire basin.
- **Argillaceous and carbonate facies:** The basin in its central-southern (outskirts of Ejura) parts has a well-exposed, relatively thick red argillaceous facies unit with a thin lens of greenish shale intercalation. Black shales are observable at the Mpraeso areas of the southeastern parts of the basin, thus the Kwahu-Bombouaka Group. There are observable exposures of a thick sequence of grey shale units in the Sabari environs of the basin, believed to be part of the Pendjari Formation of the Oti-Pendjari Group. A well-exposed carbonate, carbonates-cherty unit, cherty-carbonate unit, and carbonate unit are present at the Buipe parts, believed to define the Kodjari Formation of the Oti-Pendjari Group.

- **Paleontological evidence:** There is paleontological evidence of phytoclasts (Chuaria circularis) and palynomorphs, as well as Acritarch facies in the basin.
- **Tectonic deformation:** The basin is tectonically deformed in its central parts as well as in areas where it is in contact with the Birimian and the Dahomeyides, with evidence of faults and folds in the Buipe carbonates (Oti-Pendjari Group) and faulting of sandstones at the Ejura areas (member of the Kwahu-Bombouaka Group).
- **Hydrocarbon potential:** The evidence of organic matter, deformations, and organic matter indications (TOC and palynofacies) from outcrop samples, coupled with sedimentary facies, suggests a suitable geological setting for hydrocarbon accumulation.

Future work

The indications from this review are suggestive that there is a need for a systematic mapping of the entire basin, as well as drilling in some selected areas of the basin.

The systematic mapping, apart from generating significant data on the basin, can always be leveraged for further investigations. A mapping expedition will again provide detailed information on the sedimentary facies through the depositional processes and environment, and the tectonic events experienced by the basin can also be elucidated.

A drilling in some selected area(s) within the basin will allow the assessment of the tectonic evolution, thus, sediment supply, basin analysis, and how the basin evolved. Drill cores will allow a comprehensive understanding of the petroleum system of the basin, which will lead to a conclusive decision on its hydrocarbon prospects while guiding investor and economic decision-making processes in the basin.

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