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ORIGIN OF TONALITE-TRONDHJEMITE-GRANODIORITE (TTG) GNEISS IN THE BASEMENT COMPLEX OF SOUTHWESTERN NIGERIA: LU-HF ISOTOPIC VIEW

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Abstract

This research investigates and report the origin of Tonalite-trondhjemite-granodiorite gneiss (TTG) in the basement complex of southwestern Nigeria. The unit forms the country rock and comprise of migmatite and assorted gneisses collectively referred to as migmatite-gneiss complex. Field investigation reveals the migmatite contains palaeosome and neosome while the gneisses contain melanosome, mesosome and leucosome. Petrographic examination reveals the unit comprise dominantly of quartz, orthoclase, plagioclase and biotite with hornblende forming supporting mineral aggregate. The mineral assemblage (quartz + biotite + K-feldspar + opaque) in the rock represents medium-grade metamorphic conditions, a temperature of about 550-600^{o}C and a pressure between 3 to 10 K bar. ^{176}Lu/^{177}Hf content with values between 0.00367 to 0.001669, ^{176}Hf/^{177}Hf ratio between 0.281955 to 0.282022, initial Hf isotope values between 0.281969 to 0.282005, εHf(t) values between -3.5 to -5.2 and a two-stage model age (tDM2) between 2080 and 2161 all indicate the inherited zircons in the rock separated from the 'Depleted Mantle' around 2.8 ~ 3.0 Ga. Even though, the Negative εHf(t) values signifies high crustal input, the tDM2 age implied the magma source originated from the Chondritic Universal Reservoir (CHUR) during Mesoarchean. The simultaneous occurrence of palaeosome and neosome in the migmatite, complex tortuous veins, porphyroblasts with augen structures and prevalence of veining (mainly quartzo-feldspartic) in the gneiss probably suggests anatexis is involved in the origin of the rock. Field relationships and textural evidences revealed the Tonalite-trondhjemite-granodiorite gneiss might have originated from partial melting of a poorly differentiated granitoid.

Keywords: Nigeria, TTG-gneiss, Chondritic Universal Reservoir, crustal input, partial melting
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1. Introduction

The first 3.9 billion years of Earth history witnessed the formation of a unique and unusually widespread associations of rocks that include ultramafic komatiite lava flows, megacrystic and massif-type anorthosite, rapakivi granites and vast terranes of tonalite, trondhjemite, and granodiorite orthogneiss (TTG) (Best, 2003). Even though, several authors (e.g., Pidgeon *et al.,* 1976; Bruguier *et al.,* 1994; Ferré *et al.,* 1996) specifically mentioned the basement complex of southwestern Nigeria consists of tonalite-trondhjemite-granodiorite (TTG) gneiss. However, the term was rarely subsequently mentioned in literature or any mention about age or origin of the rock. The basement complex consists of assorted metamorphic rocks of largely Precambrian age; this particular unit is often referred to as migmatite-gneiss complex *sensu-lato*. On a regional scale, the basement rocks are broadly categorized into three petrological groups; these are, migmatite-gneiss complex, the schist belts, and Pan-African granites with minor (charnockitic and pegmatitic) rocks. Due to economic considerations, the last two are often frequently reported, while less emphasis has been placed on the migmatite-gneiss. This development has actually led to dearth of geological information on this rock in Nigeria. In addition, the scarcity of relevant data on Nigeria migmatite-gneiss resulted from its structural complexity, complicated evolution history and its polycyclic nature (Akinola and Obasi, 2020). Migmatite-gneiss is the most extensive basement unit underlying approximately half of Nigeria Precambrian domain *(*Ajibade *et al.,* 1988). Even though, this rock constitutes an integral part of the basement, its origin has always been hotly debated by scholars. Some authors believed Nigeria migmatite-gneiss is of sedimentary origin, others thought it is igneous, while a few others even believed the two sources are equally possible. However, the origin of this complex rock possibly extends beyond a synoptical view suggesting igneous or sedimentary antecedents. Trondhjemite represents a leucocratic intrusive igneous rock of tonalitic composition having plagioclase mostly in the form of oligoclase. Granodiorite is a felsic rock whose composition ranges between granite and diorite. So Tonalite-Trondhjemite-Granodiorite (TTG) gneiss is presumed to have been formed from this kind of rock. From the viewpoint of this research, the author felt the petrogenetic synopsis of TTG gneiss should embrace all fingerprints of their field attributes, structural variation, metamorphic evolution, and the source of its ancient protolith. Although, seismic data and geophysical methods were at one time largely relied on as the only means of imaging the inner parts of the crust. However, structural, and geodynamic evolution of the earth's continental plate has been linked to interplay of multiple geological processes. Consequently, the recent times has witnessed how the ancient and modern state of the lithosphere can be picked by U-Pb-Hf isotopic study of zircon which can act as a paleo-geophysical tool showcasing crust-mantle interaction through time (Hartnady *et al.,* 2018; Blichert-Toft and Albarède, 1997). Kemp *et al.* (2006) adopted Hf isotopes to reveal the time since the source of the parental magma separated from the mantle. ^{176}Hf/^{177}Hf of zircon is useful to calculate a 'model age' which gives a strong indication of the time when the basement protolith from which a granite-forming melt is generated. εHf describes the derivation of initial ^{176}Hf/^{177}Hf with respect to the chondrite uniform reservoir (CHUR), whereby a $\varepsilon\text{Hf} > 0$ indicates depletion of radiogenic Hf and $\varepsilon\text{Hf} < 0$ symbolises enrichment in radiogenic Hf. Hence, TTG gneiss (Migmatite-gneiss) in the basement complex of Nigeria is investigated here from the viewpoint of Lu-Hf isotopic study.

2. Review and Historical Underpinning

Research on migmatite dates back to early twentieth century. After the name 'migmatite' was coined, it was adopted and upheld by eminent petrologists around the world. Among others, Sederholm, (1907); Holmquist, (1921); Scheumann, 1936; Huber and Niggli, (1943); Jung and Roques, (1936, 1952); Piccoli, (1958); Dietrich and Mehnert, (1961); Scheumann, (1963); Mehnert, (1968); Dietrich, (1974); Berger and Kalt, (1999); and Sawyer, (2008) all believed that migmatites are structurally complex rocks and are sometimes difficult to describe precisely using conventional petrographic terms. After these earlier works, several relatively recent papers have been published on migmatites across the globe. However, most of these researches are descriptive rather than petrogenetic. Dietrich (1974) believed migmatites are composite, high-grade rocks containing gneissose and granitic parts on both microscopic to outcrop scales. However, Ashworth (1976) described migmatites of different grades from the Huntly-Portsoy area of NE Scotland. In his study, Ashworth described the lowest-grade migmatite in the domain as trondhjemitoid migmatite. With increasing metamorphic grade, a transformation into cordierite-granitoid assemblages occurs which eventually paved way for the highest grades noritoid migmatites. Variation in metamorphic grades of these migmatitic rocks represent facies characterized by specific mineral assemblages which is dependent on rock types. Furthermore, Ashworth, (1976) realized migmatites sourced from Trondhjemite mostly have simple (quartz-plagioclase-biotite) composition. Dietrich, (1974) revealed migmatite could be formed by: (i) *injection* where the granitic component is injected magma while the gneissose component is a metamorphosed rock. (ii) *Transformation* in which the granitic component introduced fluids and/or ions while the gneissose (amphibolite) component is a metamorphosed rock (iii) *Partial melting* (anatexis) in which melted rock constituents forms the granitic component and the amphibolitic component is not a melted rock. (iv) *Chemical metamorphism* in which the granitic component is a differentiation-mobilized ('exuded') phases and the amphibolitic component is less-mobilized or a non-mobilized phase. In addition, Dietrich suggested two other ways migmatitic-appearing rocks are formed to include (v) *Physical metamorphic differentiation* in which both the granitic and the gneissic components are segregated mineral grains, and (vi) *Isochemical metamorphism* in which the granitic and gneissose components are treptomorphosed (chemically unchanged) rock. *The main problem here again is 'how can migmatites formed from these different processes be distinguished from each other*'? However, Dietrich (1974) pointed that several composite rocks resembling migmatite are actually not migmatites because their mode of formation does not agree with the petrogenetic definition of migmatites. The author believed these 'migmatite-looking' rocks are actually composite gneisses formed through isochemical metamorphism which incorporate either physical differentiation / disruption or both. To prevent such possible confusion, Dietrich (1974) following the suggestion of Dietrich and Mehnert, (1961) suggested practical application of 'migmatoid' for migmatite-looking rocks until their origins are determined. Berger and Kalt, (1999) revealed biotite dehydration melting at 800°C~850°C and 0.5~0.7 GPa was migmatite-forming process in the Bohemian Massif, Variscan belt, Germany. The duo recognized different types of migmatites including massive and undeformed types, the stromatic types, those in which leucosome and mesosome are interlayered with components exhibiting variable degrees of deformation which is foliated, and those which bear melanosome. Berger and Kalt, (1999) realized that the aggravating difficulties of understanding migmatite-forming processes (migmatisation) which consists essentially solid-liquid phase interactions is that mechanical properties of pure solids and of pure melts are well understood while that of partially molten systems as mixture of the two are only poorly understood. Mehnert (1968) revealed the felsic (mobile) components of most migmatites did not originate *in-situ* but were intruded or injected. Winkler (1967) and Turner (1968) believed widespread occurrences of migmatites among high grade terrains resulted from partial melting *in-situ*. However, Mehnert, (1968) believed this ideology has not been adequately tested in areas of wide geographical spread. Reitan, (1969) believed partial melting of pre-existing rocks like this is a consequence of deep burial while the heat produced by friction between colliding lithospheric plates has also been suggested for migmatite generation. Bowen, (1928); and Dietrich, (1964) have favoured partial melting triggered by reduction of pressure. Wegmann (1935) suggested that during anatexis, transfer of ions and molecules as a consequence of *in-situ* transformation could lead to formation of migmatites by metasomatism or solid diffusion particularly under the influence of orogenic stresses. Partial melting as a major mode of genesis for some migmatites (Eskola, 1933) was widely supported. Cesare et al. (2011) revealed that anatexis of metapelite between 15-25 km depths of the earth (0.5 - 1 GPa) produces the highest melt volume by incongruent breakdown of biotite leading to migmatite formation. However, Kalsbeek (1970) had earlier indicated that this process produces potash feldspar, but that biotite assemblages require more severe conditions to initiate their dehydration. Dietrich, (1974) reported that when Sederholm (1907) introduced the term migmatite, his belief was that the granitic component of migmatites was *injected* while Holmquist (1916) advocated *chemical metamorphic differentiation.* Following these views, Büsch (1966) investigated the possible link between the mobile siliceous component and the restites of migmatites by petrochemical means and arrived at the understanding that the parent rocks are of intermediate composition. Working on high-temperature metapelite anatectic enclaves in peraluminous dacites from SE Spain, Cesare *et al.* (2011) discovered that droplets of granitic melt can be trapped by minerals growing during incongruent melting reactions, and that the composition of such trapped melts often resembles that of bulk melt in the system during anatexis.

3. Geological Setting, metamorphism and age

The study area is located within the Nigerian shield, it lies inside Pan-African reactivated domain specifically on the eastern side of West African craton and north-west of Congo craton. Southwestern Nigeria which constitutes western segment of the Nigerian shield (Fig. 1) has been described earlier by Pidgeon *et al.* (1976) and Bruguier *et al.* (1994) as consisting tonalite-trondhjemite granodiorite gneisses of amphibolite-facies metamorphism (Caby, 1989) and metasediments which occur as lenses in N-S synformal belts (Grant, 1978; Ajibade *et al.,* 1987; Ferré *et al.,* 1996) that are largely preserved in greenschist metamorphic grade (Turner, 1983; Rahaman, 1988). The schist belts display greenstone affinities (Klemm *et al.,* 1984) and are mostly responsible for gold mineralization in Nigeria (Woakes *et al.,* 1987). Even though, Pidgeon *et al.* (1976) and Bruguier *et al.* (1994) considered Nigeria to be one Archaean block that experienced intense Pan-African reactivation; however, Ferré *et al.* (1996) revealed that southwestern and south-eastern blocks which constitutes the Nigeria terrains may have distinct histories. Tubosun *et al.* (1984) reported that calc-alkaline Pan-African granites intruded these units around 621±10 Ma and 586 ±5 Ma. Bruguier *et al.* (1994) reporting U-Pb zircon technique presented Archaean 3040±60 Ma age for the tonalite-throndhjemite-granodiorite gneiss protolith in northern Nigeria. Rahaman (1988) revealed concordant Archaean age in similar lithologies in southwestern Nigeria. Ferré *et al.* (1996) reported two zircon ages from a migmatite unit in northern Nigeria. The first, which yielded 581±10 Ma was interpreted as age of migmatisation and the older age (617±15 Ma) which probably corresponds to inherited radiogenic lead. In the light of existing isotopic information and the Pan-African terrane model (Black *et al.,* 1994; Liégeois *et al.,* 1994), it is pertinent to compare the Nigeria shield and other orogenic provinces within the African continent that may be similar. The Nigeria shield (basement complex) which lies between West African craton and Congo craton is comparable to the Damara orogenic belt located between Congo and Kalahari cratons in three major ways:

(i). *Lithologic units:* the units in the Damara orogen (Konopasek *et al.,* 2005; Miller, 2008; Toe *et al.,* 2013) is mainly migmatite and associated gneissic components popularly known as the Abbabis Gneiss Complex (Gevers, 1931; Sawyer, 1976) was interpreted as lateral equivalence of the Congo craton (Miller, 1983). This sequence which has been strongly warped and affected by partial melting in the amphibolite to granulite facies

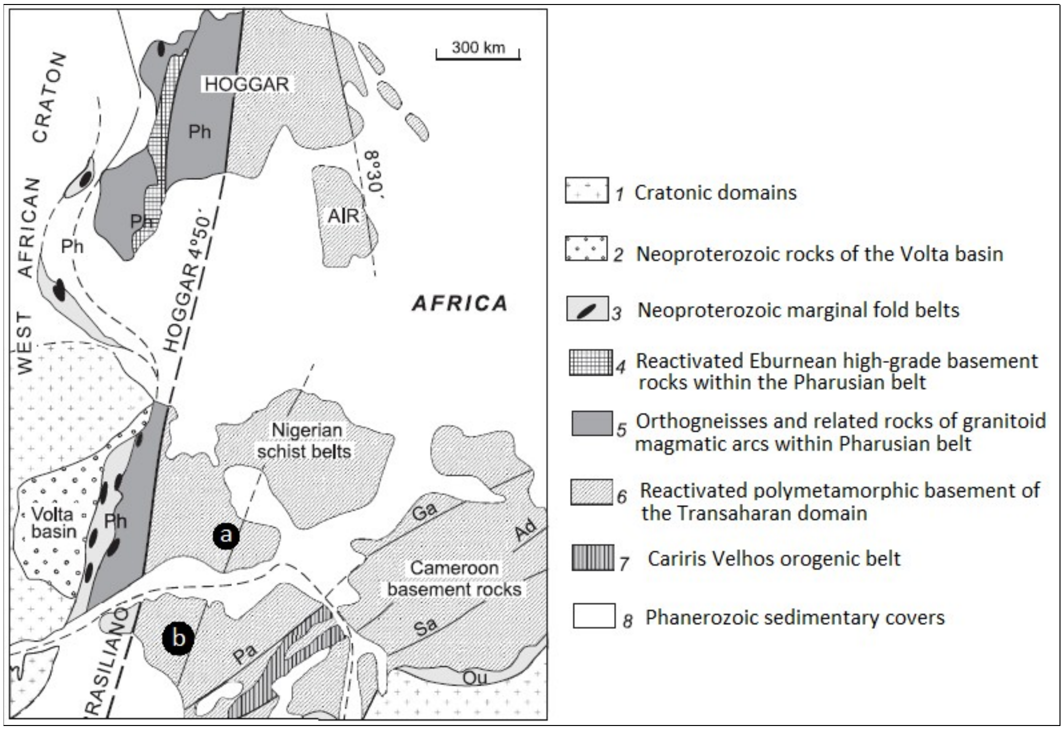

Fig. 1: Schematic tectonic framework of the Pan-African Province, the geological components and main lineaments (shear zones). Pa (Patos); a (Ile-Ife); b (Senador Pompeu); Ga (Garoua); Ad (Adamaua); Sa (Sanaga); Ou (Oubanguides). (Modified after Trompette, 1994; Kröner and Cordani, 2003).

(Sawyer, 1976) is similar to the Nigeria basement complex due to overwhelming presence of migmatite and assortment of composite gneisses that have suffered polycyclic deformation.
(ii) *Metamorphic isograd:* which marks the first appearance of an index mineral that represents a line of constant metamorphic grade in a regional metamorphic terrain going by increasing metamorphic grade through the metamorphic sequence. This line (isograd) which marks the outer limit of a metamorphic zone and mineral assemblages are similar. Even though, a small section of the Damara orogen falls within lower granulite facies, a larger portion of it is characterized by Amphibolite facies metamorphism in which incongruent melting of biotite predominates. Another lens of higher Amphibolite facies where Sillimanite + K-feldspar + melt forms the main assemblage and finally, a Sillimanite + K-feldspar assemblage. These metamorphic facies and assemblages are similar to those obtained in the basement complex of Nigeria in that the metamorphic grade of some parts of the terrain is typically Amphibolite facies (Rahaman, 1988; Ige *et al.,* 1998), while Granulite facies has been reported in few pockets of the basement complex in areas like the Ikare-Akoko area (Rahaman and Ocan, 1978; Ferre and Caby, 2006).
(iii). *Geochronology:* The Gneissic complex of Eburnean (ca. 2000–1800 Ma) age with Paleoproterozoic inheritance and Pan-African partial reworking; the Paleoproterozoic to Mesoproterozoic gneissic complexes with age between 2100–1000 Ma are adequately represented in the basement complex of Nigeria. Although Neoproterozoic sediments (ca. 840–650 Ma) of the Damara orogen were absent in Nigeria but rather, Tertiary to Resent sediment of largely Campano-Maastrichtian age. The schists and amphibolite are also older than Pan-African. Although, the marble formations in Nigeria were not dated, but similar carbonaceous lithologies are adequately represented in Nigeria basement. Syn-tectonic to late-tectonic granites (ca. 550–520 Ma) and post-tectonic granites (ca. 520–480 Ma) represents overwhelming and unequivocal evidence of the Pan-African magmatism in Nigeria. All the above indicate that migmatite-gneiss formation is rather a widespread geological phenomenon across the African continent and not localized or limited only to Nigeria.

4. Materials and methods

Geological mapping across the terrain was done on foot by creating traverses to the rock outcrops. This traverses in addition to already existing bush paths, major and minor roads make the entire area accessible. During fieldwork, conventional geological tools including hammer, Global Positioning System (GPS), compass clinometer, indelible-ink marker, sample bags, and a digital camera Coolpix L850 was used. During data gathering, rock exposures are examined *in-situ* and their structures documented. Samples are taken as lumps from rock outcrops and prepared for petrographic examination and Lu-Hf isotopic investigation using zircon extracts. Selected migmatite samples are wholesome and fresh. The rocks are chattered into smaller pieces with a jaw crusher and later pulverized in a Tema Mill. Zircon grains from the sample are picked with a pointed pin under the low-power binocular microscope. The zircons were then analysed for Lu-Hf composition and the result plotted using software. The same growth zones of the zircon used for SIMS U-Pb analysis from the samples (A1-A15) were targeted to measure their Lu-Hf isotopic compositions using a Thermo Scientific Neptune Plus MC-ICP-MS coupled to a New Wave Research UP193UC excimer laser ablation system at the Isotope Geoscience Laboratory facility of the University of Taiwan.

5. Results

5.1 Field occurrence

The flat-lying migmatite-gneiss basement is the most extensive unit and forms the country rock, it comprises of migmatite and assortment of gneisses. The migmatite unit hosts several granite intrusions which occur as batholiths and plutons. The country rock extends in all directions into the neighbouring areas and beyond. Even though, the migmatite-gneiss basement is more extensive going by land coverage, the granitoids are more prominent due to their notable elevations as they form main topographic feature of the terrain. The gneiss subunits grade into each other with gradational contacts; however, the contacts appear diffuse in few localities. Nevertheless, the main subunits are unambiguously distinguishable. For instant, other migmatite-looking outcrop of TTG-gneiss is overwhelmingly crisscrossed by veining (Fig. 2a) while the banded types show alternating bands of melanocratic (mafic) and leucocratic (felsic) minerals (Fig. 2b). However, field photographs revealed migmatites as having dark (palaeosome) and lighter parts (leucosome) forming schlieren and nebulitic structures which merge into one another. Palaeosome part of this migmatite represent the parent rock while neosome represent the newly formed felsic parts (Figs. 2c and 2d). All the basement gneisses exhibit distinct leucosome, mesosome, and melanosome (Fig. 2e). Melanosome which represents the darkest parts of the gneisses contain abundant melanocratic (mafic) minerals. Mesosome portion of these gneisses is intermediate in colour between the leucosome and melanosome, usually, it represents unmodified remnant of the parent rock. The entire rock components sometimes show strong deformation and displacement occasioned by faulting (Fig. 2f). Usually, melanosome becomes more conspicuous when it occurs between two leucosome layers. In some instances, the remnants of the parent rock (palaeosome) are arranged in rims around the neosome (Fig. 2g) where injection is the most probable mode of formation. The leucosome has pale-colour and distinctly contain quartz, plagioclase and K-feldspar. It is medium-grained but with noticeable coarser grains (porphyroblasts) of plagioclase. The melanosome is highly biotitic, while hornblende forms common supporting mineral aggregate. The melanosome is medium to fine-grain in texture. The palaeosome in the migmatite appears gneissic and transitional in colour between the leucosome and the melanosome. The palaeosome comprises of medium to coarse-grained quartz, plagioclase, biotite, muscovite and hornblende. Oyinloye, (2007) described similar features from migmatitic basement of Ado-Ekiti in Southwestern Nigeria. The author emphasized the layered and stromatolitic migmatite complex exhibits characteristic strong axial plane foliations. A common feature of the Nigeria migmatite-gneiss basement is the occurrence of distorted quartzo-feldspathic tortuous veins and ptygmatic folds with high asymmetry. The occurrence of palaeosome with complex tortuous veins, augen structures, prevalence of quartzo-feldspartic veins and distorted (folded) neosome (Fig. 2h) suggests that the tectono-thermal activities that formed the rocks probably resulted in partial melting.

5.2 Evidences of partial melting and melt segregation in SW Nigeria

Southwestern Nigeria is a complex orogenic belt located on southern section of the Pan-African belt. It forms part of the Nigerian shield which is located towards south of the Tuareg shield. It exposes a unique section of the migmatite–gneiss–granite basement which forms the root of the orogenic crust. Structural and petrologic evidences for partial melting and melt segregation within the terrain is discussed here. Structural interpretation of the basement rocks (specifically migmatite, gneisses and the granitoids) allows us to fingerprint the distinction between (i) rocks that were original partial melt which forms the metatexite (gneisses); (ii) ancient silicate melts which originated by melt accumulation in the palaeoenvironment which forms the diatexites (migmatite); and (iii) non-indigenous bodies in a host rock which may have been relocated due to lateral thrusting, overfolding, or gravity gliding (granite). According to Toe et al. (2013) and Vanderhaeghe, (2009), this petrologic observation is partly based on the dispersal and amount of the granitic fraction observed both at the scale of rock exposures and how it relates with the host rock. Following this approach, it is practical to distinguish three different structural units in the basement complex of Southwestern Nigeria. The lower unit exposed within the terrain is characterized by diatexites popularly referred to as the migmatite basement *sensu stricto*, the second unit is metatexites (gneisses) which is exposed in small pockets within the extensive migmatitic basement, while the last is numerous granitic bodies which form batholiths and plutons scattered within the country rock in several parts of southwestern Nigeria. Few examples are the Idanre Granite Complex, the Akure-Ikere Ado-Ekiti granite suites, the Omu Aran granite complex, Okenne-Igarra granite suites, and the Lokoja granite bodies.

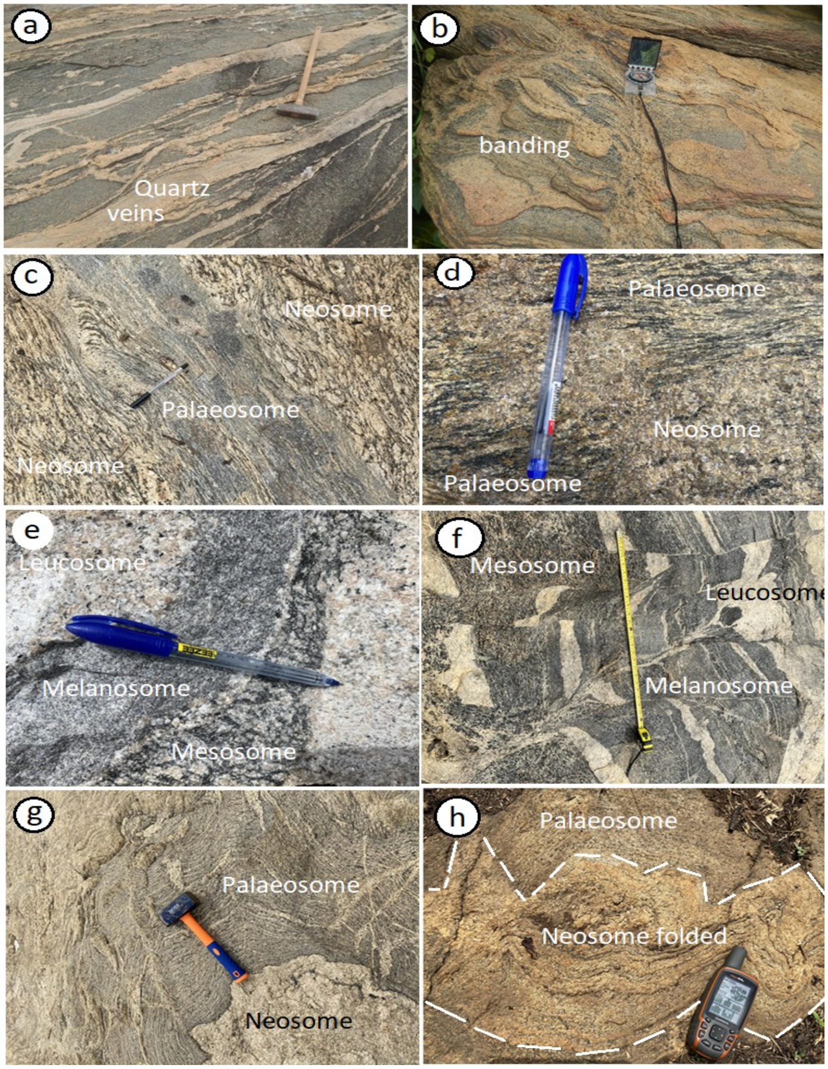

Fig. 2: Field photographs of (a) members of the TTG-gneiss overwhelmingly crisscrossed by quartz veins; (b) a banded variety of the gneiss exhibiting mineralogical banding showing interlayering of melanocratic (mafic) and leucocratic (felsic) minerals; (c) migmatite from the study area showing fine-grained palaeosome (dark) and light-coloured porphyroblasts of feldspar as leucosome; (d) migmatite (diatexite) showing remnant of older rock unit (restite) where melt has been withdrawn without replacement and younger leucosome; (e) gneissic unit (metatexite) in the basement showing fine-grained palaeosome, light coloured leucosome and neosome which is intermediate between the two; (f) leucosome component (light) in a migmatite evidently displaced by multiple system of faults; (g) Neosome component of a migmatite surrounded by palaeosome nucleation, this type of arrangement is only possible by injection; (h) gneissic basement rock (metatexite) displaying strong deformation (folding).

5.3 Petrography

Thin section petrography reveals the migmatite-gneiss units in southwestern Nigeria is composed of essentially quartz, orthoclase feldspar, plagioclase feldspar, and biotite (Fig. 3). Orthoclase feldspar appear as porphyroblasts with greyish colour and well-defined edges (Fig. 3a and 3b). These bulky grains are supported by angular to sub-angular grains of quartz which are scattered randomly within the field of view. Plagioclase are few small grains located among the chaotic mineral interlock; it is characterised by simple albite twinning. Biotite is bladed aggregates with high aspect ratio and characteristic brownish-green colour. Hornblende appear as rounded straw-green minerals with two prominent cleavage directions. The mineral assemblage: quartz + biotite + K-feldspar + opaque in migmatite from the study area represents a medium-grade metamorphic (Lower amphibolite facies) condition. The index assemblage represents a temperature of about 550-600ºC and a pressure between 3 to 10 K bar. Nevertheless, the simultaneous occurrence of K-feldspar and plagioclase might indicate a slightly higher metamorphic conditions which does not exceed upper amphibolite facies metamorphism (670-700ºC) (Ige *et al.* 1998). Sometimes, the migmatitic rock show slight variation in texture occasioned by preponderance of biotite and associated hornblende grains (Fig. 3 c and 3d). Petrographic examination revealed the gneissic rocks show dominance of quartz, feldspar, and biotite. Biotite gneiss exhibits granoblastic texture with prominence of quartz and biotite (Fig. 3e). Quartz is angular to sub-angular, quartz porphyroblasts are set parallel to the long axis of biotite laths. Banded gneiss shows porphyroblasts of quartz poorly arranged among the greenish-brown biotite laths (Fig. 3f).

5.4 P-T Evolution of the Nigeria TTG terrain.

The study area is situated on southern margin of the basement complex of southwestern Nigeria. The regional geology of Nigeria has been described in batches by various authors while the field relationship and metamorphic evolution of the area have not been adequately described. The rocks in this domain followed a path characteristic of biotite dehydration melting in the absence of aqueous fluids being dominant feature of the retrograde *P-T* path (Ige *et al.* 1998). Minimum and maximum estimates of peak temperatures (800-850°C and 900°C) respectively and pressure constraints (0.5-0.7 GPa) emerge from comparison with biotite dehydration experiments in compositionally similar systems as compiled by Kalt *et al.* (1999). Estimating the P-T conditions of the samples investigated is difficult with conventional methods as there are hardly any appropriate thermobarometers to quantify the equilibration conditions of the described assemblages. Constraints of pressure and temperature can also be derived from the stability boundaries of the trondhjemite assemblage (quartz-plagioclase-biotite), for which some of the limiting mineral reactions have been the subject of experimental investigations (Fig. 4).This method was applied to calculate the phase relations relevant for investigating tonalite-trondhjemite-gneiss (TTG) assemblage. The database of Holland and Powell (1990) and the THERMOCALC software (Powell and Holland, 1988), which provides the opportunity to include solid solutions, were adopted. This is important for modelling natural systems in which the compositions of solid solutions change with changing pressure and temperature (Schmadicke and Evans, 1995; Schmadicke and Okrusch, 1997).

5.5 Lu–Hf Isotopic Composition

For the TTG, the 15 evaluated zircon grains yielded ^{176}Lu/^{177}Hf isotopic composition with values within the range 0.00367 to 0.001669 while the ^{176}Hf/^{177}Hf ratio range from 0.281955 to 0.282022 (Table 1). The initial Hf isotope (^{176}Hf/^{177}Hf)i values range between 0.281969 to 0.282005, εHf(t) values ranges between -3.5 to -5.2. The two-stage model age tDM2 = 2080 to 2161, which mainly falls within the range 2080 to 2100 Ma. These tDM$_2$ values all indicated that the inherited zircons were separated from the “Depleted Mantle” around 2.8 ~ 3.0 Ga. Negative εHf(t) values symbolized derivation from crustal source, while tDM2 age implied magma source originated from the chondritic universal mantle reservoir (CHUR) during Mesoarchean.

6. Interpretation of Results

The TTG (represented by Migmatite-gneiss) in the basement complex of Nigeria is comparable to the Bohemian Massif in the Variscan Belt, Germany which was reported by Berger and Kalt, (1999) in that it exhibits

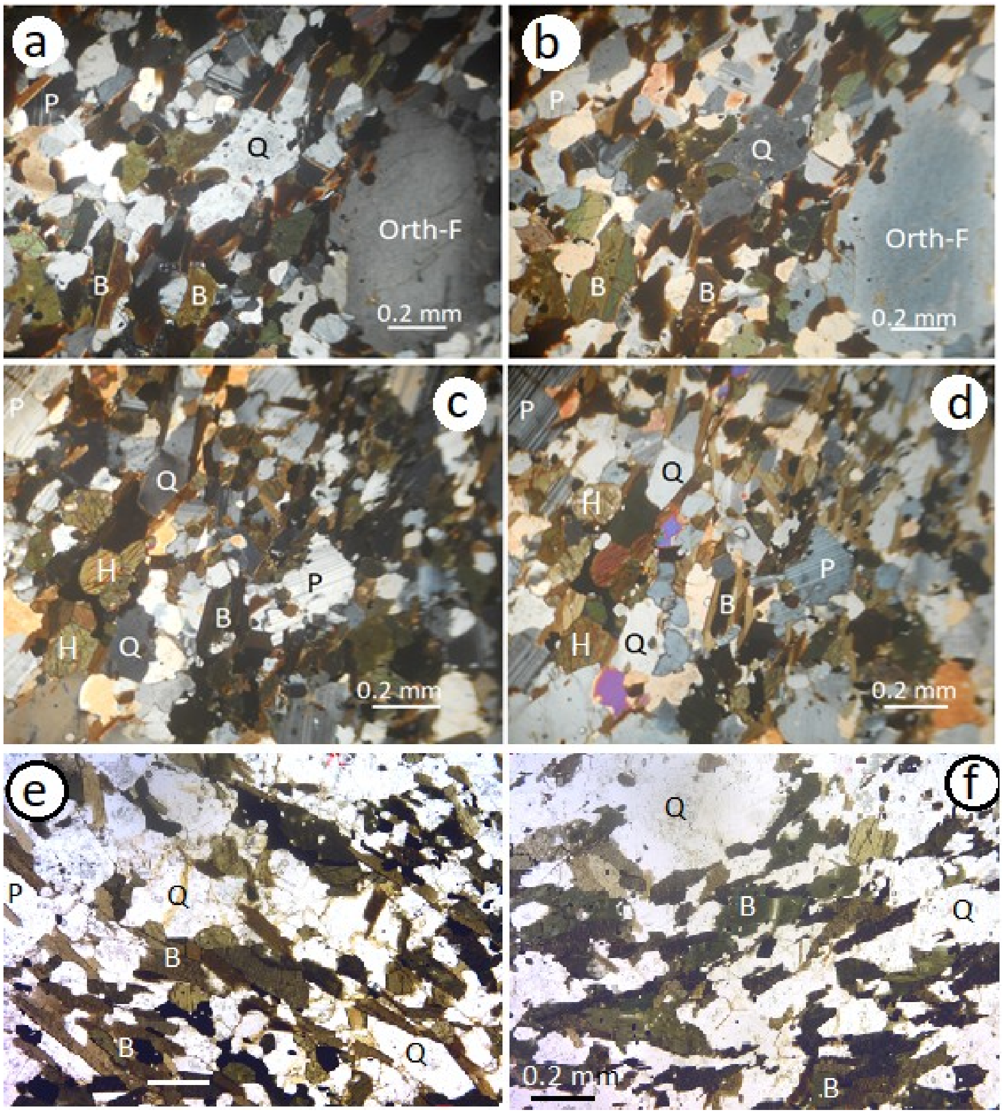

Fig. 3: Photomicrograph of TTG gneiss (migmatite-gneiss) from the study area in transmitted light showing variation in mineral assemblages (a) large porphyroblasts of orthoclase feldspar under (a) cross polarized light (b) plane polarized light and other component minerals like quartz (Q), plagioclase (P), biotite (B) and hornblende (H); (c) crossed polarized version and (d) plane polarized version showing textural variations among the migmatites occasioned by differences in the amount of biotite components; (e) biotite gneiss showing dominance of quartz and biotite; (f) banded gneiss in thin section.

structures ranging from lit-par-lit (banded) to those with nebulitic structures and those that are largely undeformed (Akinola, 2020). TTG gneiss domains often show several convincing proofs of dehydrating melting with unequivocal evidence from reaction textures, pressure and temperature estimate higher than the dry solidus for the rocks, igneous textures, and similar composition for the leucosome. All indicating anatectic melting is vital for migmatisation in southwestern Nigeria. Evidence of granitization in the basement complex of Nigeria includes melting and influx of chemical or both by which pre-existing rocks are transformed into granitoids. Geochemical evidence indicates the granite plutons associated with the migmatite are produced through partial melting of the country rock. Often, the residual metamorphic rock (restite) from which a significant quantity of itinerant silicic components has been withdrawn without replacement are quite common. These form part of field evidences that invigorates the anatectic origin for migmatite. Making inferences from petrological studies to evaluate the pressure-temperature conditions of metamorphism for the basement complex of Southwestern

Nigeria, a medium pressure Barrovian and low-medium pressure conditions was suggested by Rahaman, (1988). This suggestion is in line with the occurrence of certain index minerals. Based on exhaustive geological mapping and metamorphic mineral assemblages particularly of rocks in the Ife-Ilesha axis, the metamorphic facies are diagnostic of greenschist to lower amphibolite grade. Oyinloye (1992) reported based on petrological investigation, geological fieldwork and structural analysis of the gneissose foliation on some gneissic rocks suggest that peak metamorphism in rocks of the basement complex of Southwestern Nigeria actually reached an upper amphibolite facies.

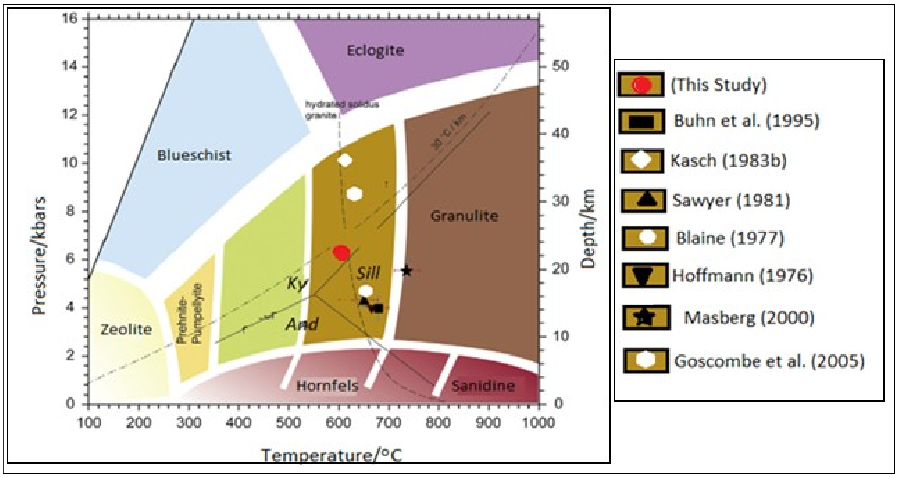

Fig. 4: Pressure–Temperature conditions of migmatite in the study area compared with published previous works and authors on similar rocks in the Damara orogenic belt. (Modified after Toé *et al.* 2013).

Annor, (1995) and Dada *et al.* (1998) have reported some age determinations by isotopic method in the basement complex of Nigeria. Most of these ages indicated that the complex is Archean to Proterozoic. However, Ajibade et al. (1987) reported two groups of ages for these rocks. One is migmatite-gneiss complex of Archaean to Paleoproterozoic while the other is Neoproterozoic age. Recently, Akinola et al. (2021) reported zircon U-Pb age of 590.3 ± 5.3 Ma (Neoproterozoic) for a charnockite intrusive in Idanre area of SW Nigeria. Even with this, the vast basement complex of Nigeria still has scanty geochronological data to actually place a geodynamic constraint on the evolution of the rocks. The Lu-Hf isotopic composition reveals the ancient magma that formed the TTG gneiss in southwestern Nigeria originated from the mantle but was strongly contaminated by crustal melts. This is revealed in the binary diagram of initial Hf *versus* Age (Fig. 5a) where the migmatite-gneiss plots within domain characterized by higher crustal inputs below the Chondritic Universal Reservoir (CHUR) field. This view is in consonance with Oyinloye, (2007) who reported that initiation of crust forming process during the Early Proterozoic (2000 Ma) in Southwestern Nigeria was typified by the Ibadan grey-gneiss which Woakes et al. (1987) considered to have been derived directly from the mantle. On binary diagram of initial $^{176}Hf/^{177}Hf$ *versus* Age (Fig. 5b), the migmatite plots close to initial $^{176}Hf/^{177}Hf$ value of 0.282 with age ranging between 1000 and 1200 Ma. This binary diagram also confirms the melt source is the mantle but was contaminated by detrital materials. This view also supports the finding of Oyinloye (2007) on provenance and evolution of basement complex rocks of Southwestern Nigeria using monazite (a phosphate enriched in light rare earth elements: La, Ce, and Nd) to place a constraint on the origin of these rocks. Monazite is interpreted as a reflection of igneous source associated with rocks of mantle origin which therefore raises a petrogenetic question. Oyinloye, (2007) inferred the presence of monazite in the crystalline rocks reveals the primitive magma source was contaminated with crustal or sedimentary materials. His argument was that $MgO/(Fe_2O_3+MgO)$ ratios of rocks of amphibolitic composition in the area is lower than basalts of pure primitive mantle and this ratio reduces exponentially from the hornblende-gneiss to granite-gneisses.

Table 1: Lu-Hf Isotopic data of the TTG (Migmatite-gneiss) gneiss from the study area

SN	point	Age (Ma)	$^{176}Hf/^{177}Hf$	±2σ	$^{176}Lu/^{177}Hf$	$(^{176}Hf/^{177}Hf)_i$	εHf(t)	tDM (1) (Ma)	tDM (2) (Ma)
A1	A17-01	1077	0.282024	1.10E-05	0.001033	0.282003	-3.5	1711	2080
A2	A17-02	1060	0.282007	1.50E-05	0.000456	0.281998	-4.1	1709	2101
A3	A17-03	1057	0.282004	1.00E-05	0.000985	0.281984	-4.6	1736	2132
A4	A17-04	1082	0.282008	1.30E-05	0.000507	0.281998	-3.6	1710	2088
A5	A17-05	1054	0.282004	1.30E-05	0.000779	0.281989	-4.6	1727	2125
A6	A17-06	1080	0.282007	1.40E-05	0.000488	0.281997	-3.7	1710	2091
A7	A17-07	1063	0.282015	8.80E-06	0.000915	0.281997	-4.1	1718	2102
A8	A17-08	1073	0.282004	2.10E-05	0.000722	0.281989	-4.1	1725	2112
A9	A17-09	1061	0.281982	1.90E-05	0.000593	0.28197	-5.1	1749	2161
A10	A17-10	1071	0.282004	1.30E-05	0.000671	0.28199	-4.1	1722	2111
A11	A17-11	1057	0.282018	1.40E-05	0.000639	0.282005	-3.9	1702	2087
A12	A17-12	1060	0.281981	1.30E-05	0.000367	0.281974	-5.0	1740	2154
A13	A17-13	1055	0.282002	1.50E-05	0.001669	0.281969	-5.2	1771	2167
A14	A17-14	1051	0.282022	2.00E-05	0.000918	0.282004	-4.1	1709	2094
A15	A17-15	1057	0.282007	1.40E-05	0.000692	0.281993	-4.3	1719	2113

Conclusion

The basement complex of Nigeria is a polymetamorphic terrain located within the southern segment of the Pan-African belt which contains migmatite, assorted gneisses and granite. The lithologies, structural components, metamorphic isograds and geochronology reveals the terrain is comparable to the Damara orogen.

Field photographs revealed the migmatite contains palaeosome and neosome while the gneiss contains distinct melanosomes, mesosomes and leucosome. Biotite hornblende-gneiss is overwhelmingly crisscrossed by quartz veins, whereas the banded-gneiss shows alternating bands of mafic and felsic minerals. Field evidences reveals the different gneissic subunits grade into each other and the gradational contacts are sometimes diffuse. However, structural attributes showed the centres of the gneissic subunits are unambiguously distinguishable.

The simultaneous occurrence of palaeosome and neosome in the migmatite, complex tortuous veins, augen structures and prevalence of quartzo-feldspartic veins and intrusive units of predominantly granite suggests that the tectono-thermal activities that affected the gneisses probably resulted in partial melting. The mineral assemblage: quartz + biotite + K-feldspar is predominant in the migmatite-gneiss basement and represents a medium-grade Amphibolite facies metamorphic condition. The index assemblage represents 550-600°C and a pressure within 3 to 10 K bar range. The simultaneous occurrence of K-feldspar and plagioclase might suggest a slightly higher metamorphic conditions which does not exceed the upper amphibolite facies metamorphism (670-700°C).

$^{176}Lu/^{177}Hf$ isotopic composition of the migmatite-gneiss which range between 0.00367 to 0.001669 and $^{176}Hf/^{177}Hf$ ratio between 0.281955 to 0.282022, the initial Hf isotope values between 0.281969 to 0.282005, εHf(t) values between -3.5 to -5.2 and two-stage model age tDM2 between 2080 to 2161 all indicates the inherited zircons were separated from the "Depleted Mantle" or Chondritic Universal Reservoir (CHUR) around 2.8 ~ 3.0 billion years ago. Negative εHf(t) revealed the original migmatitic fluid was characterized by high crustal contaminations while tDM2 age implied the magma that formed the TTG originated from the mantle during Mesoarchean. Field relationships and textural evidences suggests the TTG (Tonalite-Trondhjemite-Granodiorite) gneiss and migmatite in the basement complex of southwestern Nigeria was probably derived from metamorphism of a poorly differentiated quartzo-feldspartic rock. This assertion agrees with the conclusion of Dietrich, (1974) stating that migmatites-gneiss of regional extent which occur in former orogenic belts are ensialic in character.

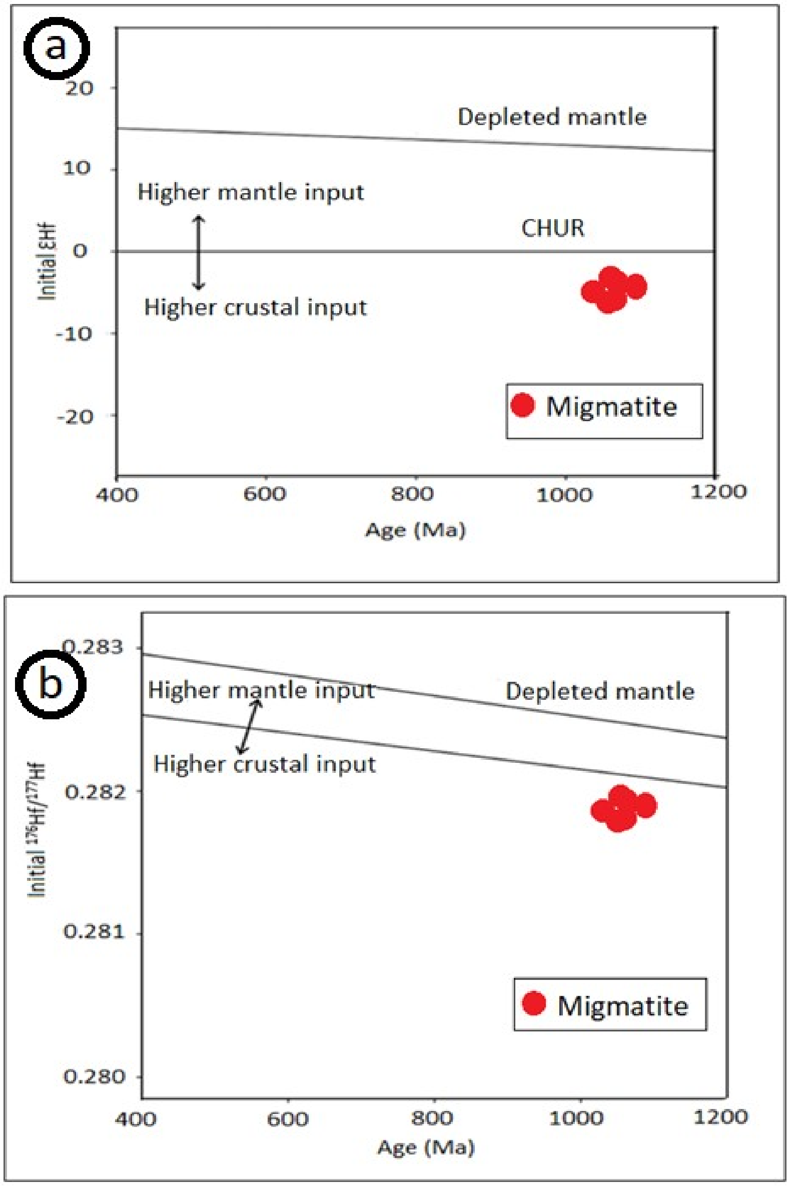

Figure 5: Binary diagram of (a) initial εHf(t) versus Age (Ma) of migmatite in the study, (b) initial $^{176}Hf/^{177}Hf$ isotope versus Age (Ma) of migmatite in the study.

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Declaration of competing interest

Ethical statement

This work is our own original idea and it has not been previously published or is not currently being considered for publication elsewhere. The paper is a reflection of our research findings without any encumbrances.

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References

Ajibade A. C., Woakes, M. R., and Rahaman, M. A. (1988). Proterozoic crustal development in the Pan-African regime of Nigeria. In: Precambrian Geology of Nigeria, GSN, Esho Pub. Kaduna.

Ajibade, A. C., Woakes, M., and Rahaman, M. A. (1987). Crustal development in the Pan-African regime of Nigeria. In: *Proterozoic lithospheric evolution.* (Edited by Kröner, A.) American Geophysical Union. *Geodynamics Series* 17. 259-271.

Akinola, O. O., Ghani, A. A., and Talabi, A. O. (2021) Lu-Hf Isotope and Zircon U-Pb Geochronometry of Idanre Charnockite, Southwestern Nigeria: *Implications for Petrogenesis. Journal of Mining and Geology, Vol. 57(1). pp. 163 – 176.*

Akinola, O. O. (2020). Geology, geochemistry and Petrotectonic setting of the Idanre Granite Complex, Southwestern Nigeria. Unpublished Ph. D Thesis, University of Malaya, Kuala Lumpur 214p.

Akinola, O. O., and Obasi, R. A. (2020). Migmatite and Gneisses in the Basement Complex of Southwestern Nigeria: a re-appraisal of their structural, mineralogical and geochemical diversity. *Journal of Applied Sciences,* 6(8), 1-17.

Annor, A. E. (1995). U-Pb zircon age of Kabba-Okene granodiorite gneiss: Implication for Nigeria's basement chronology. *African Geoscience Review*, 2 (1): 101-105.

Ashworth, J. R. (1976). Petrogenesis of migmatites in the Huntly-Portsoy area, north-east Scotland. *Mineralogical Magazine*, 40 (315) 662-682

Berger, A., and Kalt, A. (1999). Structures and Melt fractions as indicators of Rheology in cordierite-bearing migmatites of Bayerische Wald (Variscan Belt, Germany) *Journal of Petrology*, 40(11) 1699-1719.

Best, M. G. (2003). Igneous and Metamorphic petrology (2nd ed). Blackwell Publishing company. p729.

Black, R., Latouche, L., Liegeois J. -P., Caby, R., and Bertrand, J. M. (1994). Pan-African displaced terranes in the Tuareg shield (central Sahara). *Geology.* 22. 64-644.

Blichert-Toft, J., and Albarède, F. (1997). The Lu-Hf isotope geochemistry of chondrites and the evolution of the mantle-crust system. *Earth and Planetary Science Letters*, 148 (1-2), pp 243-258.

Bowen, N. L. (1928). *The Evolution of the Igneous Rocks.* Princeton Univ. Press, Princeton, N. J., 334p.

Bruguier, O., Dada, S., and Lancelot, J. R. (1994). Early Archaean component (> *3.5* Ga) within a 3.05 Ga orthogneiss from northern Nigeria: U-Pb zircon evidence. *Earth Planetary Science Letters,* 125. 89-103.

Büsch, W. (1966). Petrographie und Abfolge der Granitisation im Schwarzwald-V, *Neues Jahrb. Min.,* Abh., 104, p. 190-258.

Caby, R. (1989). Precambrian terranes of Benin-Nigeria and Northeast Brazil and the Late Proterozoic South Atlantic fit. *In:* Dallmeyek, R. D. (ed.) Terranes in the Circum-Atlantic Palaeozoic Orogens. *Geological Society of America Special Papers.* 230. 145-158.

Cesare, B., Acosta-Vigil, A., Ferrero, S., and Bartoli, O. (2011). Melt inclusions in migmatites and granulite. In: (Eds.) Marnie A. Forster and John D. Fitz Gerald, *Journal of the Virtual Explorer*, 38, (2) 1-19.

Dada, S. S., Brique, I., and Birck, J. L. (1998). Primodial crustal growth in northern Nigeria; preliminary Rb-Sr and Sm-Nd constraint from Kaduna mignatite gneiss complex. *Journal of Mining and Geology,* 34 (1) pp 1-6.

Dietrich, R. V. (1964). Igneous activity in the Southern Appalachians, *Tectonics of the Southern Appalachians* (Lowry, W. D. editor). *Va. Poly. Inst. Geol. Sci. Mem.* 1, Blacksburg, Va., p. 47-61.

Dietrich, R. V. (1974). Migmatite- a resumé. *Journal of Geological Education,* 144-156

Dietrich, R. V., and Mehnert, K. R. (1961). Proposal for the nomenclature of migmatites and associated rocks. *International Geological Congress, 21st Session (Norden),* Part XXVI, p. 1-21; Suppl. Vol. Sect. 1-21, p. 56-67.

Eskola, P. (1933). On the differential anatexis of rocks. *Bull. Comm. Geol Finlande,* No 103, p. 12-25.

Ferré, E. C., and Caby, R. (2006). Granulite Facies Metamorphism and Charnockite Plutonism: Examples from the Neoproterozoic Belt of Northern Nigeria. Proceedings of the Geologists' Association - *Geological Society of London* 118(1):47-54.

Ferré, E. C., Deleris, J., Bouchez, J. L., Lar, A. U., and Peucat, J. J. (1996). The Pan-African reactivation of Eburnean and Archaean provinces in Nigeria: structural and isotopic data. *Journal of the Geological Society of London*, v.153, p.719–728.

Gevers, T. W. (1931). The Fundamental Complex of Western Damaraland, South West Africa. Unpubl. D. Sc. Thesis, University of Cape Town.

Grant, N. K. (1978). Structural distinction between a metasedimentary cover and an underlaying basement in the 600-m.y.-old Pan-African domain of north western Nigeria, West Africa. *Geological Society* of *America Bulletin,* 89 *50-58.*

Hartnady, M. I. H., Kirkland, C. L., Dutch, R. A., Bodorkos, S., and Jagodzinski, E. A. (2018). Zircon Hf isotopic signatures of the Coompana Province in South Australia *Report Book* 2018/00019 p. 132-144.

Holland, T. J. B., and Powell, R. (1990). Holland, T. J. B. and Powell, R. 1990. An enlarged and updated internally consistent thermodynamic dataset with uncertainties and correlations: the system $K_2O – Na_2O – CaO – MgO – MnO – FeO – Fe_2O_3 – AI_2O_3 – TiO_2 – SiO_2 – C – H_2 – O_2$. *Journal of Metamorphic Geology 8, 89-124.*

Holmquist, P. J. (1921). Typen und Nomenklatur der Adergesteine. *Geol. Foren Stockholm Fork,* Bd. 43, p. 612-631.

Holmquist, P. J., 1916, Swedish Archaean structures and their meaning. *Bull. Geol. Inst. Uppsala,* 15, p. 125-148.

Huber, H. M., and Niggli, P. (1943). Uber die Namengebung bei grobgemengten Gesteinen. *Schweiz. Min. Petr. Mitt.,* Bd. 23, p. 72-160.

Ige, O. A., Okrusch, M., Schüssler, E., Schmädicke, E., and Cook, N. J. (1998). The metamorphosed mafic-ultramafic complex of Mokuro, llesha Schist Belt, southwestern Nigeria. *Journal of African Earth Sciences.* Vol. 26, No. 4. pp. 593.616, 1996

Jung, J., and Roques, M. (1936). Zoneographie des schistes cristallins du Massif Central Frangais. *Rev. Sci. Nat. Auvergne,* v. 1(4), p. 7ff.

Jung, J., and Roques, M. (1952). Introduction a l'etude zoneographie des formations cristallophylliennes. *Bull. Serv. Carte Geol. France.* 235, p. 1-62.

Kalsbeek, F. (1970). *Medd. Grønland,* 189, part I.

Kalt, A., Berger, A., and Blumel, P. (1999). Metamorphic evolution of cordierite-bearing migmatites of the Bayerische Wald (Variscan Belt Germany) *Journal of Petrology*, 40, 601-627.

Kemp, A. I. S., Hawkesworth, C. J., Foster, G. L., Paterson, B. A., Woodhead, J. D., Hergt, J. M., Gray, C. M., Whitehouse, M. J. (2007). Magmatic and crustal differentiation history of granitic rocks from Hf–O isotopes in zircon Science, 315 (2007), pp. 980-983

Klemm, D., Schneider W., and Wagner, B. (1984). The Precambrian metavolcanic-sedimentary sequence east of Ife and Ilesha. SW Nigeria. A Nigerian "greenstone belt" *Journal of African Earth Sciences.* 2, 2. 161-176.

Konopasek, J., Kroner, S., Kitt, S., Passchier, C., and Kroner, A. (2005). Oblique collision and evolution of large-scale transcurrent shear zones in the Kaoko belt, NW Namibia. *Precambrian Research,* 136, 139–157.

Kröner, A., and Cordani, U. (2003). African, southern Indian and South American cratons were not part of the Rodinia supercontinent: evidence from field relationships and geochronology. *Tectonophysics*, 375, 325– 352.

Liegeois, J.-P., Black, R., Navez, J. and Latouche. L. (1994). Early and late Pan-African orogenies in the Air assembly of terranes (Tuareg shield, Niger). *Precambrian Research.* 67. 59-88.

Mehnert, K. R. (1968). *Migmatites and the origin of granitic rocks.* Elsevier, Amsterdam, 393p.

Miller, R. M. (2008). Miller, R.M., 2008. The Geology of Namibia. Neoproterozoic to Lower Palaeozoic, vol. 2. Geological Survey of Namibia.

Miller, R. M. (1983). The Pan-African Damara Orogen of South West Africa/Namibia. *Special Publication Geological Society of South Africa.*

Oyinloye, A. O. (1992). Geology, geochemistry and genesis of the Iperindo primary gold deposits, Ilesha schist belt Southwestern Nigeria, *unpublished Ph.D. Thesis*, Univ. Wales, Cardiff, U.K. 267p

Oyinloye, A. O. (2007). Geology and Geochemistry of some crystalline rocks in Ilesha, southwestern Nigeria; implications on provenance and evolution *Pakistan journal of Sci. Ind.* (50), (4) 223-231.

Piccoli, G. (1958). II problema delle migmatiti attraverso mezzo secolo di recerche. *Periodico Mineral.,* 27, p. 1-87. [Th ere is a Spanish translation of this article: Piccoli, 1960. El problema de las migmatites a traves de med) siglo de investigaciones. *Rev. Fac Ciencias Ex., Fis. Nac. Cordoba, Comm. Mus. Min. y Geol.,* No. 37, p. 5-104.]

Pidgeon, R. T., Van Breemen, O., and Oyawoye., M. O. (1976). Pan-African and earlier events in the basement complex of Nigeria. 25th International Geological Congress. Sydney. Australia. 3. 667.

Powell, R. and Holland, T. J. B. (1988). An internally consistent dataset with uncertainties and correlations: 3. Applications to geobarometry, worked examples and a computer program. *Journal Metamorphic Geology 6. 173-204.*

Rahaman, M. A. (1988) Recent advances in the study of the basement complex of Nigeria. *In:* Precambrian Geology of Nigeria. Geological Survey of Nigeria. 11-43.

Rahaman, M. A., and Ocan, O. O. (1978). On relationships in the Precambrian migmatitic

gneisses of Nigeria. *Journal of Mining and Geology* 15, 23–32.

Reitan, P. H. (1969). Temperatures with depth resulting from frictionally generated heat during metamorphism: *in* Igneous and metamorphic geology. *Geol. Soc. Am., Mem.* 115, p. 495-512.

Sawyer, E. W. (1976). The Geology of an Area South-East of Walvis Bay. Part 1: Lithology, Sedimentation and Field Relationships. Open File Rep. Geol. Survey. Namibia, RG 3.

Sawyer, E.W., 2008, Atlas of migmatites: Quebec, Mineralogical Association of Canada, *Canadian Mineralogist Special Publication* 9, 386p.

Scheumann, K. H. (1936). Zur Nomenklatur migmatitischer und verwandter Gesteine. *Tschermaks Min. Petr. Mitt.,* Bd. 48, p. 297-302.

Schmadicke E., and Okrusch, M. (1997). Phase relations of chlorite-talc-amphibole assemblages, with applications to ultramafic rocks from the KTB pilot hole, Bavaria. *Geologische Rundschau, lKTB Supplement) 86, 212- 221.*

Schmadicke, E. and Evans, B. W. (1995). Phase relations in CMASH and NCMASH, with applications to ultramafic high-pressure rocks. *Bochumer Geologische Geotechnische Arbeiten 44, 204-208.*

Sederholm, J. J., (1907), Om granit och gneis. *Bull. Comm. geol. Finlande,* N:o 23, p. 1-110. [An English translation of this article appears in Sederholm, J. J., 1967. Selected Works: Granites and Migmatites. Wiley, New York, 608p.]

Toé, W., Vanderhaeghe, O., André-Mayer, A.-S., Feybesse, J.-L., and Milési, J. -P. (2013). From migmatites to granites in the Pan-African Damara orogenic belt, Namibia. *Journal of African Earth Sciences* 85 62–74.

Tubosun, I. A., Lancelot, J. R., Rahaman, M. A and Ocan, O. (1984). U-Pb Pan-African ages of two charnockite-granite associations from Southwestern Nigeria. *Contributions to Mineralogy and Petrology,* 88. 188-195.

Trompette, R. (1994). Geology of Western Gondwana (2000– 500 Ma). Balkema, Rotterdam. 350 pp.

Turner, D. C. (1983). Upper Proterozoic Schist Belts in the Nigerian sector of the Pan-African province of West Africa. *Precambrian Research.* 21. 55-79.

Turner, F. J. (1968). *Metamorphic Petrology — Mineralogical and field aspects.* McGraw-Hill, New York, 403 p.

Vanderhaeghe, O. (2009). Migmatites, granites and orogeny: flow modes of partially molten rocks and magmas associated with melt/solid segregation in orogenic belts. *Tectonophysics* 477, 119–134.

Wegmann, C. E., (1935). Zur Deutung der Migmatite. *Geol. Rundschau,* Bd. 26, p. 305-350.

Winkler, H. G. F. (I967). *Petrogenesis of Metamorphic Rocks,* 2nd ed. New York (Springer-Valag

Woakes, M., Rahaman, M. A., and Ajibade, A. C. (1987). Some metallogenic features of the Nigerian basement. *Journal of African Earth Sciences,* 6, *655-664.*