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Evolution of the Nigerian Basement Complex: Current Status and Suggestions for Future Research

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Abstract
The polycyclic basement rocks of Nigeria have been the subject of several isolated and local studies. Despite the huge amount of studies on the basement however, the geodynamic evolution of the basement remains a subject of debate. This study highlights some of the major existing studies on the basement complex with a view to streamlining the existing knowledge into a coherent perspective as well as identifying potential areas for future research that will improve our understanding of the evolution of the Nigerian Basement Complex (NBC). The polyclicity of the basement poses a major challenge in deciphering episodicity of the events leading to the geodynamic evolution of the region. The reported occurrences of pre-Pan-African rocks in some parts of the basement are interpreted as reflecting the relicts of reworked older crustal materials which cannot be regarded as juvenile earth materials. Thus, such Eburnean or similar older ages cannot be inferred to represent the primary isotopic age of magmatism and other associated thermo-tectonic events within the basement. Lack of integrated, comprehensive structural and isotopic data is identified as part of the missing links resulting in the present poor understanding of the complex. Integrated, regional geoscientific studies employing modern techniques and tools are needed to fully understand the geodynamic evolution of the Nigerian basement rocks. To do this, quantitative models, structural analyses and modern geochronological dating techniques are recommended. It is also recommended that mineral exploration should be intensified within the Older Granites as this will not only enhance the understanding of the mineralization potentials of these rocks but also provide clearer insights into the general evolution of the basement complex.

Keywords: *Precambrian, Nigerian basement complex, Pan-African orogeny, geochronology, geodynamic evolution, structural analyses*

Introduction

The discussion on the Precambrian geodynamic evolution usually generates controversy due to the rarity of naturally verifiable data on the physico-chemical conditions of the Earth from that era (Kohanpour *et al*., 2017). As pointed out by Hubbard (1975), many of the studies on the evolution of the Nigerian Basement Complex have been largely generalized and subjected to individual biases. Such subjective dispositions have largely resulted from the paucity of reliable data on the basement rocks.

Although there is a general agreement that the entire basement in Nigeria was affected by the Pan-African orogenic event, the extent and impact of that event remains an issue for debate. Whereas some researchers (e.g. Harper *et al*., 1973; Cahen *et al*., 1984; Dada, 2008) hold the view that the Pan-African orogeny was widespread, overprinted and obliterated all traces of older tectono-metamorphic events, others (such as Ajibade, 1988; Fitches *et al*., 1985; Kroner *et al*., 2001) argue that imprints of older events remain isotopically preserved within the Nigerian Basement Complex. More so, considering the ubiquity of the Pan-African reactivation across the Nigerian basement, the protolith of the age within the basement remains debatable (Ferre *et al*., 1996).

Even though studies on the evolution of the basement rocks in Nigeria commenced well over 4 decades ago, most of such studies are largely skewed in favour of age-dating the complex using radiometric data without paying adequate attention to other aspects. Two areas where the basement suffers from apparent neglect relative to isotope geology and geochemistry are the structural geology and numerical modeling. According to Anor and Freeth (1985), due to the paucity of structural data, most of the thermo-tectonic and orogenic events postulated for the basement complex are inferred from the correlation of available isotopic data with various dated events from different parts of Africa. Also, Odeyemi (1981) has attributed the seemingly poor understanding and classification of the Nigerian Basement Complex to be as a result of the over-reliance on isotopic data without a corresponding integration of other aspects of geosciences. Although some workers have attempted integrating structural and isotopic data for the better understanding of the evolution of the basement complex (e.g. Ferre *et al*., 1996), more comprehensive data and studies are needed in this direction.

This paper therefore, is an attempt to summarize the existing knowledge on the Nigerian Basement Complex as well as identifying areas for future studies.

Overview of the Nigerian Basement Complex

Position and Lithology of the Nigerian Basement Complex

The NBC is part of the southern end of the Trans-Sahara Pan-African mobile belt situated between the Archean-Paleoproterozoic blocks of the West African and Congo cratons (Fig.1). The basement complex is considered to be part of the reactivated Pan-African belt that resulted from the collision of the passive continental margin of the West African craton and the active margin of the Tuareg Shield. This Trans-Saharan-Pan-African orogenesis led to the development of various high grade metamorphism, massive granite plutonism and late orogen-parallel tectonics (Ominigbo *et al*., 2020; Okonkwo and Ganev, 2012).

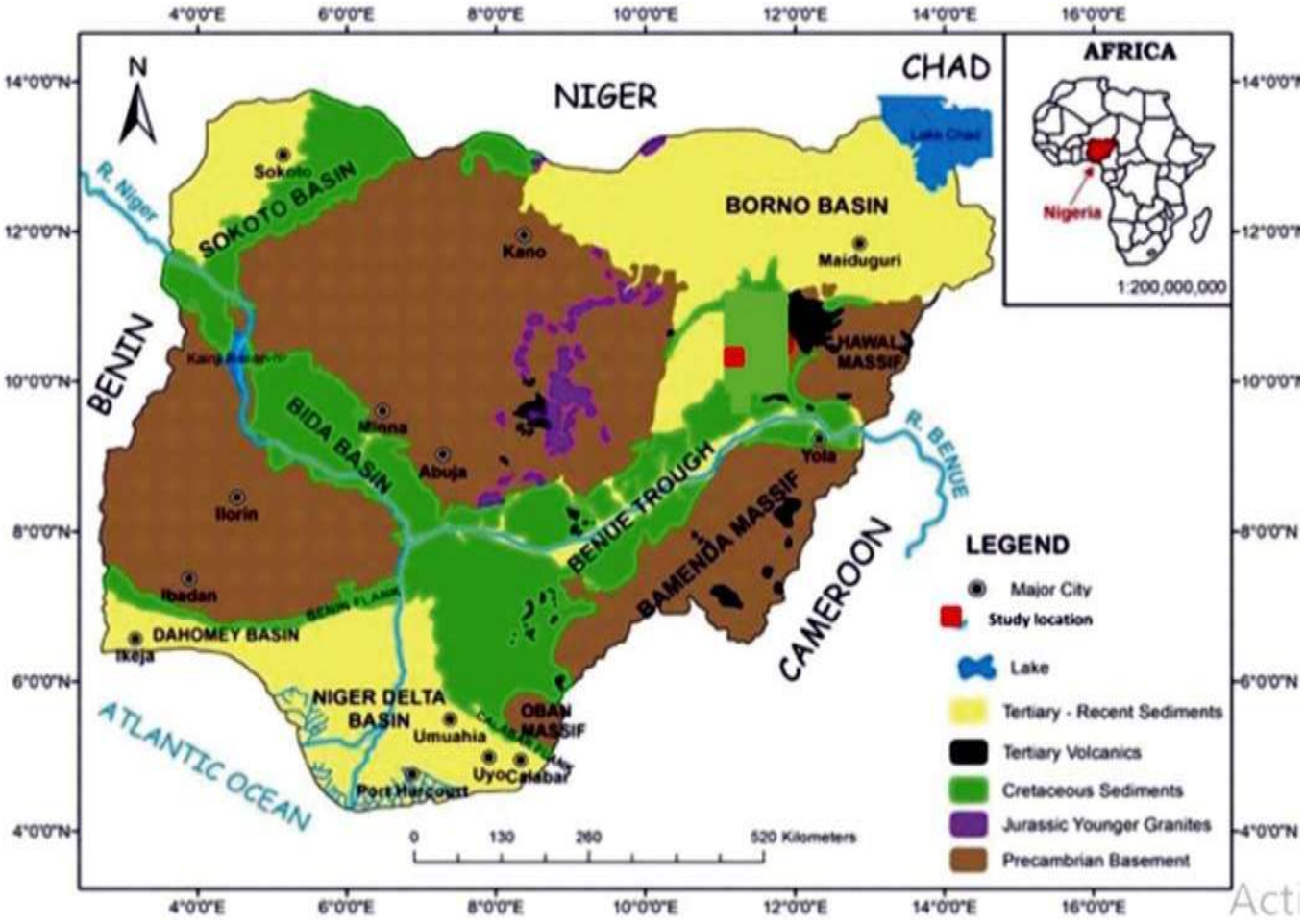

Fig. 1: Geological map of Nigeria showing the Basement Complex rocks (adapted from Jimoh *et al*., 2019)

Although there remains a debate as to the extent and effects of the Pan-African orogenic event on the NBC, there is seemingly an agreement amongst researchers that the entire basement was affected by the 650 Ma ±150 thermo-tectonic events (Ferre, 1996; Anor and Freeth, 1985). And, whereas some early researchers (e.g. Pidgeon *et al*., 1976; Brugier *et al*., 1994) considered the Nigerian basement as a singular Archean block, later studies (e.g. Ferre *et al*., 1996; Ekwueme, 1990) have demonstrated that the basement complex in Nigeria consists of at least, 2 geochronologically distinct units: an Archean province in the western part of the country and Eburnean block to the east.

Based on geochronology, stratigraphy and composition, the rocks of the NBC fall into 2 broad groups: the pre Pan-African crystalline rocks (2.8 – 1.3 Ga) comprising migmatite gnesisses and ancient granites; and the Pan-African crystalline rocks (1.1 – 0.5 Ga), consisting of the Older Granites and metavolcano-sedimentary series. Typically, the Pan-African rocks lie

unconformably on the pre-Pan-African basement (Ekwueme, 1990).

The complex is underlain by different lithological units: the migmatite-gneiss-quartzite complex, the Older Granite and the Younger Granites otherwise regarded as the Schilt Belts and the undeformed charnockites, gabbroic and dioritic rocks (Ominigbo *et al*., 2020; Rahaman, 1989; Rahaman, 1988; Odeyemi, 1981). In many places, the Older Granites intrude both the migmatite gneisses and the schists. Chronologically, the Migmatite Gneisses are the oldest rocks in the basement complex and are thought to be reworked older crust by orogenic events, with the undeformed acid and basic dykes being of later- to post-Pan-African orogeny (Haruna, 2017).

The NBC is considered to be characterized by contrasted accreted terranes (typical of the south of the Pan-African belt of West Africa) which can be grouped into 2 provinces: western Nigeria and eastern Nigeria. The western group consists of tonalite-trodnhjemite-granodiorite (TTG) type orthogneisses, amphibolites facies and greenstone facies metasediments. On the other hand, the rocks in the eastern province are predominantly made up of synformal schist belts ranging from greenstone to amphibolite facies. Whereas the petrological units in western Nigeria are Archean, their counterparts in the eastern province are typically Eburnean. More so, the general absence of gold mineralization and banded iron formations in significant amounts in eastern Nigeria support the inference that unlike western Nigeria, the east lacks Archean protoliths (Ferre *et al*., 1996).

The Nigerian Basement Complex within the context of the Pan-African Orogeny

The NBC is part of the southern part of the aggregation of allochthonous terranes in West Africa as part of the Togo-Benin-Nigeria Shield (Ajibade and Wright, 1989). Like other parts of the continent, the Togo-Benin-Nigeria Shield was affected by the pervasive Pan-African orogeny. The Pan-African orogenic event is a continent-wide event which led to the reworking of the older crust, giving rise to a polycyclic basement and imposing a broadly N – S structural trends on the region. The magmatism accompanying the Pan-African led to widespread emplacement of granites and charnockites just as the associated thermal activity imprinted mineral ages of 500 – 600 Ma in almost all the rocks in the region, Nigeria inclusive (Turner, 1983; Ferre *et al*., 1996).

Similarities have been reported between the NBC and neighboring Pan-African provinces, both in terms of petrology and geochronology. For example, the volcanic and sedimentary rocks of the Tchilit paleorift (Air, Niger) are believed to be comparable to the Anka Schist Belt in western Nigeria, just as the other schist belts in Nigeria share close similarities with the Archean greenstone belts within Pan-African province (Ferre *et al*., 1996; Turner, 1983). Notable areas of similarities include size, synclinal structures, grade of metamorphism (low grade), presence of volcanic and clastic rocks, occurrence of iron banded iron formation as well as gold mineralization. The Nigerian schists, however, differ from many other belts within the province in that sedimentary clasts predominate over volcanic rocks (Turner, 1983).

Correlations have also been made between the deformation and metamorphism in the Pan-African province of West Africa and the Himalayas of Asia. These similarities are manifested in major shear and transcurrent fault systems which are oblique to the major direction of propagation (Ajibade and Wright, 1989; Black, 1980). The polycyclicity and diversity of the rocks formed in the southern province of the Pan-African belt (the NBC inclusive) resembles the central Hoggar-Air block, north of the Togo-Benin-Nigeria Shield (Ajibade and Wright, 1989).

Geochronology and Evolution of the Basement Complex

Whereas the NBC rocks have benefitted from extensive geological field mapping, there seems to be paucity of reliable radiometric data to properly enhance the understanding and interpretation of its evolution. More so, Kroner *et al.* (2001) opine that most of the available geochronological data are largely unreliable having been derived almost exclusively from Sb-Rb dating techniques. Although the NBC is believed to have been affected by four orogenic events, the structural and stratigraphic differentiation of the rocks which presumably characterize the different events in Nigeria is difficult. This gap has been attributed to two reasons: the extensive and pervasive Pan-African event obliterated signatures of earlier orogenies, thereby making it difficult to map such older rocks. Secondly, there has been very little research efforts aimed at detailed investigation and isolation of the component units within the complex (Odeyemi, 1981; Dada, 2008).

Presently, the occurrence of the Eburnian event within the Nigerian basement remains disputed, largely due to

lack of reliable structural and isotopic data (Dada, 2008). At best, the Eburnean age is considered to be speculative and subject to diverse opinions (Udinmwen, 2015). As shown in the Table 1 below, whereas most of the isotopic ages reported support the Pan-African age for the intrusive rocks within the complex (e.g. Ekwueme *et al*., 1997; Van Breemen *et al*., 1977; Umeji and Caen-Vachette, 1984), some much older ages have also been reported for similar rocks within the complex (e.g. Okonkwo & Ganev, 2012; Oversby, 1975; Kroner *et al*., 2001).

Table 1: Selected age data on the Nigerian Basement Complex rocks

S/N	Author(s)/ Year	Rock type	Location	Method	Reported age (Ma)	Observation(s)/Remark(s)
1.	Grant (1970)	Granite gneiss; basalt	Ibadan, SW Nigeria	Sb-Sr; K-Ar	2205 ± 70; 480	2205 (Eburnean) Interpreted As Age Of Metamorphism; 480 = Cooling Age, Terminating The Pan-African Event. The Eburnean age here is comparable to the 2.2 – 2.9 Ga Rb-Sr whole rock ages reported by Onstott (1987) for the metamorphic rocks of Nimba County, Liberia.
2.	Harper *et al.* (1973)	Amphibolites and pegmatite	Northern Nigeria	K-Ar	≤ 692	Majority of the metamorphic ages fell within 490 – 550.
3.	Oversby (1975)	Banded gneiss	Ibadan, SW Nigeria	U-Pb	2750 and 590	2750 = emplacement age; 590 = age of metamorphism
4.	Van Breemen *et al.* (1977)	Granite and charnockite	Bauchi, NE Nigeria	U-Pb	610	The 610 age was interpreted as the peak of granite plutonism within the region.
5.	Umeji and Caen-Vachette (1984)	Granite	Mkar-Gboko, SE Nigeria	Rb-Sr	547 ± 38	
6.	Ekwueme, *et al.* (1997)	Granite	Obudu, SE Nigeria	K-Ar	507.6 ±10.1	They suggested a prolonged cooling period (≥110 Ma) for the granites of SE Nigeria.
7.	Ekwueme, *et al.* (1997)	Dolerite	Oban Massif, SE Nigeria	K-Ar	204.0 ± 9.9	
8.	Kroner *et al* (2001)	Migmatite gneiss	Kaduna, NNW Nigeria	Pb-Pb	3571 ± 3	This is easily the oldest age interpreted for the Nigerian basement thus far.
9.	Okonkwo and Ganev (2012)	Granite Gneiss	Jebba, SW Nigeria	U-Pb	2207 ± 20	The 2207 ± 20 Ma was interpreted to be the age of crystallization of the parent granite.
10.	Ferre *et al.* (1996)	Migmatite gneiss	Toro, NE Nigeria	Pb-Pb; Rb-Sr	580 ± 7	

The Missing Link?

The most reliable geological interpretations are those that apply the integrated approach (Kohanpour *et al*., 2017; 2020; Ominigbo *et al.,* 2021.) Unfortunately, the traditional approach in Earth Sciences researches tends to either focus exclusively on the geological attributes without paying adequate attention to the mechanism of formation (and deformation) or they tend to emphasize mechanical properties of the rocks without proper consideration for the geological origin (Aydan and Kawamoto, 1990). Apart from a few integrated studies such as Ferre *et al*. (1996), most of the existing data and literature on the evolution of the Nigerian basement tend to suffer from this bias which in part accounts for the ongoing debate about the evolution of the basement. This approach has led to interpretations with many inconsistencies about the evolution of the Nigerian basement rocks.

Structural Data

Over the years, serious focus has been on the petroliferous sedimentary basins and the highly mineralized schist belts and the Younger Granites in Nigeria with the gneisses and Older Granites suffering relative neglect. This is in large part due to the mineral and hydrocarbons exploration activities in those schist belts and sedimentary basins respectively (Gok *et al*., 2010). As a result, the structural attributes of the Nigerian basement rocks particularly the gneisses remain poorly understood. This situation has contributed to the current fairly poor understanding of the evolution of the basement complex, particularly the extent and episodicity of the Pan-African event due to paucity of comprehensive and reliable scientific data.

As pointed out by Balogun (2019), apart from a series of broad regional studies conducted on the Nigerian Basement Complex in the 1960s through the early

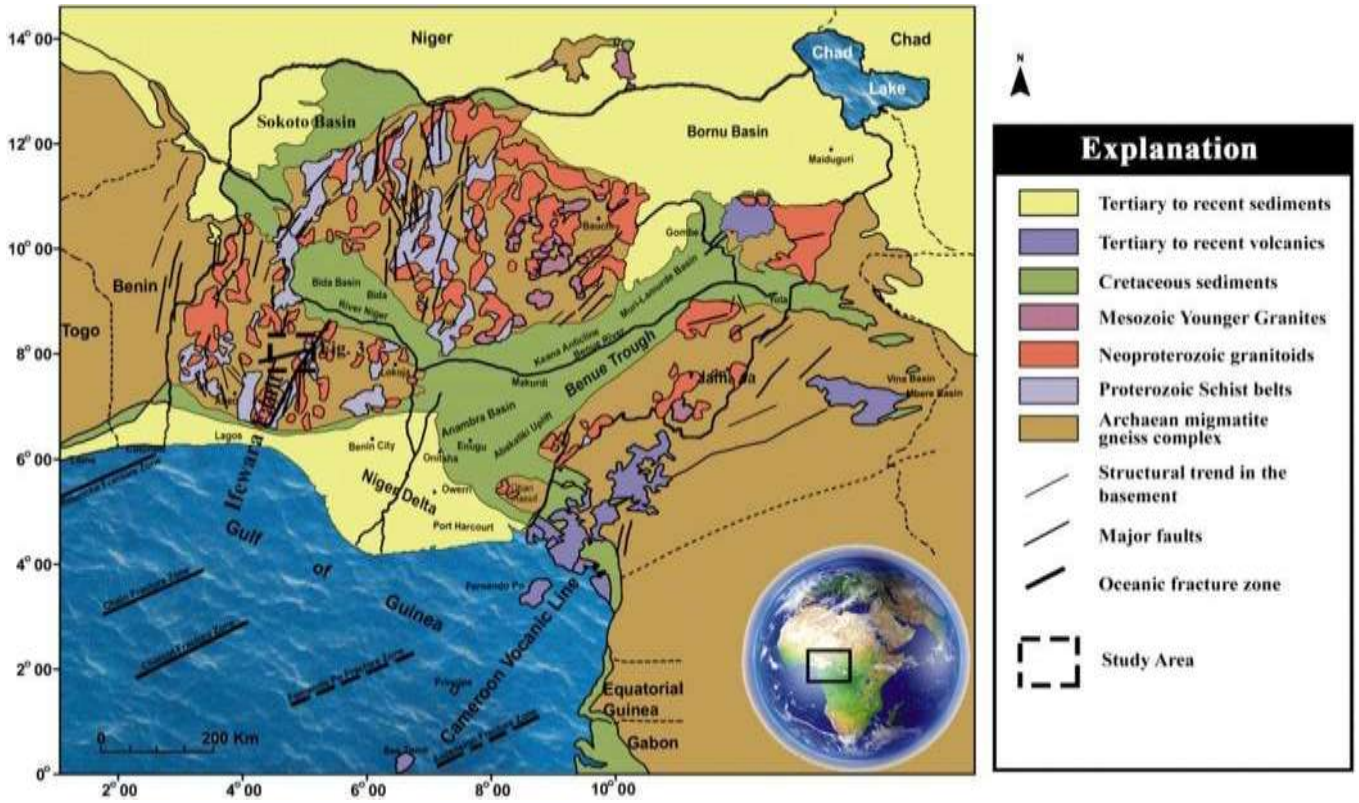

Fig. 2: Generalized geological map showing structural trends in Nigeria (adapted from Salawu *et al*., 2021)

1990s, there have been very few recent detailed studies aimed at understanding the peculiar geodynamic evolution across the various geological regions making up the NBC. As a result, there are no new significant insights gained about the geodynamic settings and structural attributes of the basement complex. Most of the earlier postulations on the thermo-tectonic events and orogenies of the Nigerian basement rocks are based on isotopic data and correlation with dated events in other parts of Africa and South America. Anor and Freeth (1985) have opined that relying solely on isotopic data for the understanding and interpretation of the Nigerian Basement Complex could be misleading.

Although some attempts have been made to integrate the structural elements into the discourse on the evolution of the basement complex (e.g. Burke *et al*., 1987; Anor and Freeth, 1985; Gok *et al*., 2010; Balogun, 2019; Ominigbo *et al*., 2021), studies on the mechanism of deformation of the complex remain largely scanty. This is particularly true of micro-structural geological studies on the Nigerian basement. According to Anders *et al*. (2014), studies of micro-fracture orientations can provide important insights into the paleostress history of rocks; the causes and processes of fault zones' development as well as the evolution of regional stress fields are well preserved in microstructures. The paucity of structural data, particularly microstructures, could be a significant missing link in the understanding and interpretation of the evolution of the Nigerian basement.

Episodicity of the Pan-African Orogeny?

Whereas there is a near consensus that most of the NBC has been affected by different orogenic events (Liberian, 2700Ma ±200; Eburnean, 2000Ma ±200; Kiberian, 1100Ma ± 100 and the Pan-African, 650 Ma ±150), the relationships between the various episodes remain ambiguous due to poor and discontinuous exposures (Anor and Freeth, 1985). For a polycyclic basement like Nigeria, it is not uncommon for reworked relicts of older tectonic events to be preserved and coexist with juvenile tectonic materials. Such a situation no doubt, makes it very difficult to decipher the tectonic history of such an area accurately (Omosanya *et al.*, 2013). As Arndt and Goldstein (1987) pointed out, dating samples that are mixtures of materials from different Earth sources or events could give misleading ages which in turn result in wrong interpretations and inferences. More so, most of the ages older than the Pan-African that have been reported for the Nigerian basement rocks were from Rb-Sr data which, according to Kroner *et al.* (2001), have been largely considered unreliable, especially among the earliest of those

isotopic data and ages in Nigeria. This makes the need for comprehensive and multidisciplinary studies (intensive geological field mapping, geophysical and geochemical analyses, airborne and remote sensing studies etc.) about the basement complex in Nigeria even more imperative. With modern advances in techniques, the uncertainties surrounding the orogenic episodes and their relationships can be easily resolved.

Recently, the use of quantitative models aimed at extrapolating back geological time and enhancing our understanding of the Earth's geodynamic evolution during the Precambrian has been advocated (Kohanpour *et al*., 2017 and the references therein; Kohanpour *et al*., 2019). As pointed out by Kohanpour *et al.* (2019), the cyclicity and evolution of supercontinents are largely controlled by magma source which is often related to the tectonic setting of such magma. They therefore opine that the integration of the geochronological data with numerical modeling would enhance our understanding of the geodynamic evolutions of the geological past. Regorda *et al*. (2020) have applied such numerical models to study the accretionary Variscan orogenic belt that separates European continental lithosphere from the Iberian Peninsula to Poland. Using 2D and 3D numerical models, they were able to map out striking contrasts in the thermo-mechanical evolution and the various episodes of that characterize the Variscan orogeny.

Unfortunately, there are virtually no published studies on the numerical modeling of the geodynamic evolution of the NBC. The integration of such quantitative models with other geological constraints will go a long way in ascertaining not just the tectonic setting of the basement complex but also the regional extent and episodicity or otherwise of the Precambrian events in Nigeria.

Suggestions for Future Research

The occurrence of pre-Pan-African rocks within the basement complex of Nigeria may have been due to the partial reworking of older crustal materials which may have been restructured and therefore, left imprints in intervening younger orogenic events, the Pan-African being the latest of such events (Hubbard, 1975). In order to ascertain the validity of the proposition that juvenile rocks of Eburnean and older ages exist within the complex, new integrated studies that combine geochronology, structural and field studies are essential. Specifically, a combination of structural and geochronological tools and techniques that will enhance the interrogation of the composition of earth materials with high degree of certainty is suggested. Such high resolution structural and isotopic analyses would help give further insights into the origin and episodicity or otherwise of the events within the basement. Such studies will also help ascertain the validity or otherwise of the Eburnian and older ages reported for some rocks within the NBC.

The recent and ongoing insecurity in the country has made geological field mapping a rather very risky adventure with many institutions scaling down the place and importance of geological fieldwork in their curricular. This must be addressed as it a common knowledge that field mapping is indispensable to effective understanding of geology and its associated processes. In order to fully understand the evolution of the Nigerian basement rocks, comprehensive geological field mapping is essential. Such field exercises must be integrated with modern laboratory techniques. Whereas there are numerous technologies and laboratory techniques available today (and they keep evolving!) for remotely studying the Earth, these processes and laboratory analyses must be carried out as important but complementary studies to geological field mapping.

Although some zircon ages have been dated and reported for the NBC, a combination of U-Pb and Hf ages to decipher the true geodynamic history of the complex is recommended. This is because for a complex and polyclic province like the NBC, a true understanding of its evolution would necessitate identifying the old, reworked crustal materials and the juvenile components. As pointed out by Choulet *et al*. (2012), zircon preserves the original characteristics of the host magma whereas Hf helps to decipher the juvenile or contaminated character of the dated material. Such an approach could help resolve the existing controversy on the pre-Pan-African ages of the NBC. Choulet *et al*. (2012) have used the integrated U-Pb and Hf isotopic data to address the similarly polycyclic West Junggar accretionary complexes in China.

Conclusions

The Nigerian Basement Complex is made up of crystalline rocks which have undergone different phases of thermo-tectonic events, the last and most significant of which is the Pan-African event. The polycyclicity of the complex has made the understanding and interpretation of the evolution of these rocks rather difficult. Although a few pre-Pan-African ages have been reported in places within the complex, these older isotopic signatures may be relicts of reworked earth

materials, making their interpretation as juvenile rocks imprints be speculative.

To satisfactorily put the debate on the age of the complex to rest, there is a need to employ integrated and comprehensive scientific studies aimed at unraveling the true geodynamic history of the rocks. To achieve this, such studies should include, amongst others, techniques and methods such as numerical modeling and structural and geochronological studies with the aim of ascertaining the geological evolution and episodicity within the Nigerian Basement Complex.

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