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A review on the provenance of the Voltaian Basin, Ghana: Implications for hydrocarbon prospectivity

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ABSTRACT

The Voltaian Basin of Ghana has taken significance as a potential oil and gas basin. Since Ghana became a petroleum-producing country, every attempt is being made to understand the sedimentary basins within the country's territorial boundaries, particularly, the Voltaian Basin. This review paper investigates studies on the Voltaian Basin drawing on a comprehensive literature review based on database searches from Scopus, Web of Science, and Science Direct, among others. Several branches of geology such as mineralogy, geochemistry, igneous and metamorphic petrology, geochronology, and sedimentary geology among others were integrated to reconstruct the source of the Voltaian Basin sedimentary rocks. Application of compositional analyses to determine provenance using petrographic, mineralogical, and geochemical techniques are also discussed. Results based on articles retrieved from the comprehensive literature review summarize the findings on provenance studies; stating the sediment source and history of the rock types in the Voltaian Basin to be most likely from the Pan-African orogenic rocks having a felsic source with some inputs from metasedimentary source rocks. Findings from provenance studies further point to the depositional environment being of shallow marine source and having a fluvial to deltaic environmental features, suggesting that the depositional environment is suitable for hydrocarbon source rocks as well as reservoir rocks formation. With regards to petroleum exploration, a lot of research work needs to be done to identify the type of sedimentary organic matter present in the shales and the limestones of the Voltaian Basin. Furthermore, the rock properties that define petroleum reservoirs such as porosity, permeability, pore type, and rock compressibility as well as electrical properties of some important sandstones need to be thoroughly investigated.

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Introduction

Sedimentary rocks worldwide have been a subject of interest in the search for petroleum resources. Globally, sedimentary basins and sedimentary rocks are increasingly gaining hydrocarbon exploration interest after major discoveries have been made in sedimentary basins through research and exploration efforts by geologists and engineers [2]. Ghana's Voltaian Basin is not an exception to this. Over the years, exploration works in Ghana have been focused on other rock formations [20,29,51,54,58,69] to deduce their source and mineral exploration prospectivity among others. The Voltaian Basin however as compared to the other sedimentary basins of the country (Tano-Cape Three Point Basin, Saltpond Basin and Accra-Keta Basin) has not seen much exploration for petroleum resources.

Interest in the Voltaian Basin heightened after Soviet and Romanian geologists in an exploration work for water in the onshore Voltaian Basin after drilling boreholes encountered traces of oil and gas in some of the boreholes drilled in the Northern and Upper East Regions [64]. Researchers and state-owned organizations have since studied the basin to understand its implication for hydrocarbon prospectivity. However, much remains to be known about the basin for petroleum exploration. Although there is intensive exploration currently ongoing in the Voltaian Basin to establish hydrocarbon presence, the provenance of the basin is one of the important characteristics that the explorationist needs to investigate at the initial stages. This is because the provenance of sediments and sedimentary rocks is a determining factor for inferring the presence of petroleum source rocks and the quality of reservoir rocks [8]. The provenance affects petroleum generation, the flow of hydrocarbons in the reservoir rock, and hydrocarbon recovery. Provenance thus has economic implications for the exploration work and the subsequent reservoir development.

Provenance studies integrate several branches of geology such as mineralogy, geochemistry, igneous and metamorphic petrology, geochronology, and sedimentary geology among others to reconstruct the source of rocks [60]. Provenance studies thus infer the sediment source and dispersal. Therefore, this review paper seeks to bring under one umbrella studies that have been conducted in Ghana's Voltaian Basin to reconstruct the depositional history of sediments. It is necessary to investigate provenance for some reasons. According to Blake et al. [17], the planet earth is dynamic, and all rocks in it are constantly under transition between the three main rock types (sedimentary, igneous, and metamorphic) which when exposed to surface conditions are later altered and broken down into sediments. The sediments thus can provide evidence of history of their parent source rocks following well-defined scientific processes and hypotheses. Geological principles and methods such as the laws of stratigraphy and stratigraphic successions are used to investigate the origin of the rock (provenance) with a high degree of accuracy [73]. Secondly, a provenance study is executed to reconstruct the tectonic, paleogeographic, paleo climatologic, and sediment history, hence identifying the source from which they originated

[73]. This investigation of the source includes the identification of the parent location and qualities of sediment source areas, the paths by which sediment is transferred from the source to the recent depositional environment, and the factors that control the composition and characteristics of such sedimentary rocks [40].

Compositional analyses are also applied to determine the origin of sediments by the use of petrographic, mineralogical, or geochemical (major, trace, and rare earth elements) techniques or a combination of any of these techniques to study the features of the sedimentary rocks in the basin, their external structures and trends, composition and establish their probable origin and depositional environments [4].

Following a given set of economic conditions, it is possible to analyze the lowest petroleum (oil or gas) flow rates required to make an exploration worthwhile [72] and also, define the economic viability, minimize expenditure and maximize returns on investment made on exploration. Thus, the provenance of the Voltaian Basin and how it affects the reservoir potential needs to be explicitly defined through more extensive research work to broaden the knowledge base already existing on the basin and to ascertain the feasibility of any exploration that may be performed in the basin.

Scholarly research articles on the provenance of the Voltaian Basin of Ghana are reviewed in this paper to identify critical research gaps and to inform further exploration of the basin. Findings on provenance studies are also discussed; stating the sediment source and history as well as the rock types and depositional environments in the Voltaian Basin as proposed by researchers which point to the type of petroleum source rocks and reservoir rocks in the basin. This provides a basis for further studies on petroleum source rock as well as reservoir quality studies.

This paper is organized as follows. The sedimentary basins of Ghana and their hydrocarbon potentials are discussed in section 2. In section 3, an overview of the Voltaian Basin and work done in the basin with regards to provenance is presented. Section 4 presents a general discussion on the influence of rock minerals on provenance studies. Known methods that are rarely used in studying provenance in the Voltaian Basin are presented in section 5 while deductions from provenance studies are discussed in section 6. In section 7, prospects for future work concerning hydrocarbon prospectivity in the Voltaian Basin are presented and conclusions drawn based on this review are given in section 8.

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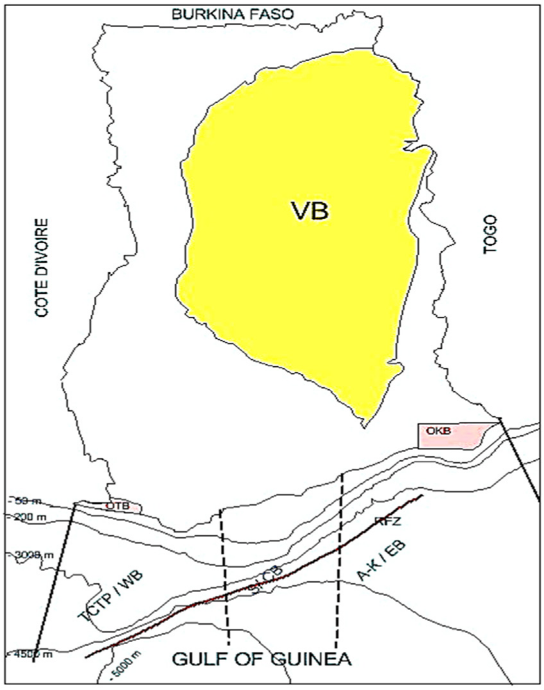

Legend

VB-Voltaian Basin

TCTP/WB-Tano Cape Three Points or Western Basin

S/CB-Saltpond or Central Basin

A-K/EB-Accra Keta or Eastern Basin

OTB-Onshore Tano Basin

OKB-Onshore Keta Basin

RFZ-Romanche Fracture Zone

Fig. 1. The four sedimentary basins of Ghana. Modified after Adda [3].
VB-Voltaian Basin, OTB-Onshore Tano Basin, TCTP/WB-Tano Cape Three Points or Western Basin, OKB-Onshore Keta Basin, S/CB-Saltpond or Central Basin, RFZ-Romanche Fracture Zone, A-K/EB-Accra Keta or Eastern Basin

Sedimentary basins in Ghana

The geology of Ghana is primarily extremely old crystalline rocks dominated by ancient crystalline rocks, comprising mainly metamorphosed deposits and granite, volcanic belts, and sedimentary basins [50]. Ancient rocks from Paleoproterozoic, Neoproterozoic, and conceivably early Paleozoic ages cover virtually all of Ghana except near the coast where Paleozoic, Mesozoic, and Cenozoic rocks are typical [26,29,50]. Important series of mineralization also show major veins of minerals which are gold-bearing and of great economic value [50]. At small areas along the coast of the country, minor occurrences of more recent unconsolidated sands, clays and gravels are observed [15].

According to Adda [3], Ghana has four sedimentary basins (Fig. 1). The four basins are the Tano-Cape Three Point Basin (The Western Basin), the Salt Point Basin (The Central Basin), the Accra-Keta Basin (The Eastern Basin) and the Voltaian Basin.

The Tano-Cape Three-Point Basin (Western Basin) is a rift section containing shallow marine to continental residues [65]. The hydrocarbon prospect of the Tano-Cape Three Point Basin has been known since the 1890s based on onshore oil seeps observed. However, the first significant oil was discovered in 2007 by Kosmos Energy when the Mahogany-1 well encountered an 885 ft gross hydrocarbon column with 312 ft of net piled pay in a Cretaceous sandstone reservoir [46]. A Santonian turbidite stratigraphic trap opened a new play fairway in the Tano-Cape Three-Point Basin and the field which was christened Jubilee Field was later developed by Tullow Oil Ghana Ltd with oil production starting in 2010. Afterward, the Tweneboa Enyenra Ntomme (TEN) Oil field and Sankofa field were discovered in the Tano-Cape Three-Point Basin.

The Saltpond Bain/Central Basin is a Paleozoic pull-apart wrench basin encountered in-between the Tano-Cape Three Point Basin and Accra-Keta Basin [65]. Based on the lithofacies and depositional environment observed, it has been stratigraphically split into formations such as Elmina Sandstones, Takoradi shales, Takoradi sandstone, Efia Nkwanta beds, Sekondi sandstones, and the Lower Cretaceous sediments. This basin hosts the Saltpond oilfield which was found in 1970 by the Signal-Amoco Consortium. The basin is marked by faulting with Lower and Upper Takoradi shales as source rocks and the

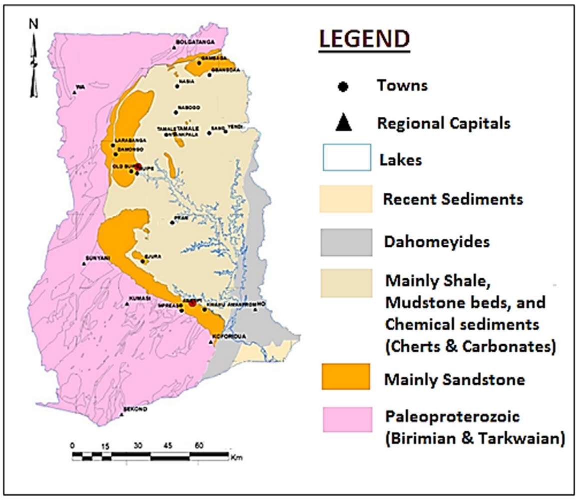

Fig. 2. The Voltaian Basin of Ghana showing the various rock types. Modified after Abu (2013).

Takoradi sandstones as reservoir rocks whereas the Accra-Keta Basin (Eastern Basin) is observed to have some shales as mature source rocks. [3].

The Voltaian Basin (Fig. 2) is one of Ghana's sedimentary basins covering the Eastern and Central parts of the country. It is a sedimentary rock formation underlying the Northern portion of the Volta Region, the Central and Eastern areas of the Northern and Brong-Ahafo Regions, and the North-Eastern Sections of the Ashanti and Eastern Regions of Ghana [3]. Covering a large part of central and eastern Ghana, the basin is comprised of consolidated sandstones, mudstones, and limestones. Out of the area of Ghana covered by the Voltaian Basin, about one-third is covered by horizontal sandstones, mudstones, shales, and some conglomerates inferred to be of late Precambrian to Paleozoic age [50,54]. The Voltaian Basin forms contact with the Birimian Formation of Ghana with sediments dated from Precambrian to Paleozoic and with an approximate thickness of 3000-4000 m. The Voltaian Formation rests on the lower Proterozoic Birimian system and corresponding Granitoids [50]. Hydrocarbon prospecting has been heightened in the Voltaian Basin. However, a well-defined petroleum system is yet to be established

The Voltaian Basin of Ghana and provenance

Lithostratigraphy of the Voltaian Basin and constraints on petroleum exploration

The basin is separated into three sections after Crook (1970), known as the Upper Voltaian, Middle, and Lower Voltaian. The Upper Voltaian contains bedded sandstones with some shales. The Middle Voltaian contains sandstones with limestones, shales with, limestones, siltstones, sandstones, and conglomerates whiles the Lower Voltaian, contains sandstones, shales, siltstones, and quartz sandstones. Ahmed et al. (1977) however challenged the basis of the above division. Owing to the work by Affaton et al. [5] and other geologists, the stratigraphic sequence of the basin was established. A newly adopted nomenclature (Table 1) divided the basin into Kwahu-Bombuaka, Oti-Pendjari, and Tamale-Obosum [5]

Carney et al. [19] using fieldwork and remote imagery analysis achieved a detailed view of the Voltaian, further justified the lithostratigraphic sequence and established the division of the basin into three main uncomformably bounded units (Kwahu-Bombuaka, Oti-Penjari, and Tamale-Obosum), with each showing a particular different stage in the formation of the Voltaian. According to Affaton et al. [5], the strata of the basin are fractured, but most areas are nearly undeformed and show a lower degree of metamorphism. More research, however, still needs to be conducted to properly understand the controversies arising.

The Kwahu – Bombouaka Supergroup is known to outcrop in four areas of Ghana, the Kwahu Plateau, Kintampo Massif, Damango Massif, and Gambaga [47]. The oldest unit of the Kwahu Group is the Yabraso Sandstone Formation which underlies the Damongo Formation and outcrops around Kintampo [5]. Above these formations are the Lower Mpraeso Sandstone Formation, Abetifi Sandstone Formation, and the Obocha Sandstone Formation [19]. The Bombouaka Group on the other hand has the Tossiegou Sandstone Formation at its base which is overlain by the Poubogou Formation and at its top lies the Panaboko Sandstone Formation [5,11,19,48].

The Oti - Pendjari Group rests unconformably on different units of the Kwahu – Bombouaka Supergroup [5]. It is composed of the Bunya Sandstone Member and Chereponi Sandstone Member which make up the Bimbila Sandstone Formation, the Tease Sandstone Formation, Ejura Sandstone Formation, Afram Formation, and the Kodjari Formation [48].

The Obosum Supergroup lies unconformably over the Oti – Pendjari Supergroup. The sediments of this Supergroup were emanated from the Dahomeyides [48]. The Supergroup is made up of the Sang Conglomerate Formation which overlies un-

Table 1
Proposed lithostratigraphic nomenclature of the Voltaian Basin by different authors (modified after [19])

[19]	[5]	Annan-Yorke, 1971		Inferred Age & Correlation
OBOSUM GROUP Tamale Sandstone Formation Densubon Sandstone Formation Dunkro Sandstone Formation Sang Conglomerate Formation **Unconformity**	**OBOSUM GROUP**	**Upper Voltaian**	Massive Sandstone Tamale Red Beds	**Neoproterozoic**
OTI- PENDJARI GROUP: Bimbila Formation: • Bunya Sandstone • Chereponi Sandstone Tease SandstoneEjura SandstoneAfram Formation: • Akroso Conglomerate Kodjari Formation: • Darebe Tuff Bupe Limestone & basal glaciogenic strata**Major Unconformity**	**PENDJARI GROUP:** • Pendjari Formation (undivided) • Kodjari Formation (undivided)	**Middle Voltaian**	Upper Green Beds Afram Shale Akroso Conglomerates Lower Green beds	
South and West Kwahu Group: • Anyaboni Sandstone • Obocha Sandstone • Abettifi Sandstone • Mpraeso Sandstone • Damongo Formation • Poubougou Formation • Yabraso & Tosseigou Sandstone	**DAPANGO-BOMBOUAKA GROUP**: • Panabako Formation • Poubogou Formation • Tossiegou Formation	**Lower Voltaian**	Basal Sandstone	**Latest Neoproterozoic**

conformably on the Oti – Pendjari Supergroup, followed by the Dunkro Sandstone Formation, then the Densubon Sandstone Formation, and finally the Upper Tamale Formation [19].

Reservoir and source rocks are yet to be studied in detail in the basin amidst the controversial formations which make petroleum exploration difficult. Also, the provenance of a majority of these formations has not yet been studied to draw on the age/timing, depositional environment, etc. of the rock formations that could help identify prospective reservoirs and source rocks. Furthermore, timing/age would subsequently help in constructing event charts to define the petroleum system which can be eventually converted to risk assessment charts for future works. A key challenge to understanding the Voltaian Basin of Ghana and its possible importance for hydrocarbon prospectivity is the paucity of literature and data on the basin. The basin may have an important oil reservoir, however, the provenance and its effect on reservoir quality are yet to be clearly defined. As a result, the presence of petroleum products (if any) is not known to further explore and exploit the resources in the basin. Furthermore, nomenclature controversies on the division of the formations in the basin arise which poses a challenge to the mapping of petroleum systems and events.

Carney et al. [19] provided new outlooks on understanding the evolution, structure, lithostratigraphy and formation of the Voltaian Basin by contrasting proposed rock units of the basin with preexisting literature on the rock units (Table 1). Carney et al. [19] showed that the basin has three main disconformable lithostratigraphic units called mega sequences or super groups. They are the Bombouka (Gambaga), Penjdari (Oti), and Tamale (Obosum) mega sequences. Bombouka megasequence resembles the Bombouka or Gambaga megasequence and show detrital and epicontinental features the Oti or Pendari mega sequence represents the middle unit and is segregated into two groups, the Kodjari Group, and the Porga Group. The Tamale mega sequence is the Upper Unit of the Voltaian Basin overlying the Oti or Pendjari Megasequence. Its characteristic features include reddish coarse-grained conglomeratic sandstones. Previous work however by [10] and Affaton et al. [5] only divided the basin into Upper, Lower, and Middle Voltaian. The different nomenclature of the lithostratigraphy of the Voltaian Basin by researchers is shown in Table 1.

Methods employed for provenance studies in the Voltaian Basin

Fieldwork (sampling and field observation)

Field observation of the stratigraphy, lithology, sedimentary structures, fossils, and facies were used to provide enough information that aided in the interpretation of the relative time of formation of rocks, depositional environments, energy during deposition of rocks, grain sizes and other factors influencing the source of the rocks present in different study areas. Facies analyses through sample description and field observation also provided information on the provenance of the basin [2,3,9]. These observations and fieldwork are done through systematic field mapping.

Petrographic studies

A useful tool used to understand sandstone and diagenesis of the basin from works discussed is laboratory analysis. No investigation can fully replicate natural conditions. There however exist various ways to speed up laboratory processes and perform tests under near-natural or natural conditions [43]. Some researchers applied petrographic studies in the study of the Voltaian Basin [2,3,5,9,11,19]. The authors made thin sections and studied these samples under a petrographic microscope to observe the composition and mineralogy (minerals, grain size, and sorting) of the rocks on a micro-scale.

Microscopic methods

X-ray diffraction (XRD) is employed to establish mineralogy and identify clay-rich minerals and relative amounts. Thin sections, mineralogy, and XRD clay typing were used to infer geology, mineralogy, composition, texture, size, shape, arrangement of grains, and depositional environment which give information on provenance [2,9]. Clay minerals within the Kwahu-Bombuaka and whole rock analysis by X-ray diffraction were analyzed by Amedjoe et al. [9]. In related work in Sandstone from the Khashm El Galala (North West Gulf of Suez, Egypt) however, scanning electron microscopy (SEM) and observation of main diagenetic features such as compaction and cementation [68] were employed at the laboratory to study provenance.

A broad variety of petrological methods are used to define rocks and analyze core data and infer the source of the rock. Standard techniques comprise transmitted and reflected light optics, back scattered electron microscopy (BSEM), cathodoluminescence procedures merged with light optics of BSEM, and point chemical analysis of secondary X-rays in the SEM [42,75].

In the study of the Voltaian Basin of Ghana, however, an optical and compositional study of detrital heavy and trace elements was used for provenance studies [2,3,9,19]. Mineralogical investigations of samples of both sandstone and carbonate succession were also applied in the study of the provenance of the basin using x-ray diffraction and thin section analyses [35].

Provenance studies also provide information on the age/timing of deposition of rock sediments which can further tell the petroleum prospectivity of the basin. When the source of the rock and history of sediments is defined, the age of the rock dating from the source to the present and the timing of depositions can be deduced. The age and timing of the deposition of the rocks will also provide a valid basis to reconstruct the burial history and with a known geothermal gradient, the temperature history of the sedimentary rocks can be deduced [39]. Noteworthy, hydrocarbon prospectivity is influenced by the timing and age of the rock. In the Voltaian Basin, the detrital zircon dating approach was applied by Anani et al. (2021) and Abu et al. (2018) to the Bombouaka/Gambaga Group which suggested a wide range of ages from 1000Ma-2200Ma. It was later observed that while the age range of 2000-2200Ma implies inputs from West African craton as sediment source, 1000-1200Ma proposes source from both the West African Craton and the Amazonian Craton [47]. Further studies thus should be conducted in the basin to conclude on a more acceptable timing and age of the basin.

Provenance studies in the Voltaian Basin

Major elements are used to sufficiently determine the source rocks of sediments of the basin. A study of sandstones from the middle Voltaian Oti-Pendjari Group in the Anyaboni and surrounding areas of the basin through elemental analysis suggest a quartz arenite or -sub-arkose provenance [12] (Table 2). The provenance of sediments in the basin is further grouped through the use of discriminate function plots of major elements into felsic igneous, mafic igneous, intermediate igneous and quartzose sedimentary source rocks employing practical indicators as proposed by Roser et al. [67].

However, when samples from the Kwahu Group of the Voltaian Basin were standardized to average Neoproterozoic cratonic rocks, they were observed to be enrichening in trace elements such as Cr, Co and V which proposed some inputs from a mafic source [7]. Major element geochemical data of sandstones from the middle Voltaian Oti-Pendari Group additionally suggest sediments are in a passive continental margin [12].

Geochemical analysis are used to find the relative abundance of rocks [21]. The use of geochemical analyses in the study of the Voltaian Basin sedimentary rocks proved useful in highlighting the provenance of the sediments, their climatic environment, and their source as well [9,33,67]. Major and trace elements geochemistry help deduce the provenance of the basin because the Voltaian sandstones are enriched in trace elements. Except for Th and Hf which are low, the Rare Earth Elements (REE), Th and Sc are typically acknowledged as among the most reliable pathfinders of their ability to withstand fractionation [24,71]. Geochemical studies thus are a tool greatly implored to deduce the source/origin (provenance) of rocks and are mostly coupled with petrography. The source of the sandstone from the Bombouka group of the Voltaian (Northeastern Ghana) for example, has been analyzed from their petrography and whole rock geochemistry [14]. The source of ten sandstone units from the late Proterozoic Buem Structural Unit (southeastern Ghana) have been studied using petrography, major and trace element composition analyses by Osae et al. [63] to determine their provenance and tectonic setting (Table 2). The petrographic analysis by Osae et al. [63] showed quartz-rich sandstones with granitic and metamorphic

Table 2
Summary of studies on provenance in the Voltaian Basin

Sn	Author (year)	Study Area	Method	Conclusion
1.	Anani et al., [13]	Kwahu-Morago and middle Voltain Oti-PendjariGgroup)	Zircon typology	Kwahu-Morago sandstone sediments form the sedimentary basin is the birimian supergroup with a nominal contribution form the Amazonian craton. Oti-Pendjari sandstone group, however, from immature calc-alkaline magmatic arcs.
2.	Abu et al., [2]	Tosseigou, Poubougo, and Panabako formations	Paleocurrent analysis, petrography, and geochemistry	The most probable dominant source area is at the northeastern parts where the Paleoproterozoic Birimian exists.
3.	Amedjoe et al.et al. (2018)	(Kwahu group and Oti group of the Voltain from Agogo at the southeastern part of the basin)	Geochemical analyses (trace elements and rare earth elements)	Mainly felsic areas with minor mafic inputs.
4.	Anani et al., [14]	Bombouaka group	Petrography and whole-rock geochemistry	The sandstones are quartz arenites derived most likely from granitoid.
5.	Kalsbeek et al., [48]	Lower Voltaian Bombouaka group and the middle Voltain Oti group and the Upper Voltaian Obosum group	Zircon geochronology	Derived from Pan-African arcs.
6.	Anani [11]	Kwahu sandstone and Anyaboni sandstones	Modal plots	The groups differ because of tectonic movements but they are from the same Supergroup.
7.	Akontoh [7]	Anyaboni formation of Kwahu group	Petrography and geochemistry	Mainly quartz arenites with internal quartzose.
8.	Osae et al. [63]	Buem structural unit	Provenance	Quartz rich and from granitic and metamorphic basement rocks
9.	Anani (2013)	Middle Voltain Oti-Pendari group in the Anyaboni and its surrounding areas	Major and trace elemental analyses	Sediment are quartz arenites and arkose
10.	Affaton et al. [5]	Bombuaka group	Zircon geochronology	Quartz-rich

sources. The use of major and trace element geochemical compositions showed a subtle enrichment in high field strength elements which suggests the provenance as being of a mature sediment source. [63]

The modal analysis further carried out by Anani et al. [14] on sandstones from Bombuaka Group in the northeastern part of Ghana by point-counting indicated that the sandstones are quartz arenites and $SiO_2/A1_2O_3$, Zr/Sc and the Th/Sc revealed that the sandstones are mature with depletion in CaO and Na_2O but increased in K_2O, Ba, and Rb [14].

The provenance history of sediments is also assessed from their geochemical compositions [30,41,44,66,70]. The geochemical analysis also informs on weathering activities and impact in the provenance area [27,60,70], and the tectonism [30,67]. Noteworthy, the provenance of the Voltaian Basin has been investigated by researchers following the geochemical composition proposed by other researchers. However, [19,22,47,48] used other methods (regional mapping, dating, and petrography) to study the basin. Thus, geochemical methods were not the sole methods employed.

The detrital zircon dating approach, for example, was performed on Neoproterozoic to lower Paleozoic Voltaian Basin rocks and sandstones of the Pan-African Dahomeyide belt in Ghana. It showed a wide age range of 1000Ma-2200Ma. Although the age range 2200Ma-2200Ma indicates Birimian Supergroup, the age range from 1000Ma-1200Ma suggests both the West African Craton and the Amazonian Craton as sediments' provenance as proposed [47]. More studies conducted on the basin will thus clarify this disparity. Considering the sandstone provenance, Anani et al., [12] indicated provenance as being from the Pan African Orogenic Rocks. Sedimentary processes however produce a variety of sediments in texture and mineralogy hence posing a difficulty to petrographic interpretations [74]. Sandstone geochemical data have been analyzed and provenance deduced [11,47,48,55] with less attention on the mudstones and siltstones.

In other basins globally, however, geochemistry of shales and siltstones are employed and considered more accurate sediments provenance indicators [1,6]. In the Voltaian Basin on the other hand, shales and siltstones are yet to be considered

[9]. Thus, studying the provenance of the basin at a wider scale using the siltstones and mudstones as well will broaden the knowledge base on the basin and better suggest hydrocarbon prospectivity. As basins result from plate tectonics that results in flooding of the continents [16], a link between provenance and sedimentary basins in an environment can be made, hence depositional environments can help to deduce the provenance.

The formation of sedimentary facies and structures is dependent on the environment in which they are formed and deposited. Facies thus can be interpreted by studying depositional environments. Energy levels for instance show the type of sedimentary facies. The classification of sediments into basins is therefore based on the observed structures and depositional environment's conditions and processes [16,49,53].

Applying field mapping and petrographic analysis, six sedimentary facies have been identified by Abu et al. (2018) in the Bombouka-Gambaga Group of the NE Voltaian Basin, Ghana. These are; F1, which is characterized by wave like ripple marks, F2 which shows some flutes on micaceous shales; F3 containing ripple marks; F4 identified by parallel and cross layering; F5 with cross beds on quartz-rich sediments at the southern portions and a distinctive well-formed burrow (Skolithos) at the southern part describes facies F6. Abu et al. (2018) further discovered the sediments to be of shallow marine depositional with near shore environments (fluvial, flood plain, deltaic, aeolian, tidal flats and shoreface). Although there exists a favorable environment for hydrocarbons to be formed, the overlying sediments are not compact enough to provide the temperatures and pressures needed for hydrocarbon formation. Studying weathering which marked the contact between the middle Oti-Pendari and the lower Gambaga Group deduced the sequence as typically shallowing, thickening, and coarsening upward (Abu et al., 2018).

The influence of rock minerals on provenance

The mineralogical composition of rocks is a vital tool in provenance analyses following the Bowen reaction series [18]. Because sedimentary rocks are detrital, any mineral can occur in them [61]. Clay minerals are the most abundant minerals in mudrocks [62]. Because quartz is stable under surface conditions, it is most abundant in sandstones and second most abundant mineral observed in mudrocks [23]. Feldspars however are the most common minerals in igneous and metamorphic rocks [34]. Feldspars further break down to clay minerals and quartz but they are still observed as the third most abundant minerals in sedimentary rocks. Carbonates are also commonly observed in mudrocks and sandstones [59]. Knowing the minerals dominant in the rock thus provides information on the source of the rock. The composition of fine grained sedimentary rocks is especially helpful for provenance studies because they give a representative view of the average crust in an area due to their small grain sizes, uniformity and permeability [23,71].

Chemical and mineralogical composition is deduced by whole rock analysis of sediments [71] with special attention to REEs, high field elements and major elements. A suite of geochemical methods by Nader (2017) has also been applied to sandstone and carbonates constraining the source, timing and conditions of carbonate cement growth [36].

Known methods rarely used in studying provenance in the Voltaian Basin

U-Pb zircon geochronology

Uranium-Lead dating employed to study the basin used the radioactive decay of uranium into lead to deduce the age and thus infer a possible source. In each instance, the method was applied to zircon because it is chemically inert and not disturbed during weathering and accepts uranium and thorium atoms in their natural form (crystal structure) but strongly rejects Lead. Though a useful method in the study of rock provenance, it is seldomly applied in the Voltaian Basin of Ghana. Other radiometric dating techniques have been employed to study rocks in other basins [1,9,11–14] but not in the Voltaian Basin of Ghana.

Point counting

This is another method used in evaluating the composition of rocks by determining the mineral or grain observed at a large number (usually 300 to 500) of points in a slide [31]. It is a petrographic method. Although work was done by several researchers [1,9,11–14] in the study of the Voltaian Basin using petrographic analysis, point counting was not employed. Point counting provides information on the relative amount of rock-forming minerals, and the grain size dispersal of the rocks which are of utmost importance for the proper classification of rock and thus deducing its provenance and characteristics.

The Gazzi Dickenson method or technique of point counting

This is often employed coupled with ternary diagrams. It is employed in the design of ternary diagrams, such as Quartz Feldspar and Lithic Fragments (QFL) diagrams. The Dickinson ternary diagram shows the source area of clastic rocks, highlighting that the tectonics in the source area control the source of the sandstones to a particular degree. Therefore, this knowledge can be used to investigate the history of the provenance area [28,32,45]. This has not yet been analyzed in the Voltaian Basin.

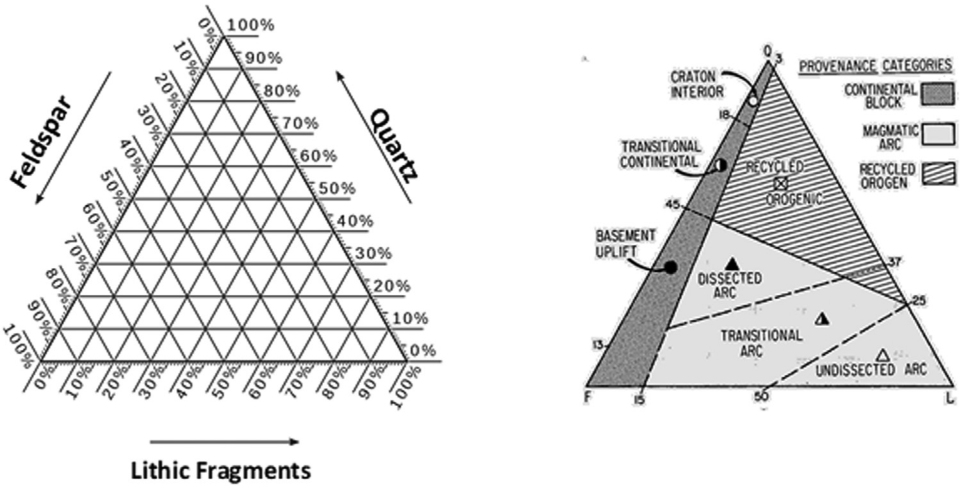

Fig. 3. QFM diagram after Pettijohn et al., (1987) and Dickenson et al., [28]

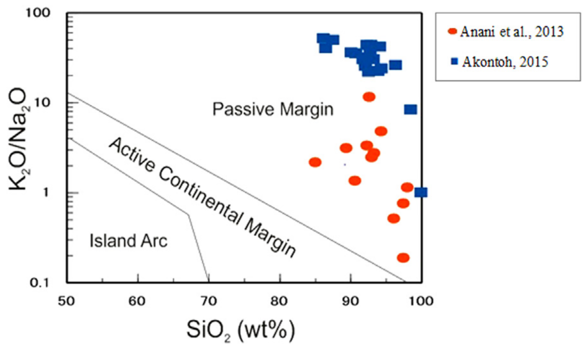

Fig. 4. Provenance discrimination diagram using major elements (K_2O/Na_2O and SiO_2) in sandstones from Anyaboni and surrounding areas. (Source: [7]).

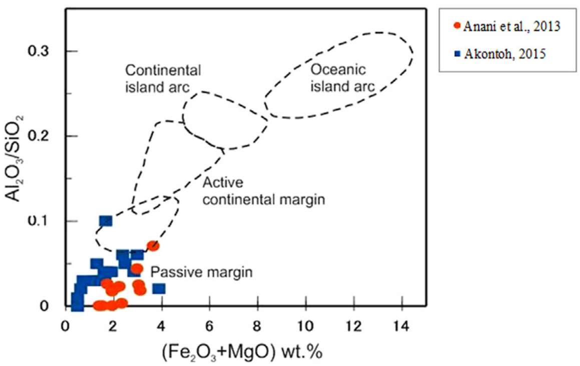

Fig. 5. Provenance discrimination diagram using major elements (Al_2O_3/SiO_2 and Fe_2O_3 + MgO) in sandstones from Anyaboni and surrounding areas (Source: [7]).

Discriminate function plots

Qm-F-Lt ternary diagram [28] shown in Fig. 3, indicates the mineral composition of sandstones. The sandstone ternary diagram depicts the number of lithic grains used for the detailed classification of rock sources. Dickinson [28] showed that mean compositions of sandstones derived from different kinds of provenance areas tend to lie within different fields on the diagrams. Three main classifications of provenance areas thus were determined as continental, magmatic, and recycled orogens. Variants of each can be related to a particular tectonic setting and hence infer the provenance.

In the Voltaian Basin, the sandstone of the Anyaboni Formation of the Kwahu Group plotted based on Figs. 4 and 5 as proposed by Akontoh [7] and based on reference to work by Anani et al., [12] reveals a predominant felsic source rocks and a negligible contribution of intermediate source rock as the provenance. The trend also supports the alteration of K-feldspars into muscovite and illite.

The samples were totally on the passive margin of the diagram (Figs. 4 and 5) implying that the samples had enough time to undergo reworking backed by the high SiO_2 content. The sample fields further suggested felsic source rocks with probable metasedimentary source rock inputs The climatic condition showed a semi-humid climatic condition with a low CIA (Chemical Index of Alteration) value [7].

Radiometry

K–Ar radiometric analyses is one of the rock dating techniques applied globally to solve sedimentary and diagenetic problems. It is however yet to be employed in the Voltaian Basin. A new emphasis on using elastic depositional analogues to predict reservoir quality has arisen [25,37,38,56]. Provenance thus may influence the type of reservoir rock present and its development.

Deductions from provenance studies in the Voltaian Basin

Discriminant functions of major elements have grouped the possible provenance of sediments in the basin into felsic igneous, mafic igneous and quartzose sedimentary source rocks. Discrimination diagrams based on the major element's geochemistry of Anani et al., [12] suggests that the sediments were derived from recycled sedimentary rocks. However, when the samples were normalized to average Neoproterozoic cratonic rocks they showed enrichment in ferromagnesian trace elements such as Cr, Co and V which suggest mafic source.

The tectonic discrimination based on major element geochemistry of sandstones suggest deposition in a passive continental margin with possible sediments from the Pan African Orogeny. The detrital zircon dating approach also provided a wide range of ages from 1000Ma to 22000Ma such that the determination of sediment provenance varied. While the age range of 2000Ma-2200Ma indicates source from the Birimian Supergroup with inputs from the West African Craton, the age range of 1000Ma-1200Ma also suggests the amalgamated West African Craton as sediment's source (Abu et al., 2018; [12]). Ternary diagrams based on the discrimination method by [7,9] suggests felsic source rocks with possible metasedimentary source rocks inputs. The climatic condition of sediments also on a bivariate diagram indicates semi-humid climate conditions with low CIA values [7].

Petrographic analysis also shows that the sandstones are quartz rich and are primarily from granitic and metamorphic basement rocks which are typical of the cratonic interior [3,9]. The index of compositional variability values and $SiO_2/A1_2O_3$, Zr/Sc and Th/Sc values indicate that the sediments are mature [7].

Prospect for future research work: Implications for hydrocarbon prospectivity

Provenance studies can be used to deduce depositional environments, climatic conditions, tectonics, and the source of sediments during deposition. For example, it is known that source rocks from continental sources may contain organic matter that can generate gas while those of marine origin generate oil upon maturation. Moreover, petrographic studies during provenance investigations can help identify the presence of organic matter in possible petroleum source rocks. Conditions under which petroleum source rocks have been deposited can be deduced from provenance studies and this can aid in interpreting if there is a possibility of organic matter preservation. This can help understand the potential source rocks in the Voltaian Basin. It is well known that petroleum source rocks are usually shales or limestones. The Kwahu-Bombuoka and Tamale-Obosum Group of the Voltaian Basin have been studied and seen to contain shales while limestonse are widely found in the Oti-Pendjari [5,9,19]. However, no petrographic studies have been carried out on outcrops of such rocks in the basin to identify preserved organic matter. In future exploits, Rock-Eval pyrolysis and geochemical analysis can be carried out on rocks (shales and limestones) that have been observed to contain organic matter during the proposed petrographic studies. This will help quantify the quantity and quality of organic matter preserved if any.

Provenance affects reservoir quality [8]. Reservoir quality is influenced by many factors including depositional environment, relative sea level change, grain types, grain size, sorting and matrix proportions among others. These factors have a direct influence on two of the main parameters that define reservoir quality, namely, porosity and permeability (Morad et al., 2012). These parameters define a reservoir rock's ability to store and transmit hydrocarbons, respectively. Petroleum reservoirs are usually sandstones or carbonates. Sandstones and shales are found in the Oti-Pendari Group of the Voltaian Basin [12]. Carbonate rocks contain various pore types resulting from a combination of depositional processes and diagenetic alterations [52,57]. According to their sizes, pores can be categorized into micro, meso and macro pores (Archie, 1952; Pitman, 1971). Complicated deposition and diagenetic history may result in the development of diverse pore types and a complex pore evolution. Thus, reservoir quality is controlled by interdependent factors including the origin of the sediment, depositional environment, weathering and climatic conditions, compaction, depth of burial, fluid pressure and structural deformation (Morad et al., 2012). Thus, buttressing the hypothesis that provenance affects reservoir quality. Provenance is, therefore, a defining factor of the type of reservoir rock present. Yet, the provenance and reservoir quality of the Voltain Basin of Ghana have not been studied together for hydrocarbon prospectivity.

Conclusions

This paper reviewed the early and recent studies conducted on provenance studies in the Voltaian Basin of Ghana. Drawing on comprehensive literature, this review showed that the origin of sediments of the Voltaian Basin rocks points to possible sediment contribution from the Pan African Orogenic rocks and suggests felsic source rocks with metasedimentary inputs. The review further points to the depositional environment being of shallow marine source and having a fluvial to deltaic environmental features. Such depositional environments usually house excellent petroleum reservoir rocks and possible hydrocarbon source rocks. However, the hydrocarbon prospectivity and petroleum play system of the basin is yet to be clearly defined.

Due to the paucity of literature especially on the basin for hydrocarbon prospectivity, some key areas where significant controversy remains, and where work remains to be done have been highlighted. These include further studies on possible source rocks in the basin including shales and limestones. Also, in-depth reservoir quality studies on selected sandstones within the Kwahu-Gambouaka, Oti-Pendjari as well as the Obosum Groups need to be conducted to clearly define the implications for hydrocarbon perspectivity. Also, controversies on the nomenclature and age of the Voltaian Basin rocks need to be resolved to improve the definition of the petroleum system within the basin should one exist. This will reduce hydrocarbon exploration risk.

Ages of shales, limestones, and sandstones of the basin for instance are yet to be studied in detail. The ages however are important in defining the petroleum system and hence the hydrocarbon prospectivity of the Voltain Basin. The ages also help in constructing events charts which is crucial in the exploration of hydrocarbons. A recommendation is that research on the Voltaian Basin is made not only on the rock characteristics but ages as well. The provenance of the basin when studied in detail alongside the dating of the ages of the Voltaian Basin rocks as well as the timing of deposition will provide information to better define hydrocarbon prospectivity.

Also, despite the studies on provenance in the Voltaian Basin, the shales and siltstones have not been comprehensively studied for provenance. The shales and siltstones are thus recommended for further studies. Again, reservoir parameters of rocks in the basin that will determine if the rocks can store as well as transmit hydrocarbons have not been studied. These parameters are key to the feasibility of any petroleum exploration work and future resource development in the basin. Future works should take a keen interest in investigating the properties of sandstones and limestones with regards to porosity, permeability rock compressibility, and electrical properties.

In general, this review showed that the Voltaian Basin sedimentary rocks have not been studied much for their hydrocarbon prospectivity. Some geologists and researchers have studied the possible source of rocks in the basin (provenance) and depositional environments and the findings can be a basis for further work to be carried out to clearly define the presence of hydrocarbons and the feasibility of a petroleum exploration work. Conclusively, more studies should be conducted on the basin on the possible source and reservoir rocks to be able to define hydrocarbon prospectivity.

Declaration of Competing Interest

The authors declare no competing interests

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