

Uranium Occurrences and Exploration Potential of Nigeria

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Abstract

Uranium is a naturally-occurring radioactive element that is used mainly to generate nuclear power to produce relatively cheap electricity. Several developing countries have strived to acquire and utilize nuclear technology, as well as own the needed uranium raw materials. Although uranium can be found in trace amounts almost everywhere on the Earth's surface, economically recoverable concentrations as ore deposits are limited to a few geological environments. Out of more than 20 countries that mine uranium ore worldwide, only five countries account for over half of world's annual production, and 75% of such production is derived from sediment hosted and unconformity related deposits. Since the 1970s, Nigeria has aspired to find viable uranium deposits within its borders, particularly after vast deposits of uranium were discovered in the neighbouring country of Niger Republic in the 1960s. Despite Nigeria's supposed uranium mineralization potential, only a few occurrences have been discovered, none of which are economically viable. The known uranium occurrences are classified into four types based on their geological setting and mode of occurrence: (i) magmatic dissemination in peralkaline granites; (ii) epigenetic fissure-filling veins in granites/rhyolites; (iii) sandstone hosted; and (iv) phosphorite uranium. The sandstone hosted occurrences are of two subtypes; tectono-lithologic and stratiform. A conceptual framework is proposed utilizing several criteria to develop an exploration model that is focused on targets with substantive mineralization potential. Based on this model, it seems only the stratiform sandstone type uranium is considered as having any future exploration potential in Nigeria. Fortunately, the country is endowed with several Cretaceous riftogenic sedimentary basins, such as the Gongola Basin, Yola Basin, Borno Basin, Lower Benue Trough and Mamfe Embayment that contain several hundred meters thick basal arkosic sandstones and conglomerates of fluvial to deltaic origin and formed in rapidly subsiding depocenters overlying crystalline basement rocks. The formation of sandstone uranium deposits is often dependent, among other factors, on the nature, abundance and the reactivity of the uranium reducing agents which include organic materials, biogenic H₂S and hydrocarbons. Several areas that have potential sources for uranium and the conducive environment to precipitate and preserve uranium within the stratigraphic sequence are proposed as potential exploration targets.

Keywords: Uranium occurrences; epigenetic vein-type; sandstone type uranium; ore genesis; exploration targets

INTRODUCTION

Uranium (U) is a naturally-occurring radioactive element that is used both for war (nuclear weapons) and for peaceful purposes. The peaceful applications include use as fuel in nuclear reactors to generate

electrical energy, and in lesser amount, for the production of medical isotopes that are used in radiotherapy and other medical treatments. Several developed and developing countries, the so-called “emerging nuclear energy countries” including Nigeria, aspire for the capacity to use nuclear energy and also possess their own uranium raw materials (World Nuclear Association, 2018). Uranium can be found in trace amounts of 2 to 4 ppm in most places on Earth, but economic concentrations that form mineable ore deposits are few. Out of more than 20 countries that mine uranium ore worldwide, only five countries (Kazakhstan, Australia, Canada, Russia and Niger) account for over half of the world’s annual production, and 75% of such production is derived from sediment hosted and unconformity related deposits Bruneton and Cuney, 2016). Africa is a notable world producer of uranium, contributing about 18% of world production. Among the major producers are Niger, Namibia, Malawi and South Africa. Of considerable relevance to Nigeria, are the vast deposits of uranium in Niger Republic, a neighbouring country in the Sahel to the north, which shares similar geological environments as Nigeria. Niger Republic contributes about 6% of world uranium production.

Uranium was first discovered in Niger Republic in 1956 by the French Bureau de Recherches Geologiques et Minières (BRGM) while prospecting for copper deposits (Fig. 1). The subsequent exploration program was taken over by the French Atomic Energy Commission (CEA) which initiated follow-up and systematic exploration between 1960 and 1968 that led to the discovery of several uranium deposits. These mineral deposits including those at Arlit, Akouta and Azerlik produce about 3000 tons of uranium annually from what is regarded as Africa’s highest-grade uranium ores, ranging from 0.2% to 0.6% with average of 0.4%U (Kinnard et al, 2016; Pagel et al; 2005). Uranium deposits occur exclusively within sandstones in Late Paleozoic and Early Mesozoic continental sedimentary basins in the western part of the country (Fig. 1). The deposition of uranium-bearing sedimentary rocks was controlled by repeated tectonic movements along ancient N-S trending lineaments that created uplifted blocks (horsts) and sediment-filled basin (Bowden et al, 1981) ((Fig. 2). Uranium mineralization appears as tabular deposits that are irregular, elongate or lenticular, and parallel to the depositional trend of the host arenites, with local roll front structures (Pagel et al, 2005) Deposits occur from surface to subsurface depths of over 250 feet.

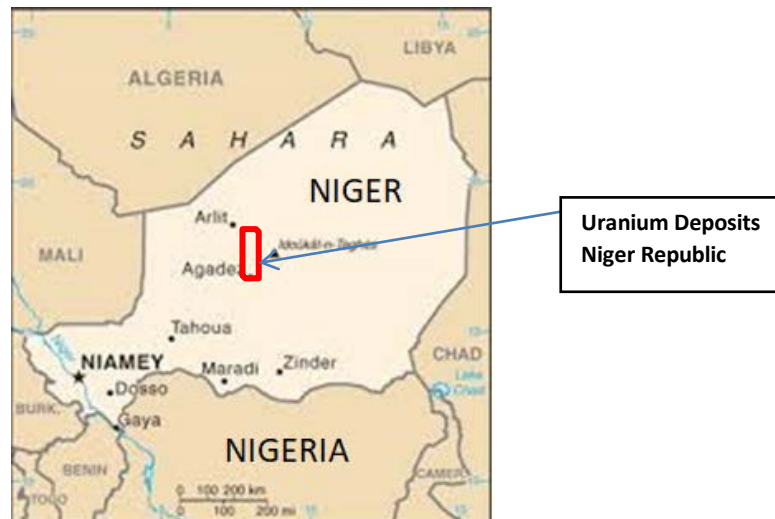


Figure 1: Geographical location of Nigeria and Niger Republic

Nigeria shares similar geological characteristics as Niger Republic, but only a few occurrences of uranium have been reported in Nigeria, and relatively little is known about their subsurface geological occurrence and origin. This paper presents a review and synthesis of existing knowledge on uranium mineralization in Nigeria with the objective of developing a genetic model and conceptual framework that can be useful for future uranium exploration in Nigeria. The author utilizes his substantive research work and knowledge of mineral deposits and metallogeny of Nigeria (Olade, 1976, 1980, 1981, 1964), coupled with field experience in prospecting and exploration for uranium deposits in northwest Canada (Olade, 1972; Olade and Goodfellow, 1979).



Figure 2: Tabular sandstone-type Uranium deposits, Niger Republic

HISTORY OF URANIUM EXPLORATION IN NIGERIA

Since the 1970s, Federal Government of Nigeria had shown special interest in the search for uranium resources as raw material for the development of a potential nuclear energy program. Furthermore, the discovery of extensive uranium deposits in neighbouring Niger Republic in the 60s was also a contributing factor. Uranium exploration began in 1973 when the then Geological Survey Department (GSD) commissioned aerial radiometric surveys that covered large areas of the country at a nominal spacing of about 2 km. The areas covered were: (i) the Middle Benue Trough and the adjoining regions. (ii) Ugep in Cross River State, (iii) Niger/Benue Confluence (Kogi State) (iv) Jos Plateau and surrounding areas; and (v) Sokoto and Dange areas (Nwegbu, 2014). The survey which was completed in 1976 identified some anomalies of considerable interest. In 1974, the GSD investigated and delineated the uraniferous pyrochlore in the peralkaline granites of Ririwai Hills in Kano State and Kigom in Plateau State. The Nigerian Mining Corporation (NMC) was established in 1972 by Decree number 30, which empowered the parastatal to 'explore, prospect for, and mine all minerals, except coal and petroleum'. NMC assumed the responsibilities for preliminary uranium prospecting and geological mapping of the targeted areas until the Nigeria Uranium Mining Company (NUMCO) was created in 1979 (out of NMC).

NUMCO was established as a public/private partnership with the French company *Total Compagnie Minière* (TOTAL) which owned 40% of the shares as a technical partner, with the mandate to prospect, explore and develop uranium deposits in Nigeria. NUMCO with initial collaboration with NMC carried out uranium exploration involving ground radiometric and hydrogeochemical surveys and geological mapping that covered more than 100,000 km² mainly in northeastern Nigeria (Adamawa, Taraba and Bauchi State) near the border with Cameroun Republic. After some years of detailed subsurface investigations involving drilling, logging and chemical analyses at the Mika, Ghumchu, Zona and Mona Lope prospects, only about 200 tons of uranium ore averaging about 0.2%U were demarcated (NUMCO, 1983, 1986). (The author was privileged with knowledge of these activities while supervising of PhD research work on this area at the University of Ibadan) (Ojo, 1982). Due to the disappointing results of the exploration program, funds for further exploration 'dried up' leading to the demise of NUMCO's partnership with the French company. NUMCO was disbanded in 1989, and its assets finally liquidated in 1996. Meanwhile during the transition in 1993, the Federal Government transferred the responsibilities of NUMCO to the Nigerian Geological Survey Agency (NGSA).

In 2003, efforts for uranium exploration were revived, and the NGSA commissioned additional aerial radiometric survey using high precision devices to cover a few priority areas to enhance and complement the earlier exploration activities, particularly in the Upper and Lower Benue Trough (Arisekola et al, 2017). On October 17, 2005, the News Agency of Nigeria, citing a report released by the Ministry of Solid Minerals and Development reported that uranium deposits of "great value" had been discovered in six Nigerian states (Cross River, Adamawa, Taraba, Plateau, Bauchi and Kano) by the British Geological Survey team that helped organize follow-up field activities,, but no details were given (WISE, 2019). In 2006, the (moribund) Nigerian Atomic Energy Commission (NAEC), which was first established in 1976 by legislation, was reactivated and charged with responsibilities that includes "prospecting for and mining radioactive deposits". In March 2009, the Federal Government signed a cooperative agreement with Russia that provided for technical assistance in uranium exploration and

mining. A further broad agreement in June 2009 envisaged the construction of a Russian power reactor and a new research reactor. In July 2011 Russia's Rosatom State Nuclear Energy Corporation and NAEC finalized a draft intergovernmental agreement to cooperate on the design, construction, operation, commissioning of an initial nuclear power plant (World Nuclear Association, 2019).

Since the detailed exploration activities of NUMCO ended in the late 80s, relatively little uranium exploration has taken place in Nigeria, apart from reports of 'discoveries' by the British and Chinese "explorers" in 2005 and 2007 respectively with no follow-up reports or investigations (Tsang et al, 2018). The NAEC has delegated its efforts in geological exploration to the NGSA, but there is little or no information about ongoing investigations. Recently, the thrust of the NAEC exploration strategy has been to encourage both the local and foreign private sector companies and investors to participate in the prospecting and exploration for uranium in Nigeria (Karniliyus and Ekedegwa, 2018). These efforts coupled with recent attempts to revitalize the minerals and mining sector, have encouraged some local private companies working in partnership with foreign partners from China, Korea and Australia to acquire exploration and mining leases for uranium, which hopefully will encourage more detailed uranium exploration.

GEOLOGICAL SETTING

Nigeria lays within the Pan-African mobile belt of West Africa, sandwiched between the West African Craton to the west, the Trans-Saharan Metacraton to the east and the Tuareg Shield to the north (Fig. 3). About half of the entire landmass of Nigeria is underlain by Precambrian crystalline rocks while the remaining half is covered by sedimentary and volcanic rocks of Cretaceous to Quaternary age (Fig. 4). The major rock groups are: (1) Precambrian igneous and metamorphic rocks, (2) Jurassic Younger Granites, (3) Cretaceous to Quaternary sedimentary rocks, and (4) Tertiary to Recent volcanic rocks (Oyawaye, 1972; Rahaman, 1976).

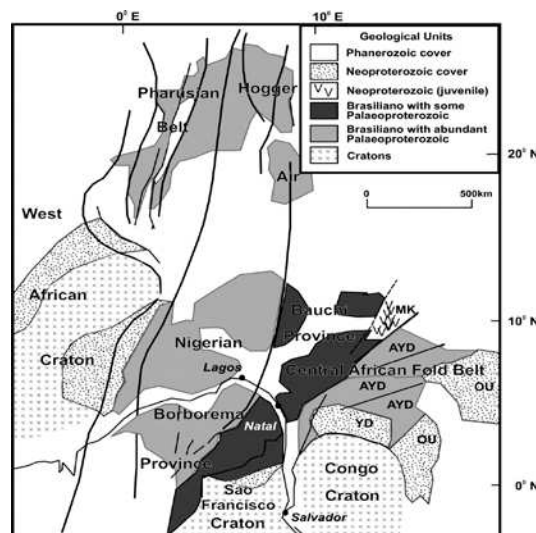


Figure 3: Major tectonic elements in the West African basement complex

The Precambrian basement rocks are composed of reactivated high-grade gneisses and infolded, low-grade supracrustal schist belts intruded by synorogenic to post-orogenic granitic rocks and pegmatites of the Older Granite suite, aged 600 - 450 Ma. These rocks are well exposed in four major areas of the country: the north-central, southwestern, southeastern and northeastern regions (Fig. 4). The Jurassic Younger Granites are high-level intrusives confined to the Jos Plateau and surroundings in north-central Nigeria. More than 50 ring complexes are known in Nigeria, and the dominant rock types are peraluminous biotite granites, peralkaline riebeckite-arfvedsonite granites and metaluminous hornblende and fayalite bearing granites. Other minor rock types include syenites, rhyolites, trachytes, gabbros and dolerites (Bowden, 1970).

Cretaceous to Quaternary sedimentary rocks (with volcanics) occur in sedimentary basins located along the marginal areas of the country; in the southwest, southeast, south-central, northwest and northeast regions (Fig. 4). They were formed during the opening of the Atlantic Ocean in the Early Cretaceous and subsequent depositional activities. These sedimentary basins include the Lower, Middle and Upper Benue Trough, East Dahomey Basin, Bida (Nupe) Basin, Anambra Basin, Borno Basin and Sokoto Basin. Several thousand meters (2000-6000m) of continental, deltaic and shallow marine sediments accumulated within these basins. Volcanic activity involving the emplacement of rhyolites and alkali basalts and rhyolite and lamprophyre dikes occurred during the Cretaceous (Olade, 1978). Tertiary to Recent volcanic rocks of alkaline basaltic composition occur in the Jos Plateau, Biu-Mambilla Plateau and other parts of the Upper Benue Trough and extending along the Cameroonian Volcanic Line (Benkhelil, 1987).

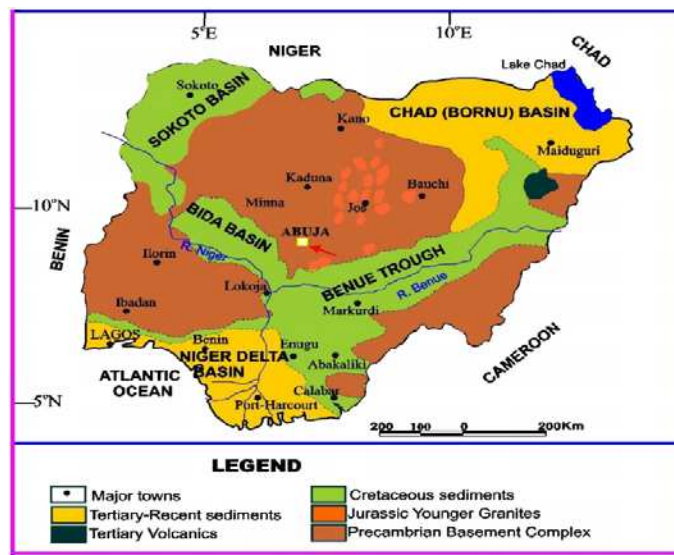


Figure 4: Simplified geological map of Nigeria

Tectonic evolution and structural deformation within the crystalline basement and the sedimentary cover rocks have been described by Rahman (1976) Nwachukwu (1972) and Benkhelil (1989). The Precambrian rocks were subjected to several cycles of orogenic activity of which the last and most pervasive was the Pan-African Orogeny (600 my), that involved folding, faulting and granite plutonism (Oyinloye, 2006). Prominent NE-SW trending folds and NNE-SSW trending transcurrent fault systems that are several hundred kilometers long are typical of the basement complex of the Nigeria-Benin shield, probably extending further north through the Niger Republic into the Hoggar massif (Fig. 3). Unlike the Niger Republic where there was sedimentation starting from the Mid-Paleozoic (Carboniferous and Permian) through the Mesozoic, the Nigeria-Benin Shield remained a zone of regional uplift without sedimentary deposition until the Late Mesozoic (Cretaceous). In the uplifted shield areas, there were doming, rifting, magmatism and sedimentation accompanying the final opening of the Atlantic Ocean during the Cretaceous along a triple-plate junction (Grant, 1971; Olade, 1975; 1980)...

The Triassic-Jurassic emplacement of high level, anorogenic, alkaline intrusive complexes of the Younger Granites was connected with mantle-plume activity (Bowden, 1970) while Cretaceous sedimentation was accompanied in the Benue Trough by initial magmatic activity involving the emplacement of alkali basalts and lamprophyres in the south (Benkhelil, 1989) and alkaline rhyolites of the Burashika Group and alkaline basalts in the Upper Benue dated 147 ± 7 Ma and 104 ± 5 Ma respectively. (Benkhelil, 1987; Coloun et al, 1996), Magmatism was mainly confined to the fault zones, except in the Abakaliki area where intrusive activity was widespread. The accumulated Early Cretaceous sediments were subjected to two phases of deformation, the first was in Late Albion - Cenomanian and characterized by NE-SW trending shear zones (Ojo, 1984), while the second deformation was a more pervasive Santonian tectonic event resulting from intense compressional stresses that generated

numerous NE-SW trending folds, faults and fracture systems, many of which are believed to be reactivated basement faults (Benkhelil, 1987; Ogunleye and Okujeni, 1992).

OCCURRENCE OF URANIUM IN NATURE

Uranium occurs in nature in a wide variety of geological environments as traces, or as primary and secondary minerals. Uranium is found in two main oxidation states, U^{4+} and U^{6+} . The U^{4+} state is stable in reducing conditions, weakly soluble in most geological conditions, and is the main valence occurring in uranium ore minerals. However, because uranium is also a very mobile element, it is easily oxidized to form uranium oxides and hydroxides that may be concentrated in situ or remobilized into secondary environments, such as fault zones, or as replacement of primary structures or textures (Dahlkamp, 1993; Bruneton and Cuney, 2016). The average concentration of uranium in rocks is an average of 3 ppm, while the cut-off grade for most minable deposits is set at 1000 ppm (0.1%), but can be as low as 500 ppm (0.05%) depending on mining conditions. The most common primary uranium mineral is uraninite or pitchblende (UO_2), although other minerals such as coffinite and brannerite do occur (Table 1). There are several secondary uranium minerals that are usually brilliantly colored, including autunite, carnotite, torbenite and uranophane. Mineralized pegmatites and leucogranites often contain a suite of minerals in which uranium is combined with rare earths (REEs) such as betafite and davidite (Kinnaird, et al, 2016).

Uranium deposits are formed by a variety of geological processes, ranging from magmatic fractionation at great depths within the crust/mantle to evaporation at the Earth's surface. The International Atomic Energy Agency (IAEA) has classified uranium deposits into fifteen major types based on their geological setting and orebody morphology (IAEA, 2009). However, there are about six most prominent groups (i) unconformity-related deposits, (ii) sandstone-type deposits, (iii) breccia-type deposits, (iv) paleo-placer deposits, (v) vein-type deposits (vi) intrusive hosted deposits and (vi) uranium in phosphate rocks or phosphorite. Uranium is mined in some 20 countries worldwide, but 51% of world production comes from five countries: Canada, Australia, Russia, Kazakhstan and Niger (World Nuclear Association, 2019). In Africa, the leading producers are: Niger Republic (sandstone type), Namibia (intrusive rock), South Africa (paleo-placer) and Malawi (sandstone-type). Sandstone uranium deposits account for approximately 30% of annual global production, while unconformity related deposits constitute about 45% (Brunsten and Cuney, 2016).

Table.1: List of Common Uranium Minerals

URANIUM MINERALS	
Primary Uranium Minerals	
Name	Chemical Formula
Uraninite or Pitchblende	UO_2
Coffinite	$(U_{4+}, Th)(SiO_4)_{1-x}(OH)_4$
Brannerite	UTi_2O_6
Davidite	$(REE)(Y, U)(Ti, Fe^{3+})_{20}O_{38}$
Secondary Uranium Minerals	
Name	Chemical Formula
Autunite/Meta-autunite	$Ca(UO_2)_2(PO_4)_2 \cdot 11H_2O$
Carnotite	$K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$
Kasolite	$Pb(UO_2)(SiO_4) \cdot (H_2O)$
Saleeite	$Mg(UO_2)_2(PO_4)_2 \cdot 10 H_2O$
Torbenite	$Cu(UO_2)_2(PO_4)_2 \cdot 12 H_2O$
Tyuyamunite	$Ca(UO_2)_2(VO_4)_2 \cdot 5-8 H_2O$
Uranocircite	$Ba(UO_2)_2(PO_4)_2 \cdot 10 H_2O$
Uranophane	$Ca(UO_2)_2(HSiO_4)_2 \cdot 5 H_2O$

URANIUM MINERALIZATION IN NIGERIA

Uranium occurrences in Nigeria are located mainly within igneous and sedimentary rocks in six States: Kano, Plateau, Bauchi, Adamawa, Taraba and Cross River (Table 2). The area with most occurrences is in the Gongola Basin of the Upper Benue Trough (NE Nigeria) at Gubrunde, Kanawa, Ghumchi, Mika and Monkin-Maza which are epigenetic veins localized within brecciated granites and rhyolites, while at Zona, Dali and Mayo Lope, mineralization is hosted by Cretaceous sandstones (Funtua, 1995; Saleh, 2013). In southeastern Nigeria, within the Lower Benue Trough around Idomi-Ugep in Cross River State, uranium is reported to have been discovered in sandstones. Other minor showings are found in the Kaffo Valley (Ririwai Complex) in Kano State and Kigom (Plateau State) in the Younger Granite Province of central Nigeria (Bowden et al, 1981). Some Nigerian phosphates are slightly radioactive, such as at Ifo, Ogun State and Dange/Sokoto in Sokoto State, but the uranium levels are very low (<70 ppm) (Obaje, 2013).

Table.2: Location and Type of Uranium Deposits in Nigeria

S/ N	Location	State	Type of Deposit	Uranium Concentration
1	Kaffo Valley	Kano	Magmatic	0.006 - 0.015% ¹
2	Kigom	Plateau	Magmatic	<0.002% ²
3	Mika	Taraba	Vein type	0.03 - 0.12%U ³
4	Ghumchi	Bauchi	Vein type	0.03 - 0.20%U ³
4	Kanawa	Adamawa	Vein type	<0.002% ⁴
5	Gubrunde	Bauchi	Vein type	-
6	Mokin-Maza	Taraba	Vein type	-
7	Zona	Taraba	Sandstone Hosted	0.001 -0.013% ⁵
8	Dali	Taraba	Sandstone Hosted	-
9	Mayo Lope	Taraba	Sandstone Type	0.18 – 0.25% ⁶
10	Idomi-Ugep	Ross River	Sandstone Type	-
11	Ifo	Ogun	Phosphorite	0.002% ⁷
12	Dange	Sokoto	Phosphorite	0.007% ⁸

(Sources: ¹ Bowden et al, 1981; ² Omada, 2003; ³ Nwegbu, 2014; ⁴ Okujeni and Funtua, 1994; ⁵ Ogunleye and Okujeni, 1992;; ⁶ NUMCO, 1983; ⁷ Obaje et al, 2014; ⁸ Adesanwo et al. 2010)

Uranium occurrences in Nigeria can be classified into four types:

1. Dissemination in peralkaline granites
2. Vein-type mineralization in brecciated granites and rhyolites
3. Sandstone-hosted deposits (tectono-lithologic and stratiform subtypes)
4. Phosphorite (rock phosphate) uranium

1. Uranium in Peralkaline Granites

The Jurassic alkaline intrusive complexes (Younger Granites) of central Nigeria (Fig. 5) represent a distinct metallogenic province characterized by magmatic disseminations of columbite and pyrochlore, and lode deposits of cassiterite, wolframite, sphalerite and molybdenite (Bowden and Kinnard, 1978; Olade, 1980, 1981; Kinnard, 1984). Peralkaline granites within some of the intrusive complexes are associated with strong radiometric anomalies attributed to the presence of U and Th in accessory minerals (Nwegbu, 2014, Kinnaird and Nex, 2016). The most notable occurrence is in the albitized peralkaline granite of Kaffo Valley in the Ririwai Complex, Kano State (Fig. 5). Uranium levels in the albitized arfvedsonite granite (Fig. 6) ranges from 60 -145 ppm, while Th concentration is as high as 350 ppm (Bowden et al, 1981). The associated Ririwai albitized biotite granite that is host to Sn-W-Zn mineralization also shows elevated U values, ranging from 30 - 81 ppm (Bowden et al, 1981). The other intrusive body associated with radiometric anomaly is the peralkaline granite of the Kigom Complex located about 40 km southwest of Jos in Plateau State (Fig. 5). The host rock is the arfvedsonite granite which is not intensely albitized. Uranium values range from 4 - 19 ppm, with Th levels of 21 - 34 ppm. The molybdenite mineralization in the Kigom lode is found within a different body of riebeckite biotite granite (Fig. 7) (Omada, 2003).

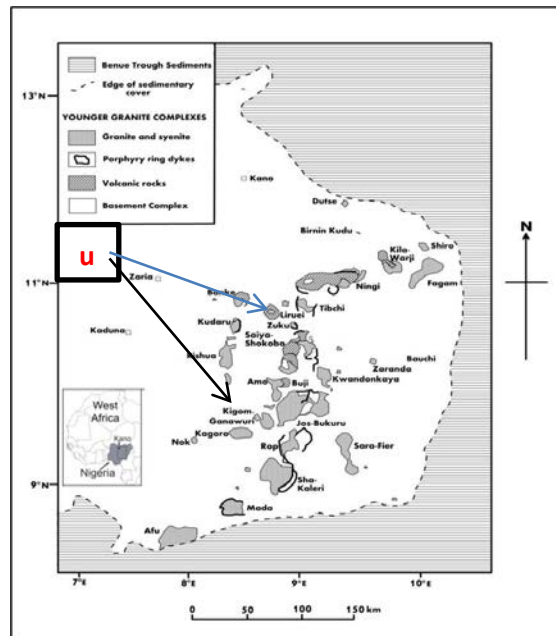


Figure 5: Map of the Younger Granites Showing Uranium Occurrences

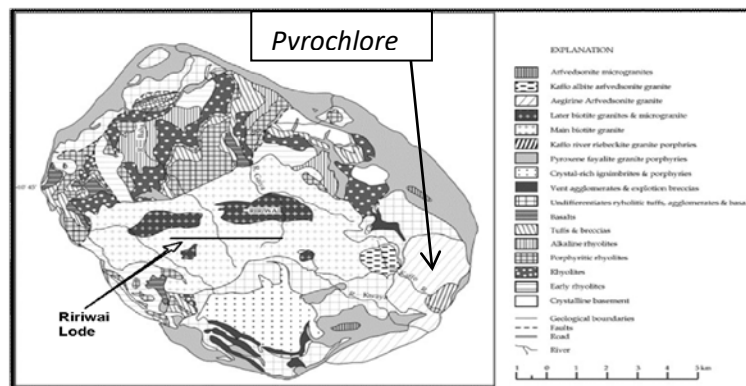


Figure.6: Geology of the Ririwai Complex (Modified after Kinnard, 1985)

The uranium bearing mineral in the Kaffo Valley has been identified as pyrochlore (Ca, Na, Ce) (Nb, Ti, Ta) $2(\text{O, OH, F})$ - a niobium oxide that typically contains small amounts of Th and U in lattice substitution. Beer (1952) in a partial analyses of the pyrochlore showed that it contained up to 4.3% UO_2 , while a microprobe analysis indicated up to 7% U_3O_8 (Ogunleye et al, 2006). The uranpyrochlore occurs as an accessory mineral disseminated within the intensely albitized peralkaline granite (albite-arfvedsonite granite) (Bowden, 1985). The biotite granite at the core of the Ririwai intrusive complex is also albitized and mineralized with disseminated columbite, and vein-type cassiterite, wolframite and sphalerite (Olade and Ekwere, 1981; Kinnard, 1985). A rare occurrence of pyrochlore as accessory mineral in the albitized biotite granite around the Ririwai lode was reported by Ixer et al (1987) as containing up to 17% UO_2 . In terms of economic potential, the disseminated pyrochlore appears in discontinuous patches covering only a few hundred square meters in dimension within the southeastern margin of the granite cupola (Kinnard and Nex, 2016). The low uranium concentration in the peralkaline granite coupled with the dispersed nature of pyrochlore, and confinement to shallow depth make hard rock extraction of uranium unprofitable. In the Kigom complex, the arfvedsonite granite is not intensely albitized which may explain the relatively low uranium concentration (< 20 ppm), although the Th values

are as high as 45 ppm. Thorite was identified as an accessory mineral in the arfvedsonite granite which may partly account for the elevated radioactivity (Omada et al, 2003).

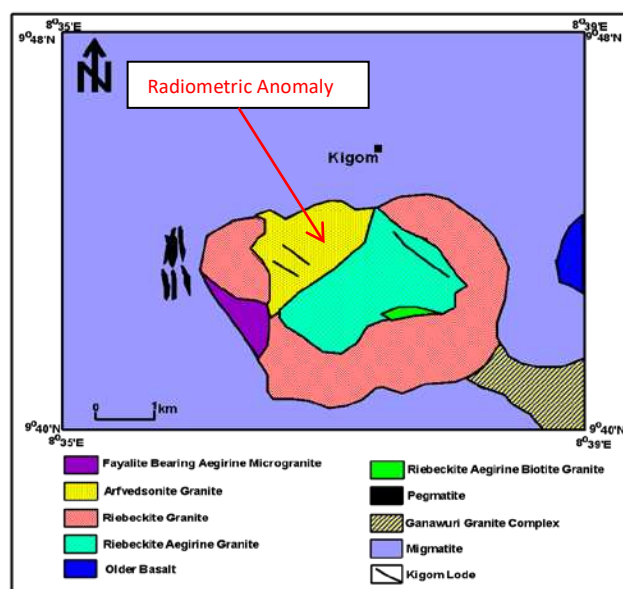


Figure 7: Geology of the Kigom Complex (After Omada et al, 2003)

2. Vein-type Uranium Mineralization in Granites/Rhyolites

Vein-type uranium mineralization occurs within shear zones and fractures in granites and rhyolites of the Gubrunde Horst in the Upper Benue Trough, northeastern Nigeria (Figure 8). Three uranium prospects were discovered and explored by the Nigerian Uranium Mining Company (NUMCO) in the 80s at Mika, Ghumchi and Kanawa (Funtua et al, 1992). Other vein occurrences were subsequently found at Gubrunde and Mokin-Maza in Taraba State (Saleh, 2013; Haruna et al, 2017). Epigenetic vein-type uranium minerals in the Bima Sandstone at Zona and Dali are described elsewhere as sandstone-hosted mineralization (Table 2). The geological setting of the vein-type occurrences is characterized by fault-bounded uplifted blocks of Precambrian basement rocks surrounded by rifted sub-basins within the middle Gongola Basin, Upper Benue Trough. The most prominent is the Gubrunde Horst - a large uplifted area of crystalline massifs produced by block faulting between two series of NE-SW trending rejuvenated basement border faults. It is bounded to the north by basalts of the Biu Plateau and to the west by Cretaceous sediments (Fig. 8) (Funtua et al. 1992; Saleh, 2013); The rocks in Gubrunde block are rejuvenated Archean migmatites and gneisses, intruded by Pan-African Older Granites of porphyritic and medium-grained varieties (Suh and Dada, 1997).

Early Cretaceous to Tertiary igneous activity gave rise to alkaline rhyolite lavas and dykes, lamprophyres, phonolite and alkaline basalts of the Burashika Group dated as 147-105 my old (Ojo, 1982; Benkheilil, 1987)). Uranium mineralized veins are the fissure-filling type in which the uranium minerals, mostly pitchblende, coffinite and autunite occupy fractures and brecciated/shear zones in a variety of host rocks particularly Pan-African porphyritic granites, rhyolites and Cretaceous sandstones, rarely straying into the surrounding basement gneisses. The major occurrences are at, Mika, Ghumchi, Gubrunde, and Kanawa which are described in more detail below (Funtua et al, 1992; Saleh 2013). The age of mineralization is post-Albian but pre-Turonian, and may be related to tectonic activity and magmatism that occurred in that geological interval (Ojo, 1984; Benkheilil, 1987).

Mika Prospect: The Mika uranium occurrence located in Mika, in Taraba State has been described in some detail by Funtua (1995), Suh and Dada (1998) and Tsang et al (2018). The uranium veins and disseminations form two lodes localized within brecciated medium-grained and porphyritic granites of the Older Granite suite (Fig. 9). They are intruded in places by Jurassic-Cretaceous rhyolites (Fig. 8).

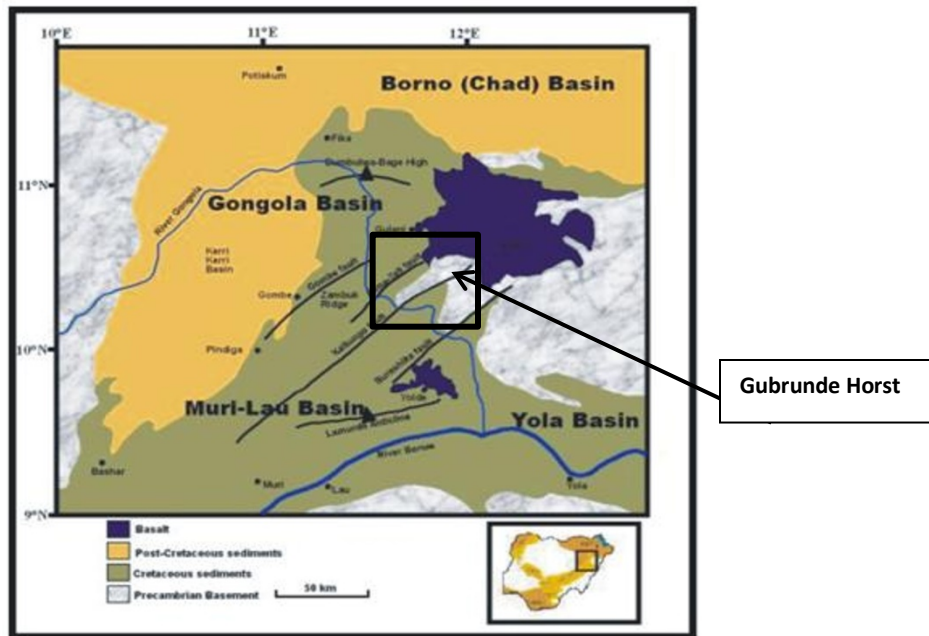


Figure 8: Location of the Gubrunde horst, Gongola Basin, Upper Benue

Mineralization is structurally controlled, and associated with NE-SW trending faults and fractures. There are two major types of mineralization; *primary* mineralization at depth that occurs as disseminated or vein-type pitchblende, and *secondary* (supergene) mineralization occurring smears on fractures and brecciated zones near the surface. Pitchblende is the primary ore mineral while the secondary minerals are mainly autunite and coffinite which are products of surface leaching of pitchblende (Funtua and Okujeni, 1996). Detailed exploration by NUMCO identified two major lodes at Mika in which the main lode in the west extends for about 10m, striking NNW-SSE and gently dipping, while the second lode to the east of similar orientation extends for about 8 m (Tsang et al (2018), Trenching along the lodes have exposed quartz-pitchblende veins and veinlets accompanied by microcrystalline quartz and goethite.

Hydrothermal alteration of the mineralized host rocks is widespread and involves sericitization, kaolinization, silicification and hematization (Funtua, 1995). Brecciated zones in the granites are most often silicified. Isotopic dating of primary pitchblende from Mika indicated U-Pb age of 148 ± 12 Ma for the crystallization (Maurin and Lancelot, 1990). The age of pitchblende mineralization seems synchronous with the Burashika igneous activity, dated as 147 ± 7 Ma (Culoun et al, 1996). NUMCO conducted subsurface drilling at Mika in the 1980s involving 23 boreholes and 435 m of drill cores. The overall ore grade ranged from 0.03% to 0.12%U (Suh and Dada, 1998), and ore reserve was estimated as 52 tons of 0.06%U at 130m cut off of 0.03% (Nwegbu, 2014). After recent exploration activities by a private company at Mika, Tsang et al (2018) suggested that the occurrence is a good uranium prospect but requires more comprehensive subsurface investigation to evaluate its economic potential.

Ghumchi Prospect: The Ghumchi uranium occurrence in Adamawa State is hosted by fine-grained porphyritic granite intruded by lamprophyres along a NW-SE trending mylonitized, sheared and brecciated zone that extends for more than 15km along strike (Fig. 9) (Saleh, 2013). Primary pitchblende and secondary uranium minerals - coffinite and meta-autunite are found in veinlets that occur within the mylonite-foliated granite and breccias. Hydrothermal alteration in the mineralized area is characterized by silicification (quartz-rich) and ferruginization (goethite-rich) zones (Suh and Dada, 1998). The Ghumchi prospect was explored by NUMCO by drilling 65 boreholes and logging 6000 m of drill cores. Uranium concentration varied considerably, with values of up to 2000 ppm (0.2%) but averaging 900 ppm (NUMCO, 1983; Arisekola et al, 2017). The ore reserve estimate was 100 tons of 0.09%U with a cut-off of 0.03%U at 200 m. U-Pb isotopic dating of coffinite at Ghumchi indicated the age of 14 ± 3 Ma for its

crystallization which reflects Neogene mobilization of uranium and formation of secondary minerals (Maurin and Lancelot, 1990).

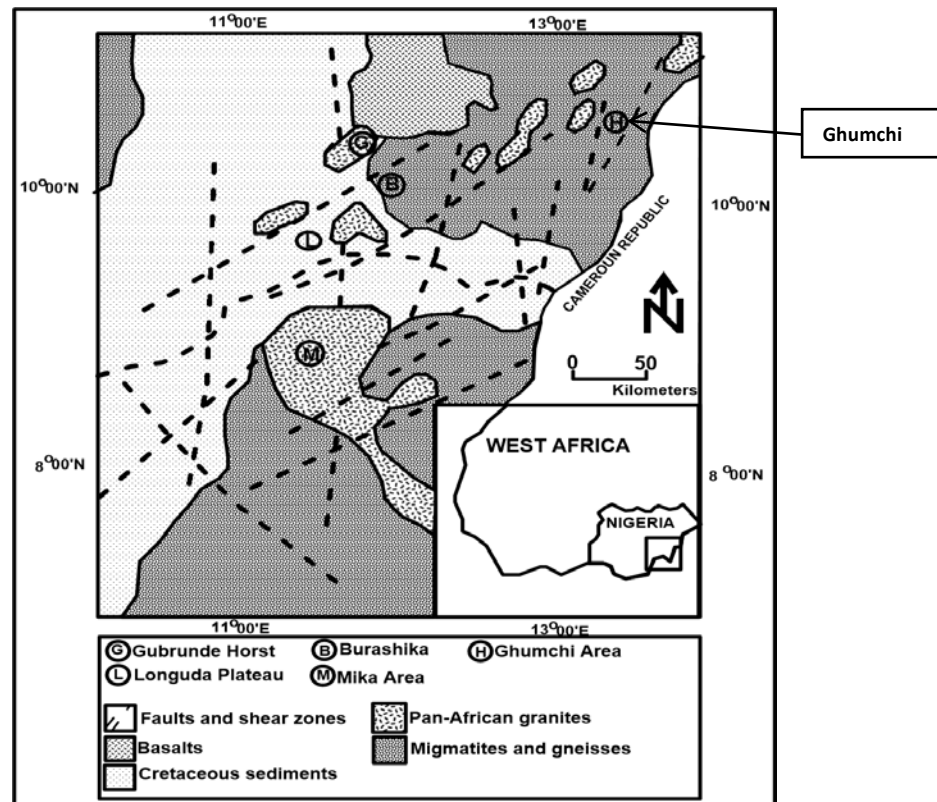


Figure 9: Geology of Mika and Ghumchi Uranium Occurrences (Modified after Tsang et al, 2018)

Kanawa Occurrence: The Kanawa uranium occurrence near Kanawa village is situated almost at the center of the Gubrunde Horst where it is localized by a N-S trending and steeply-dipping shear zone within a brecciated porphyritic granite host rock (Fig.10) where mylonitic rocks at the center of the mineralized zone grade outwards into fault breccias. Intrusive rhyolites that are sometimes mineralized occur along the fault zone (Funtua et al, 1992). Uranium mineralization occurs as veinlets that contain spotty pitchblende and metaautunite. Other secondary uranium minerals are phosphor-uranylite, kasolite with traces of pyrite, galena and chalcopryrite (Funtua et al, 1992).. Hydrothermal alteration is pervasive in the mineralized areas, involving silicification, ferruginization and phyllosilicate alteration of the feldspar into sericite and chlorite (Saleh, 2017). Concentrations of uranium in ferruginized mylonite samples are less than 200 ppm (Okujeni and Funtua, 1994; Saleh, 2017). The extent of the Kanawa mineralization has not been fully evaluated by subsurface drilling, but the surface exposures are spotty and of limited extent.

Gubrunde Occurrence: The Gubrunde occurrence is located at the SW margin of the Gubrunde Horst, north of Gubrunde village (Fig. 10). Uranium is found in pockets and dissemination along a N-S trending shear zone that extends discontinuously for over 4 km between granite and younger rhyolite intrusive (Saleh, 2013; Haruna et al., 2017). The mineralized fractures are sporadic, trending NNE-SSW, but characterized by intense alteration and brecciation. Ore minerals are spotty pitchblende, meta-autunite and coffinite, with traces of galena and chalcopryrite. The Gubrunde mineralization has not been explored by subsurface drilling, and is believed to be of little economic potential.

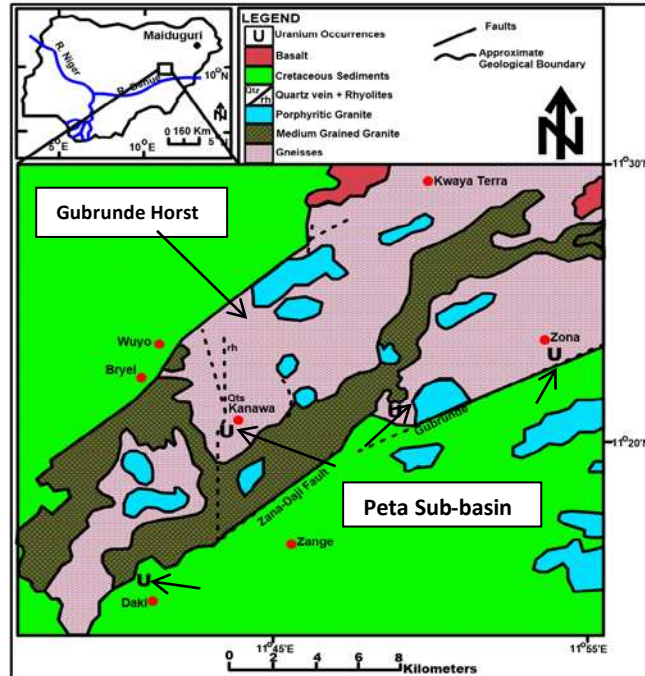


Figure 10: Geological map showing Uranium mineralization, NE Nigeria
(Modified after Ogunleye and Okujeni, 1993)

3. Uranium in Sandstones

Sandstone-hosted uranium occurrences have been reported from two areas in the Benue Trough: (1) in the Cretaceous basal sandstones of the Bima Formation in the Upper Benue Trough, NE Nigeria, and in the basal sandstones and conglomerate of the Asu River Group in the Lower Benue Trough, SE Nigeria. Uranium mineralization in the Upper Benue occurs in the Zona, Deli and Mayo Lope areas while in the Lower Benue Trough, radiometric anomalies and discoveries have been reported in the Idomi/Ugep area of Cross River State. The basal sandstones and conglomerates of both the Bima Formation and Asu River Group are hundreds of meters thick, arkosic in composition, and directly overlie the Precambrian crystalline basement. Although the uranium occurrences are confined to sandstone units, they are of two subtypes: tectono-lithologic (controlled by structural features) and stratiform (parallel to bedding).

Zona Prospect: The Zona uranium prospect is localized within the Bima Sandstone along a NE-SW trending fault zone (Zona-Dali Fault) which lies on the northeastern flank of the Peta Syncline in the Middle Gongola basin of the Upper Benue Trough (Fig. 10). Another center of uranium mineralization can be found along the same fault to the southwest at Dali. The Peta Syncline is a small riftogenic sub-basin, created by block faulting and filled with sediments of the Bima Sandstone. The Zona mineralization has been investigated by several workers (Ogunleye and Okujeni, 1992; Suh et al, 2000; Ogunleye et al; 2004). The host Bima Sandstone is subdivided into three arenaceous members by Suh et al (1998) and described in detail by Haruna et al (2012). The B1 - basal coarse-grained to conglomeratic sandstone; the B2 - medium-grained sandstone with minimal fines; and B3 - fine-grained sandstone with intercalated siltstone and claystones. Uranium is confined to the B2 and B3 brecciated sandstone members, although localization is obviously structurally controlled, at the intersection of a set of NE-SW trending shear zone and a N-S fracture system (Ogunleye and Okujeni, 1992).

Uranium mineralization at Zona appears at the surface as patches in two major locations, each about 500 m² in which uranium minerals are disseminated or in veinlets within brecciated sandstone. Ore minerals are coffinite with some spotty uraninite, and metaautunite, (Suh et al, 2000). Wall rock alteration in the mineralized zone comprises of a silicified zone; a red-brown ferruginized (hematite) zone and a brownish/yellowish-brown ferruginized (goethite) zone. There is evidence of minor kaolinitization of

the arkosic host rock. Geochemical ‘fingerprint’ of the altered rocks is characterized by elevated SiO_2 , Fe, As, Ba and W levels, and depleted alkalis, Zr, Rb and Sr (Ogunleye and Okujeni, 1992). Uranium content of mineralized samples at the surface ranged from 10 to 128 ppm (Ogunleye and Okujeni, 1992). At Dali, the uranium showing occurs along the same Zona-Dali Fault about 30 km southwest of Zona (Fig. 10). Mineralization is also in the Bima Sandstone with spotty uraninite (Dada and Suh, 2006). Not much is known about the occurrence, but it is obviously of low economic potential.

Mayo Lope Prospect: The uranium mineralization at Mayo Lope is situated not far from Zona, and localized within the basal unit of the Bima Sandstone in the Mayo Lope syncline within the Peta sub-basin. The uranium is described as “stratiform” and encountered at depths ranging from 200 to 350m below the land surface (NUMCO, 1983; Nwegbu, 2014; Arisekola et al., 2017). NUMCO drilled a few boreholes at this prospect, and detected uranium concentrations of 0.18% to 0.25%U, with a mean value of 0.2%U (NUMCO, 1983). No additional information was provided on the tonnage, but based on geological indicators, Mayo Lope appears to be sandstone-type uranium mineralization. It deserves more detailed investigation, although the depth of mineral deposition of over 250 m could pose a challenge to potential extraction.

Idomi-Ugep Uranium Discovery: The presence of radiometric anomalies in conglomeratic sandstones in the Lower Benue Trough in Cross River State was reported in the 1970s (Nwegbu, 2014). There are no reports of subsequent ground follow-up investigations, perhaps due to the difficult forest terrain and deep regolithic cover. However, in August 2017, the Cross River State government announced the discovery of substantial uranium deposits by a team of Chinese explorers near Idomi/Ugep in the Yakur LGA and other areas in Yala LGA (Daily Trust, August 23, 2017)(World Nuclear Association, 2019). The host rocks are presumed to be the basal sandstones and conglomerates of the Asu River Formation, extending into the Mamfe embayment. Currently no further details or follow-up investigations have been reported. However, the geological environment is very promising for a sandstone-type uranium mineralization.

4. Phosphorite Uranium

Phosphorite or phosphate rock is a marine sedimentary rock that contains 18-40% P_2O_5 , as well as traces of uranium, ranging from 50 - 200 U ppm, but may reach 3000 ppm (0.3%), such as deposits at Andra Pradesh, India and in the Central African Republic (Kinnaird et al, 2016). The main mineral in the phosphate rock is apatite $\text{Ca}_5(\text{PO}_4)_3(\text{OH}, \text{F}, \text{Cl})$, or fluorapatite ($\text{Ca}_5(\text{PO}_4)_3\text{F}$). Radioactivity in phosphorite originates from trace uranium and its radioactive decay-chain nuclides (Cathcart, 1975). From the 1980s to the mid-1990s, approximately 20% of mined uranium in the United States was a byproduct of phosphate fertilizer production, before decreasing uranium prices made extracting uranium from phosphate rock unprofitable (Kim et al, 2016). Many countries in Africa, including Morocco, Algeria and Egypt produce uranium as a byproduct of phosphate mining.

Phosphate rock occurs within Nigeria’s Cretaceous-Tertiary sedimentary basins, particularly in the Sokoto and East Dahomey Basins. Notable localities are in Sokoto State at Dange, Gidan Bauchi, Illela, Gada and Kalambaina (Ogunleye et al., 2002), within the Paleocene Dange Formation and Dukamaje Formation of the Sokoto Basin. Phosphate also occurs at Ifo and Oja-Odan in Ogun State within the Eocene Oshoshun Formation of the East Dahomey Basin (Reymemt, 1964; Kogbe, 1981). Thickness of the phosphate layers ranges from <1 – 5 m, and the reserves are estimated as 5 million tons in Sokoto deposits and 1 million ton at Ifo, Ogun State (Obaje, 2013). Uranium concentration in Nigerian phosphates ranges from 22 ppm U in Ogun State to 65 ppm in the Sokoto State which compares favorably with 72 ppm U in the Togo phosphate rock (Adesanwo et al, 2010; Obaje et al, 2014). However, ideally, for uranium to be profitably extracted as a byproduct, the concentration should reach at least 300 ppm (0.03%U)... In Morocco where 33 million tons of phosphates are mined annually, it has been difficult to profitably extract the uranium as a byproduct because of its low concentration of 0.025%U.. Consequently, the prospect for extracting uranium from the Nigerian phosphate is nil, because of the small size of the phosphate deposits and their low uranium concentration.

ORE GENESIS

Based on the characteristics of uranium occurrences in Nigeria, they can be classified into three major genetic types: (a) magmatic dissemination; (b) epigenetic fissure-filling veins; and (c) sediment hosted

mineralization. Magmatic dissemination deposits are characterized by the random or uniform scattering of ore minerals in igneous host rocks. Their origin is usually connected with the process of magmatic crystallization and fractionation. The origin of uranium mineralization in the Kaffo Valley and Kigom is similar to that of other peralkaline granites (Olade and Goodfellow, 1979; Cuney, 2014)). During magmatic crystallization-fractionation of peralkaline melts, U and other large, highly-charged and incompatible elements, including, Th, Zr, Nb, Ta and the REE's are not accepted into the structure of rock-forming minerals, and therefore become concentrated in the residual fluids. Such fluids are often rich in alkalis (Na and K) and volatiles (F, Cl, OH) which may enter into late-stage accessory minerals or form specific minerals (Cuney, 2014). Pyrochlore appears along with other refractory minerals such as zircon, xenotime as accessory minerals in the granites with U and Th substituted in the mineral structure.

The mineralized peralkaline granites in Nigeria contain two minerals that are significant components of the host rocks; albite (Na feldspar) and arfvedsonite (Na amphibole). In the Kaffo Valley, the dissemination of pyrochlore is accompanied by widespread albitization (Na metasomatism). The occurrence of fluorite in the mineralized zone may suggest that the U and Th enrichment was probably facilitated by a fluorine-carrying volatile fraction of the granitic magma (Cuney and Friedrich, 1997). Based on the mineral association, it can be surmised that mineralization in substantial quantity can only occur if the ore forming fluid is a highly fractionated peralkaline melt enriched in sodium (Bowden et al., 1981). The lack of economic concentration of pyrochlore at Kaffo Valley may very well reflect the low abundance of uranium in the source area or the residual melt was not highly fractionated enough to accumulate uranium in high concentrations in the granite cupola. Considering the genetic relationship between pyrochlore and albite-arfvedsonite granite, it is apparent that the proportion of this type of granite within the Younger Granite Province is so small that the chances of finding economic concentrations of pyrochlore is extremely low.

The vein-type uranium mineralization is the most common, and confined to fault zones mostly in the area around the middle Gongola Basin where block faulting was associated with emplacement of alkaline volcanic rocks and hypabyssal intrusives. The deposits show similar characteristics but the lack of substantial lateral and vertical extent of the veins suggest they are not deep seated enough, and of relatively low economic potential. The presence of rhyolites and lamprophyres in the mineralized zones has been controversial. Some research workers have suggested that the rhyolites are closely, if not genetically related to the uranium mineralization (Funtua et al., 1992; 1999; Saleh, 2013). But, it is also plausible that the relationship between the two could be fortuitous, that the rhyolite dykes are just occupying the same structural features as the mineralized zones.

The origin of the vein-type uranium has been discussed by several researchers (Funtua et al., 1992; Ogunleye and Okujeni, 1993; Funtua and Okujeni, 1996; Suh et al., 1998; Saleh, 2017; and Tsang et al., 2018). The consensus of opinion is that primary vein-type uranium mineralization in northeastern Nigeria is epigenetic and formed by low-temperature(?) hydrothermal solutions as indicated by the fissure-filling mode of emplacement and the nature of wall rock alteration. The temperature of formation is not known because there is no fluid inclusion study, but evidence from other base metal deposits in the Benue Trough environment may indicate epithermal temperatures of <200°C (Olade and Morton, 1980; Akande et al., 1988). There were probably two phases of mineralization; one involving hydrothermal fluids heated by volcanic activity that formed primary pitchblende and coffinite with traces of chalcopyrite and galena, while the second phase involved the formation of secondary uranium minerals such as autunite, meta-autunite and kasolite by heated meteoric or ground waters through remobilization of primary minerals. The possible sources of uranium include the Jurassic-Cretaceous alkali rhyolites that occur as dykes and lavas within the Upper Benue Trough (Funtua and Okujeni, 1992), and (ii) the Pan-African potassic two-mica granites that are widespread within the crystalline massif and are the most common host rocks (Haruna et al., 2017; Saleh, 2017). Both groups of rocks contain sufficient uranium that could be leached by ore-forming solutions (Cuney, 2014). The volcanic activity could be the direct source of hydrothermal solutions or provided the heat to mobilize deep seated water into potent ore-bearing solutions.

A genetic model is proposed in which hydrothermal solutions of volcanic origin or deep-seated waters mobilized uranium and other elements from rhyolites or granites, and precipitated pitchblende,

coffinite and minor sulfides into fissures created by shearing and brecciation of crystalline rocks along major faults and fracture systems. The ore forming solutions were rich in Si and Fe, producing pervasive silicification, ferruginization and occasional argillization of host rocks. Subsequent remobilization of uranium by meteoric or ground water produced the secondary uranium minerals. U-Pb isotopic dating of ore minerals confirmed the two phases of mineralization (147 Ma and 14 Ma), each coinciding with peak periods of Cretaceous and Tertiary volcanic activity in the Benue Trough. Pb/Pb data on galena associated with the primary minerals provide an isotopic composition comparable to those of alkaline volcanic rocks (Maurin and Lancelot, 1990).

The sandstone-hosted uranium occurrences at Zona and Dali are found in sandstones along shear zones of a major fault system; hence they are classified as tectono-lithologic (IAEA, 2009). Their origin is probably similar to the vein type mineralization in crystalline rocks, although the uranium could originate from the sandstone host rock as suggested by Haruna et al (2012). On the other hand, the uranium could emanate from other sources and concentrated along the fault zone within the permeable Bima Sandstone. The latter interpretation is consistent with the fact that uranium is found mainly within the well-sorted, uniformly textured but more fractured upper members, and not the poorly sorted but less permeable basal conglomeratic unit of the Bima Sandstone. The uranium occurrence at Mayo Lope appears stratiform and different from the Zona deposit. It is of considerable interest, and may represent a sandstone-type uranium mineralization similar to those in the Niger Republic (Pagel et al, 2005). In addition, it is probable that the uranium discovery in the Idomi-Ugep area of the Lower Benue Trough is a product of similar tectonic, stratigraphic and lithologic environments. Such uranium in basal sandstones and conglomerates could be formed by leaching from the underlying Precambrian granites and gneisses during weathering, and subsequent precipitation in the sandstones during deposition.

URANIUM EXPLORATION POTENTIAL

The search for uranium deposits in Nigeria had for long, been a priority of the Federal Government. It is believed that the ownership of such resources and the acquisition of appropriate nuclear technology can assist the country in generating cheap nuclear power for electricity production despite the country's petroleum wealth. One ton of uranium can produce as much energy as 16,000 tons of coal or 8000 barrels of oil (Wikipedia). In 2009, Nigeria signed a cooperative agreement with Russia that includes assistance with the exploration and mining of uranium, and transfer of nuclear technology, including construction of a Russian power reactor and a new research reactor (World Nuclear Association, 2013). Initial efforts in the exploration for uranium in the 1970s by the GSD focused on the alkaline granites of the Jos Plateau and surroundings areas. This was followed in the 80s by NUMCO's discovery and exploration of the uranium-bearing veins in northeastern Nigeria which ended up in a failure to find economically viable deposits. It is quite apparent that uranium in commercial quantities does not exist in both the intrusive-hosted and vein type mineralization in Nigeria, and exploration efforts need to focus on other geological environments and targets.

Conceptual Framework for Exploration

According to Kyser (2016), the exploration for uranium deposits can be quite complicated because it involves the application of various tools that require the exploration team to be knowledgeable in the techniques that need to be used, including geologic mapping, remote sensing, geophysics, and geochemistry, as well as the metallogeny of the area, historical exploration results, and ore deposit models that promote the development of an effective exploration strategy. To this end, it is pertinent to develop appropriate conceptual framework for selecting target areas with the best uranium mineralization potential. A review of current world supply of uranium according to deposit types (IAEA, 2016) shows that among the 15 types of deposits, almost all economic (minable) uranium deposits that exist, come from just two types: the *unconformity-related* and *sandstone-type* uranium deposits which constitute over 75% of current world production (Fig 9) (Bruneton and Cuney, 2016). Consequently, for the purpose of realistic exploration strategy, these are just the two types of deposits that should be the focus of uranium exploration in Nigeria. However, for unknown reasons, the unconformity-related uranium deposits (related to an unconformable contact separating crystalline basement from an overlying thick sedimentary sequence) are confined mostly to the Proterozoic Era, whereas sandstone deposits are found throughout geological time (IAEA, 2009; Bruneton and Cuney, 2016). They occur in clastic sedimentary rocks, mostly

medium to coarse grained immature sandstones and conglomerates, deposited in a continental fluvial or deltaic sedimentary environments overlying crystalline basement rocks (World Nuclear Congress, 2018).

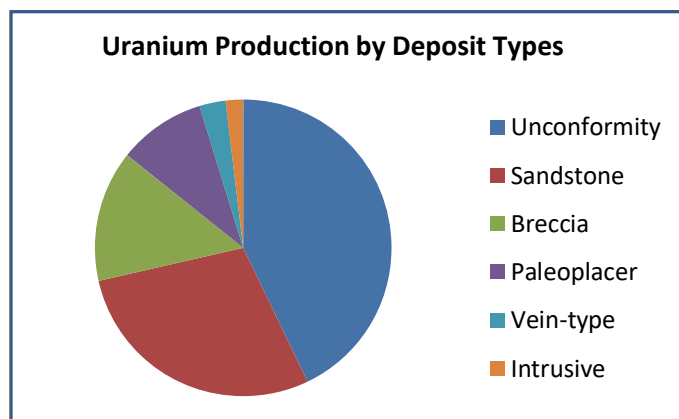


Figure 11: Uranium production by deposit types (2016)

In Nigeria, Cretaceous sedimentary basins contain several thousand meters of sediments located with few exceptions, within fault-bounded depocenters of which the most prominent are the Benue Trough, Bida (Nupe) Basin and Borno Basin (Nigeria's portion of the Chad Basin) (Fig. 2). The stratigraphic sequences are characterized by basal arkosic sandstones and conglomerates (with intercalated shale horizons) of substantial thickness overlying the Precambrian basement complex. In a review of the geology of uranium deposits in Niger Republic, Bowden et al (1981) noted that, if sedimentary uranium deposits occur in Nigeria, the most likely horizons are in such Cretaceous continental sediments of the Bima Sandstone in the Benue Valley. Kinnard and Nex (2016) also mentioned that there is considerable potential in Nigeria for sandstone uranium deposits to occur at the contact between the basement complex and uranium-bearing cover rocks. Olade (1980) discussed the metallogeny of intracontinental rifts and aulacogens, and espoused the potential of riftogenic basins such as the Benue Trough to accumulate uranium and base metal deposits. Several examples of sandstone-type uranium deposits in rift basins have been described, including the Karoo Basin, South Africa, (Turner, 1985), Ordos Basin in China (Jin et al, 2020) and the East Arm of Great Slave Lake (aulacogen) in Northwest Territories Canada (Olade, 1972).

The search for viable uranium deposits in Nigeria should focus on areas in the Cretaceous sedimentary basins where uranium could accumulate in the continental basal sandstones and preserved from subsequent marine transgression. Such areas offer the best prospect within the known tectonic, stratigraphic and lithologic environments in particular, within the Benue Trough and Bornu Basin (northern extension of Benue Trough), uranium could be leached from the Precambrian crystalline rocks and Jurassic alkaline intrusive rocks and volcanics, and precipitated within the basal sandstones of the Cretaceous Bima Sandstone in the Upper Benue and Bornu Basin, and in similar rocks of the Asu River Group and its equivalent Mamfe and Awi Formations in the Lower Benue Trough (Petters, 1978; Bassey et al, 2013). However, it is pertinent to note that the formation of sandstone uranium deposits may depend, amongst other factors, on the nature and abundance and the reactive nature of the uranium reductant, such as the nature and abundance of organic material in the host rock or by the introduction of hydrogen sulfide and hydrocarbons.

Target Areas for Uranium Exploration

Based on the conceptual framework presented above, some areas within the sedimentary basins are recommended as targets for systematic uranium exploration: The Bida Basin has been excluded because of its highly oxidizing environment with the prevalence of iron ores throughout its depositional history which are not conducive to uranium precipitation. The following basins are of considerable potential for sandstone type uranium deposits:

- 1) Mamfe Basin
- 2) Calabar Flank;
- 3) Sub-basins within the Gongola Basin
- 4) Yola Basin
- 5) Bornu Basin

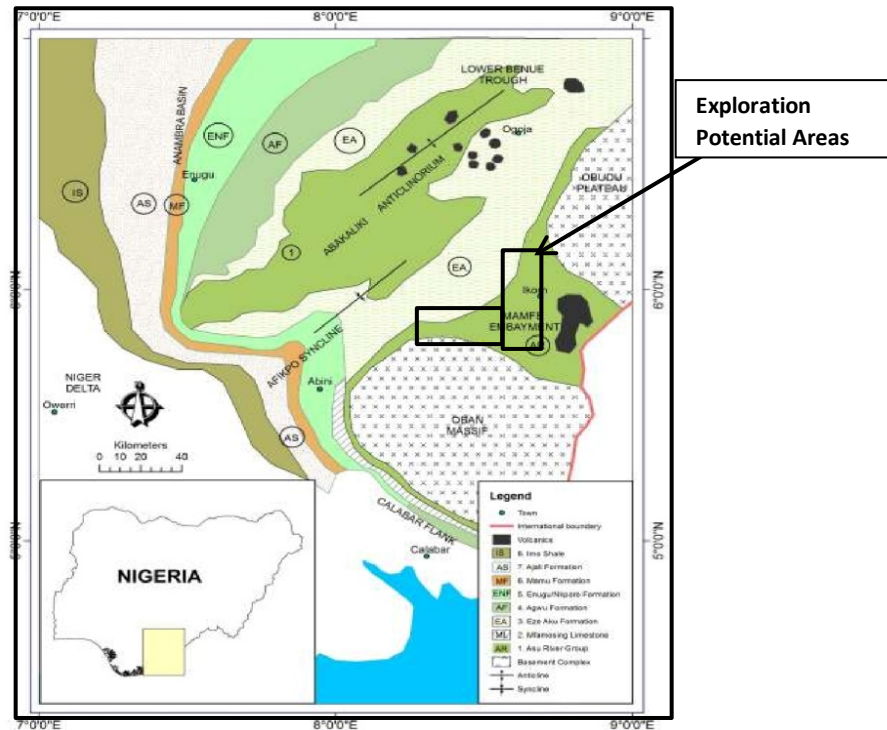


Figure 12: Mamfe basin and Calabar Flank, Lower Benue Trough

The Mamfe Basin is a small E-W trending intracontinental rift basin that forms a side arm of the southern portion of the Benue Trough, extending into Cameroon Republic (Fig.12). It is filled with Albian to Cenomanian basal arkosic sandstones and conglomerates with interbedded shales (Mamfe Formation) that range in thickness from 1000 to up to 4000 m (Bassey et al, 2013). The sequence rests unconformably on the Precambrian crystalline basement, and the rocks were not affected by the Coniacian transgression (which could wash away uranium precipitates). The western portion of the Mamfe Basin lies in Nigeria and the sediments are synchronous with the basal Asu River Formation. Strong aeroradiometric anomalies have been detected in the areas around Idomi-Ugep of Yakur Local Government Area (LGA) extending into Yala LGA in Cross River State. As shown in Figure 12, there are extensive exposures of these sandstones that are attractive for uranium prospecting and exploration. Another area of interest is around the Calabar Flank in the southern portion of Lower Benue Trough underlain by the basal arkosic and coarse grained sandstones and conglomerate of the Awi Formation of Aptian-Albian age (Adeleye and Fayose 1978), lying unconformably on the Precambrian basement rocks of the Oban massif (Fig. 12). The Awi Formation is about 50 m thick, and is equivalent to the Asu River Formation and Mamfe Formation.

The Upper Benue Trough in northeastern Nigeria is split at the midpoint into two arms: Gongola and Yola Basins. Uranium occurrences are known within the Bima Sandstone in the middle Gongola Basin (Zona, Dai and Mayo Lope) but not in the Yola Basin (Fig. 13). The Zona and Dali occurrences are structurally controlled while the Mayo Lope is described as stratiform. Haruna et al (2012) has described the tectono-lithologic evolution of the Bima Sandstone and its potential for hosting sandstone type uranium mineralization. Because of the intensive block faulting in the middle Gongola Basin, several small sub-basins were created containing thick sequences of the Bima Sandstone, such as the Nahantsi,

Kurkude, Shani and Peta sub-basins (Haruna et al, 2012). These sub-basins have considerable potential for hosting sandstone uranium deposits (Fig. 14). The Yola arm is also a potential target for uranium exploration (Fig. 13).

The Borno Basin is a northward extension of the Upper Benue Trough and contains up to 6000m of Cretaceous to Recent mostly continental and lacustrine sediments, characterized at the base by sandstones and conglomerates of the Bima Formation. The stratigraphic sequence is thick but should not detract from its uranium mineralization potential. In recent years, there has been substantial exploration for hydrocarbons in this Borno basin, and such effort and data collected can facilitate the search for uranium using information from gamma ray logs and evaluation of drill cores from deep wells. The Bida Basin is unique in that most of the sedimentary deposits are continental coarse clastics (fanglomerates and sandstones) without marine transgression. The environment of deposition was highly oxidizing, with widespread deposition of ironstones. Such conditions may not be very conducive for the precipitation of uranium deposits in sediments.

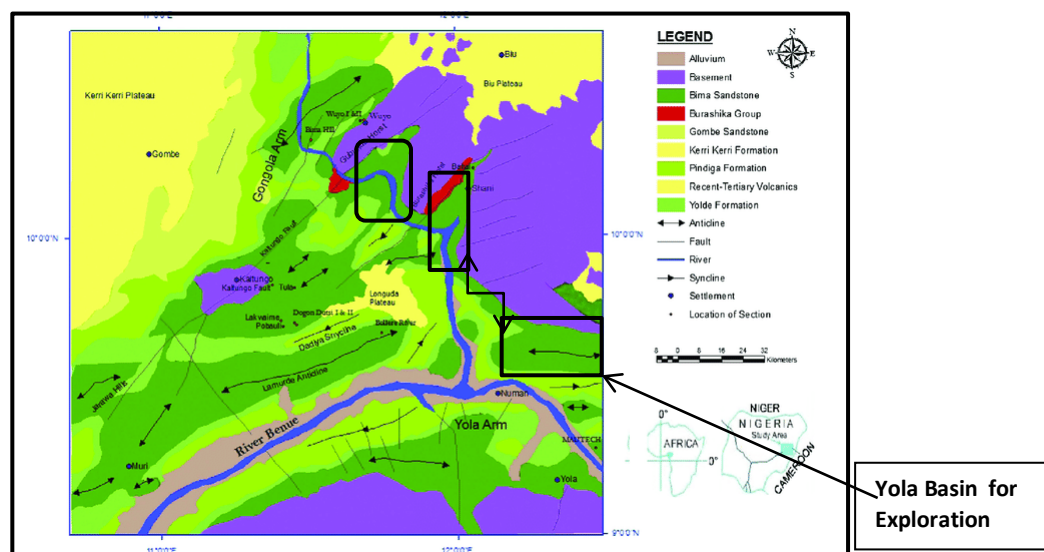


Figure 13: Geologic map of showing sub-basins of Upper Benue Trough. NE Nigeria (Modified after Haruna et al, 2012)

The Nigeria Atomic Energy Commission (NAEC) was resuscitated in 2006 and charged with the responsibility, among others, for the exploration for uranium minerals in Nigeria. Currently, this responsibility has been delegated or devolved to the Nigeria Geological Survey Agency (NGSA), with support from university research centers providing limited laboratory services (Karniliyus and Ekedegwa, 2018). Also, there has been concerted effort to attract the private sector and other foreign investors to participate in Nigeria's uranium venture, aided by the liberalization of procedures for acquiring exploration and mining leases. However to achieve substantial progress, government agencies must be willing to provide the needed and accurate geoscience data, including topographic and geological maps, as well as aerial and ground radiometric survey data. The future prospects of finding viable uranium deposits in Nigeria will depend on a well-funded strategy of conducting systematic exploration for sandstone-type deposits within designated areas. Recently, there were reports of hydrocarbon exploration and discoveries in the Borno Basin. It is well known that uranium deposits may occur in hydrocarbon basins because hydrocarbons help precipitate uranium by process of reduction. Notable examples have been reported in Kazakhstan (Jaireth et al, 2008); China (Cai et al, 2005; Huang, et al, 2005) and Texas, USA (Reynolds and Goldhaber (1978). While exploring for crude oil, in the Borno Basin and other basins, information gathered from gamma ray logs and drill cuttings can be valuable in uranium exploration.

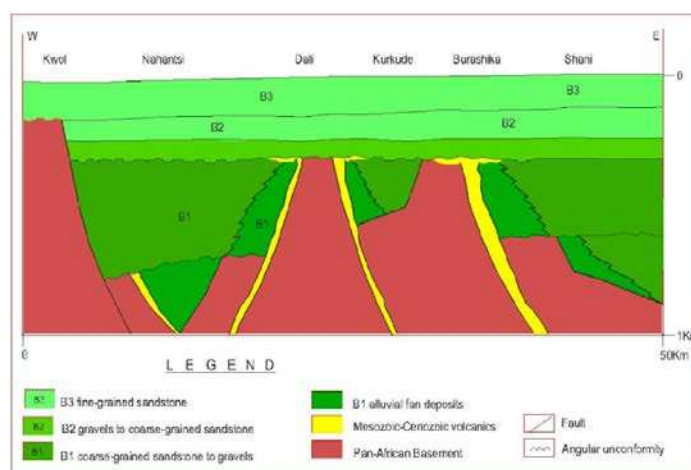


Figure 14: Cross-section of Sub-basins within the Gongola Basin

(After Haruna et al, 2012)

CONCLUSION

Nigeria is a country with considerable potential for the discovery of viable uranium deposits if well-funded systematic exploration is focused on sandstone type uranium deposits within the Lower and Upper Benue Trough and its northern extension in the Borno Basin where crude oil was recently discovered. The close association between uranium deposits and hydrocarbon-bearing basins is well known. The basal sandstones and conglomerates in the Benue Trough and the side basins of Mamfe and Yola are prime targets for uranium exploration involving the use of geophysical and geochemical methods accompanied by geological mapping. The government agencies charged with the responsibility for uranium exploration should provide basic geoscientific information such as up to date topographic and geological maps as well as aerial and ground radiometric survey data that can encourage the private companies and investors to participate in uranium exploration venture by conducting more detailed exploration including subsurface drilling in target areas. The Nigerian National Petroleum Company exploring for crude oil in the Borno Basin and other basins should be cognizant of the spatial association of uranium with hydrocarbons and include such perspective in its exploration strategy.

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