Journal of Mining and Geology Vol. 57(1) 2021. pp. 163 - 176 0022-2763

Lu-Hf Isotope and Zircon U-Pb Geochronometry of Idanre Charnockite Southwestern Nigeria: *Implications for Petrogenesis*

Akinola, O.O.[1], Ghani, A.A.[2] and Talabi, A.O.[1]
[1]Department of Geology, Ekiti State University, Ado-Ekiti, Nigeria.
[2] Department of Geology, University of Malaysia, Kuala Lumpur, Malaysia.
Corresponding E-mail: abel.talabi@eksu.edu.ng

Abstract
The research presents new information on Lu-Hf isotopic composition and zircon U-Pb age to explain the origin of Idanre charnockite in relation to granite plutonism in Nigeria. Field assessment showed intermix of granite and charnockite on a single outcrop in the neighbourhood of the study area suggesting contemporaneous formation of the two rocks.The range of emplacement age of Idanre charnockite as revealed by $^{206}Pb/^{207}Pb$ age dating is 569 ~ 613 Ma with a mean value 590.3 ± 5.3 Ma (MSWD = 0.82).Furthermore, $^{176}Lu/^{177}Hf$ isotopic ratio (range: 0.000416 ~ 0.000935), initial $^{176}Hf/^{177}Hf$ ratios (range: 0.281957 ~ 0.281984) and εHf(t) (range: -14.8 to -16.6) indicated that magma was derived from melting of crustal components. Two-stage model age tDM2 (range: 2400 ~ 2500) suggested that the magmatic fluid contain components that were separated from the primitive mantle during Neo-archean. Zircon morphology and Th/U ratio revealed that the charnockite had magmatic origin. The zircon U-Pb age coincided with Neoproterozoic (Pan-African) orogenic episode. The age of Idanre charnockite is comparable to granitoids and charnockite intrusive units located within and beyond Nigerian borders.

Keywords: *Charnockite, Idanre, Lu-Hf, εHf(t), tDM2 age, magmatic*

Introduction

Nigeria Charnockite

Charnockite has been an interesting rock in the basement terrain of Nigeria for three reasons; the controversy that trails its origin and classification, its common association with granitoids and its petrologic significance which stems from unique colour and application in polished blocks. The controversial origin makes petrogenetic synopsis of the rock a major task. Several previous researchers believed it is magmatic while others claimed an origin related to metamorphism from granulite facies domain. These different ideas have considered field geology, geochemistry, geochronology, or a combination of some of these to decipher the true origin. The lithologic link between charnockite and granites has been reported from different parts of the Nigeria basement and different authors have interpreted these associations differently. Some occur as discrete bodies isolated from granite units, some are located adjacent to granite plutons while in few cases, some are located within the core of granite bodies.

In Nigeria, research works on charnockite are not common like its granite counterpart probably due to its not being widespread like granitoids which form a major component of the basement complex. However, among recent works are Ademeso (2009) who investigated deformation traits in a charnockitic unit around Akure southwestern Nigeria. Ekwueme and Kroner (2006) reported that charnockite are formed on a regional scale and linked charnockite in Obudu area with adjacent tectono-metamorphic and widespread event in Cameroon which was marked by charnockite-granulite formation and migmatization (Toteu et al., 1994, 2001). This corroborates Cooray (1977) earlier suggestion that charnockites in Nigerian Basement exhibit several characteristics which signifies metamorphic origin and should be referred to as of a hypersthene gneiss. Ekwueme and Kroner (2006) further stated that the idea of Hubbard (1975) suggesting widespread granulite-facies metamorphism being responsible for occurrence of charnockite in Nigeria was disputed by authors like (Orajaka, 1971; Rahaman and Ocan, 1978; Tubosun et al., 1984) who upheld magmatic origin. However, Kilpatrick and Ellis (1992) indicated possibility of charnockite originating from both magmatism and metamorphism. Oyawoye (1962, 1964) believed Nigeria charnockite is metamorphic and presented a metamorphic model. Olarewaju, (1987, 1988) reported that charnockite was formed through magmatism and suggested fractional crystallization model. Ademeso, (2009) reported that Rahaman et al. (1988) presented a tectonic evolution model while Dada et al. (1989) offered a model supporting igneous origin. However, the researcher wants to believe that even if both metamorphism and magmatism could trigger charnockite formation, at least only one stands sure for any unit among several others in a particular area of the basement; except a single pluton can be formed simultaneously by the two methods. This study investigates zircon U-Pb age and Lu-Hf isotopes' geology of Idanre charnockitic rock located within the basement complex terrain of Southwestern Nigeria with a view to shed more light on its petrogenetic significance.

Location of Study

Idanre and environs (study area) lie between latitudes 7°00' N to 7°14' N and longitudes 5°00' E to 5°14' E (Fig. 1). The study area covers southwestern corner of the topographic map sheet of Akure stretching across an area of approximately 676 km² (the Ondo State Capital). Idanre lies to the SSW of Akure, it is situated on the eastern side of Ondo town and southeast of Owena. Idanre area is accessible and has major road linked with Alade and Akure in the north and Owena in the northwest. The area is unique for having the highest concentration of Granite in Nigeria which is responsible for its tourism potentials. However, despite its popularity as tourists' destination, yet it is geologically one of the least known regions in southwestern Nigerian. It contains one of the largest mountain ranges making up the highlands of Yorubaland plateau which attains a height of 900 m in Idanre town. The amazing topographic view of the terrane occasioned by magnificent Idanre granite complex has not attracted vigorous geological investigations for two main reasons. First, the steep slopes and rugged topography have constituted a barrier to geological studies; secondly, due to crude oil, granite domains are regarded as economically unviable in Nigeria. Roughly, the area occupies central part of the Basement complex of southwestern Nigeria.

Topography

The topographic map shows that conical hills form the main relief feature of Idanre area. The general terrain has an elevation ranging between 180 - 620 m above the mean sea level. This spectacular characteristic feature indicates that Idanre town is situated on flat terrain surrounded by steep and sparsely vegetated lofty hills. The hills, being the charming scenic beauty of the town has also attracted the attention of geologists and tourists

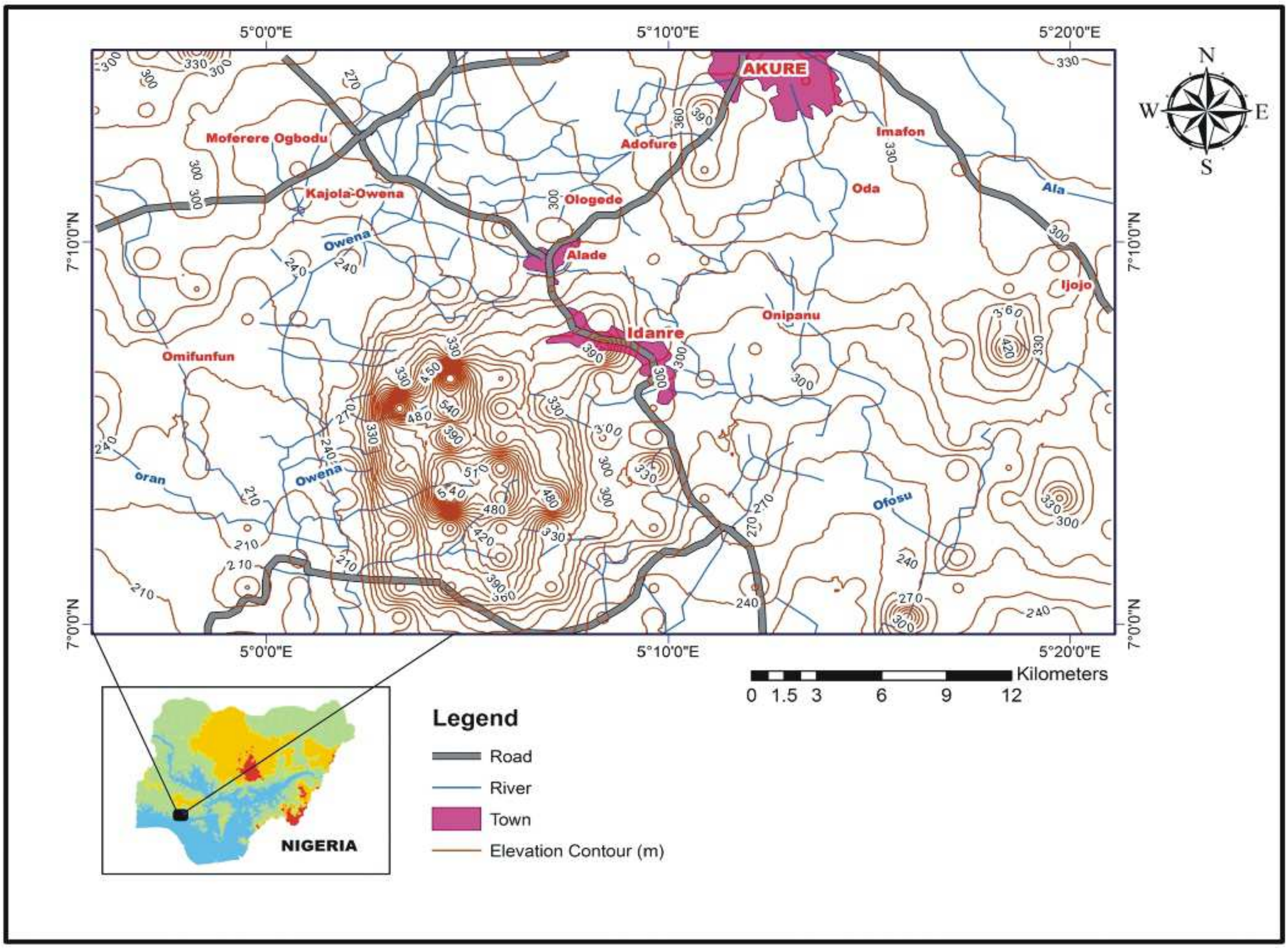

Fig. 1: Location of study

in the recent time. Geomorphologically, the study area has an undulating topography occasioned by massive granite bodies which surround the town of Idanre. The Idanre Hills spreads out into a vast expanse of land extending beyond the built-up areas of the town. The northern, western, and eastern parts of the study area form relatively flat terrain (Fig. 1). This topographic variation reflects some lithologic control as low-lying and highly denuded rocks of gneissic composition occupy the lowlands and plains while the granitoid form prominent hills. The elevation of this terrain impressed a unique weather condition on the study area as it receives orographic rainfall more than the surrounding neighbourhoods.

Climate and Weather Condition

The Idanre area experiences a tropical climate that is warm throughout the year. However, the wet season is humid and cloudy; the dry season is warm, muggy, and partly dry. The study area experience high temperature range between June and October. However, the most pleasant weather conditions are recorded between June and September. The overall temperature typically fluctuates between 65°F to 87°F (18.33°C ~ 30.56°C), it rarely extends outside the range (58°F ~ 91°F). The wet season lasts about 7 months, from early April till end of October, with about 45% possibility of a given day being a wet day. The probability of a wet day peaks about 80% in September. Unlike temperature, which typically exhibits nocturnal and diurnal variations, the dew point tends to change gradually. Consequently, while temperature may drop at night, a muggy day is typically followed by a muggy night. The average daily solar energy per square meter does not vary significantly over the course of the year, throughout the year it remains within 0.5 kilowatt-hours of 4.7 kilowatt-hours. Based on direct measurements and observations, the changing climatic condition reflects interplay of cloud cover, temperature and humidity and wind. The precipitation is orographic and is distinct; its distribution differs significantly from the neighbouring Akure and Owena towns.

Geological Setting

Regional Geology

Nigeria basement forms part of a regional domain known as Pan-African orogenic belt (Adetunji et al., 2016). It is located on eastern side of the Man shield segment of West African craton and directly south of the Tuareg shield (Fig. 2). The latter, according to Gasquet et al. (2008) represents preserved remnant of Pan African terrain that collided with West African craton.

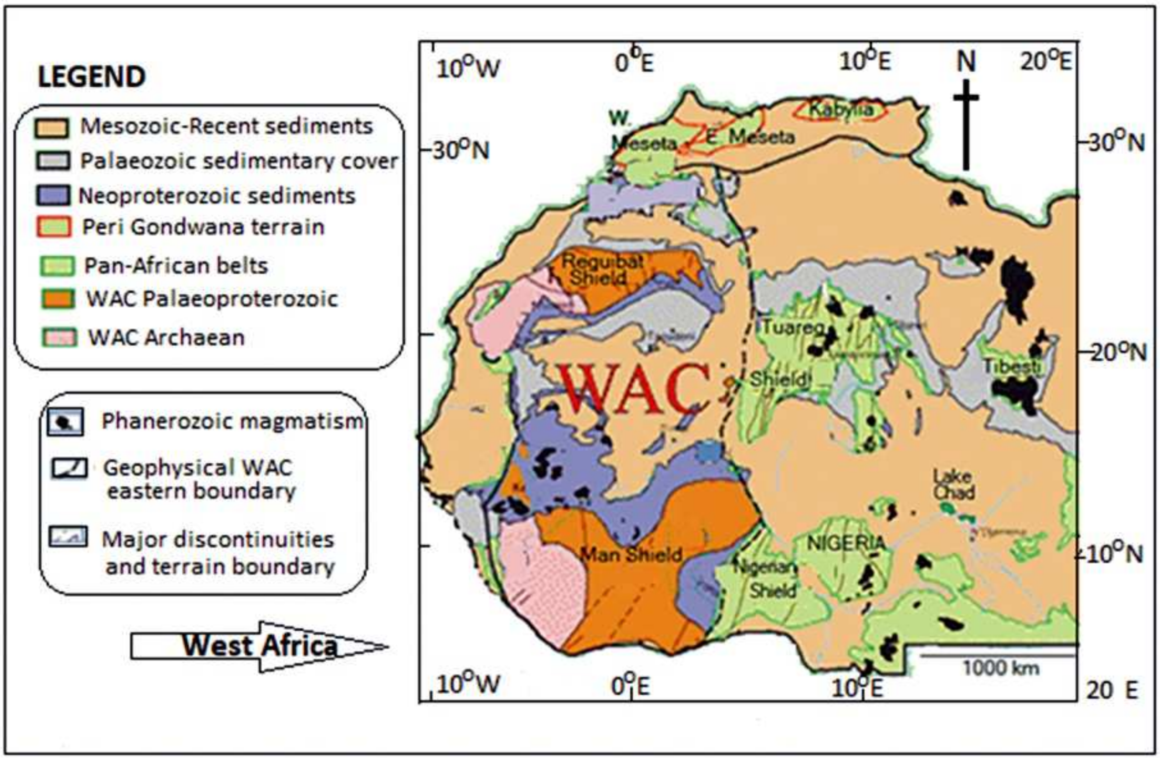

Fig. 2: Regional Map of Nigeria basement in relation to Man shield, Tuareg Shield, and the Pan African belt. (after Fabre, (2005) and Liégeois, *et al*., 2005). (WAC: West African Craton)

Nigeria is underlain by crystalline rocks of Precambrian (Paleozoic-Proterozoic) age. The rocks are the migmatite-gneiss complex, the Schist Belts and the Older granite, Mesozoic granitoids, rhyolite and sedimentary sequences and Cenozoic volcanic rocks (basalts and trachyte). Others are the sediments (sands, shale, sandstones, and lignite) and alluvial sands intercalated with clays and pebbles (Fig. 3). Hockey et al. (1986) noted that the intensity of metasomatism and structural reconstruction of the basement during Pan-African tectono-thermal activities is of a magnitude that obliterated older orogenic signatures. The migmatite-gneiss complex is most widespread (Rahaman 1988), structurally complex (Hockey et al., 1986; Oluyide 1988) and heterogenous (Elueze 1982; Rahaman et al., 1988). The unit is Archaean-Paleoproterozoic in age (Grant 1970; Rahaman et al., 1984; Ekwueme 1990; Dada et al., 1993; Ekwueme and Kroner 1992). The Schist belt comprises dominantly of supracrustal units of schistose assemblages that are preserved in low-grade metamorphism (Ajibade 1976; Turner 1983). The schist belts are infolded into the older gneissic units and have age range between Paleoproterozoic to Mesoproterozoic (Fitches et al., 1985; Annor 1998).

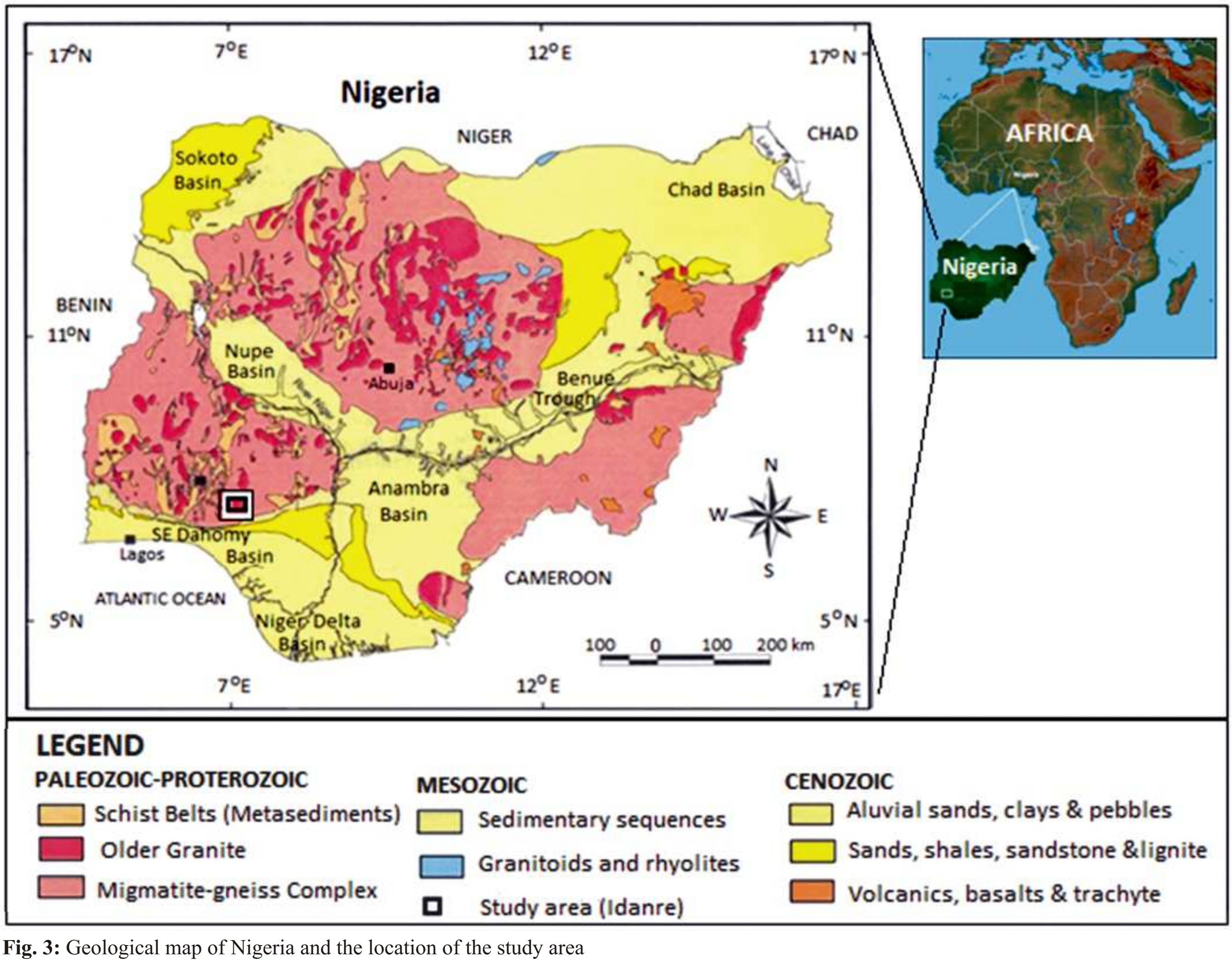

Fig. 3: Geological map of Nigeria and the location of the study area

The granitoids, often referred to as Older granite comprise of granites, granodiorites, adamellite, charnockite, aplite and pegmatite (Rahaman 1988). The granitoids are deep sited orogenic plutons that are now exposed on Earth's surface. They are exclusively Pan-African (Neoproterozoic) in age (Matheis and Caen-Vachette 1983; Tubosun et al., 1984; Key et al., 2012; Adetunji et al., 2016).

Geology of Idanre Area

Idanre area is underlain by migmatite, granite and charnockite (Fig. 4). Migmatite the main country rock of low-lying units with widespread deformation. Granite occurs as prominent steep sided plutons throughout the terrain while charnockite occur as small rounded units within the centre of porphyritic granite.

These granitoids exist in three textural forms (fine-grained, coarse-grained undifferentiated type and the porphyritic). The charnockite unit under investigation for age determination occur at the centre of the porphyritic granite unit. Idanre area is topographically unique for having breath-taking landscape occasioned by these towering granite masses.

Charnockite in Idanre occur as masses with low to average heights and are characterized by unique greenish-grey colour and exfoliation (spheroidal) style of weathering. Texturally, it is a medium-grained rock containing interlocked aggregates of plagioclase, quartz, biotite, pyroxene, orthoclase, and magnetite which is evidently visible in hand specimen. The first three minerals account for over 85% of the bulk mineralogy, others constitute less than 16% of the rock.

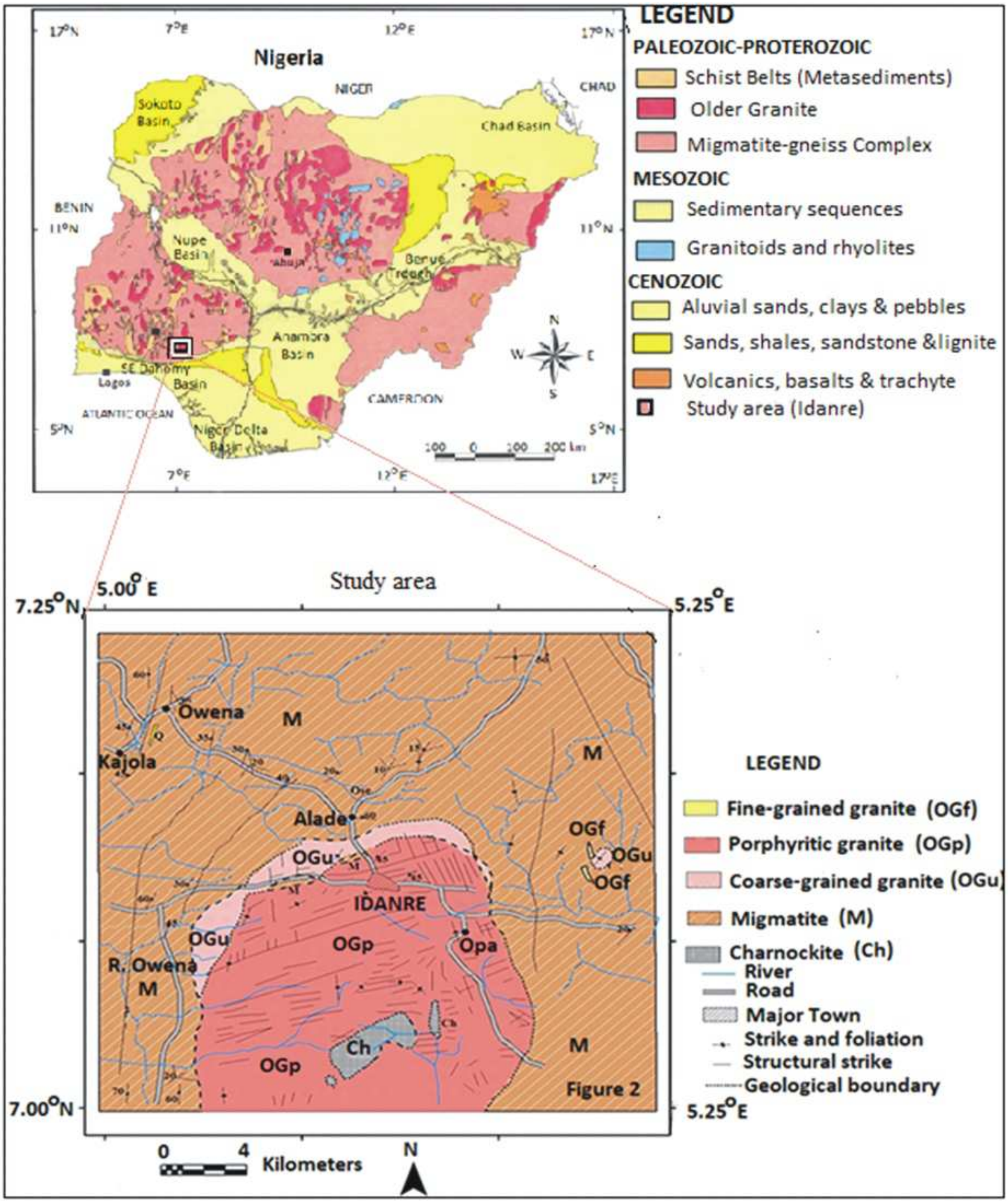

Fig. 4: Geologic map of study area

Tectonic Implication

The entire reactivated terrain of Nigeria which is commonly called Nigeria shield extends into the Brazilian Orogeny of South America prior to Gondwana continental break up originated during Neoproterozoic (750-450 Ma). Southwestern Nigeria basement form one of two large areas where the Precambrian crystalline rocks are exposed. The tectonic evolution of the basement was conceptualized in the works of Rahaman (1988). However, several earlier workers (e.g. Burke and Dewey 1972; Caby et al., 1981; Leblanc 1976; Burke et al., 1977; Black et al., 1979) have recognized the cryptic suture separating West African craton from Pan-African domain which has specific geodynamic implications. Burke and Dewey (1972) suggested closure of an Atlantic-type ocean by continent-continent collision while Black et al. (1979) relates this closure to active eastern continental margin and passive western continental margin along this suture line. The belt was formed by several massive continental blocks which shifted westward in drifting overlapping tectonic cycles to intersect the eastern margin of West Africa craton during oblique collision (Ferré et al., 2002). This movement was accomplished above a Benioff zone that dips eastward slipping under the Pan-African province (Bessoles and Trompette 1980). The Pan-African belt comprise of two (northern and southern) parts, the northern part consists of area around the Pharusian belt (Tuareg shield) towards east, west, and north (Liégeois et al., 2003) while the southern section extends from Pharusian belt downward into northern fringe of Congo craton (Adetunji et al., 2016). The Nigeria segment consists of two (eastern and western) parts separated by a structural divide recognized through remote sensing. This structural discontinuity which occurs on a regional scale has not been studied in detail. The western terrain has an origin linked with continental rifting processes which post dated a crustal extension followed by development of graben structures upon which rocks of the schist belts were laid down (Ajibade 1980; Elueze 1992). The overall transformation of this terrain resulted from effects of this oblique collision, the Nigeria-Tuareg shield areas towards West African craton developed high-temperature warping which climaxed in anticlinal structures and wrench-faults (Kröner and Stern 2005). Rahaman et al. (1988) therefore suggested a model involving opening and closing of an ocean basin behind the island/volcanic arc (Pharusian belt). "The presence of basalts of possible oceanic origin, island arc and marginal trough volcano-elastic assemblages, widespread calc-alkaline plutonism and paired metamorphic belts, including high-pressure eclogitic schists, strongly suggest that active subduction processes were at work" (Caby et al., 1979).

Granite belts which produced granitoids of mainly calc-alkaline affinity that the charnockite is associated represent plutonic equivalents of the volcanic rocks removed by erosion resulting from subduction of oceanic crust beneath the western continental mass about 600 Ma. This triggered crustal thickening and resulted in deformation of the sedimentary sequences, reactivation of the litho-facies and the emplacement of the Pan-African granites (McCurry 1976).

Materials and Methods

The methods adopted during the research include fieldwork and sampling as well as laboratory works. During field exercise, outcrop exposures were examined, textural and structural features were documented and described while laboratory works entailed thin section petrography, zircon extraction process, zircon selection procedure, cathodoluminescence and Laser Ablation. Zircon geochemistry, U-Pb geochronology and Lu-Hf isotopic investigation.

Fieldwork and Sampling

Systematic geological mapping was conducted on the study area using conventional mapping tools like GPS, sledge hammer, compass clinometer and other accessories. Methodological approach involves standard geological sampling technique which ensured that weathered samples were avoided. Twenty charnockite samples were collected form outcrop exposures randomly. Samples were labelled and processed for both geochronological and Lu-Hf data analysis. Samples weighing approximately 4 kg were used for zircon U-Pb dating, and another for Lu-Hf isotopic studies. The samples were reduced by crushing in a jaw crusher and later pulverized in a Tema mill and were subsequently subjected to sieving.

Laboratory Procedures

Zircon grains in the pulverized rock was separated through conventional method picking them under a binocular microscope. Due to morphological variations, only 25 zircon grains among many with variable sizes and shapes were analysed. Only good and viable spots believed to carry reliable information about BSE images were selected as ablation spots for Lacer Ablation procedures. Before dating, transmitted, and reflected light images and Back scatter electron image (BSE) of the zircon grains were captured using petrological microscope attached to cathodoluminescence (CL) facility and a JEOL JSM- 6510 scanning electron microscope (SEM) linked to GATAN mini-CL detector. All geochronologic evaluations including CL and BSE imaging was undertaken at SEM facility of Geosciences Department, National Taiwan University, Taipei.

Results

The results in this study are presented in Tables and figures. Table 1 represents petrographic analysis; Table 2 is the result of U-Pb geochronology while Table 3 shows the Lu-Hf isotopic composition.

Petrography

Idanre charnockite contain quartz, biotite, plagioclase and hornblende (Table 1). Biotite as bladed mineral aggregate with red to brownish colour (Fig. 5a), plagioclase occurs as albite crystals with large parallel fractures aligned obliquely to the twin plane (Fig. 5b). The prominent Carlsbad twins are supported by biotite exhibiting colour that ranges between red, yellow, and green (Fig. 5c). Biotite laths exhibit characteristic bird view structure. Hornblende is irregularly shaped stubby dark green mineral with two prominent cleavages. Smaller grains of quartz are dispersed around the interstices of biotite and albite crystals. Few quartz grains are euhedral, but some are subhedral with no visible alteration, some are transparently clear. Some slides contain pyroxene with characteristic mesh texture and colour that range between yellow and pink (5d).

Zircon Morphology and Chemistry

Zircon grains from charnockite vary in size between 100 and 250 μm and exhibit weak oscillatory zoning. In some, zoning is poorly defined, in few cases however, the oscillatory zoning is almost indiscernible (Fig. 6). The non-apparent metamorphic rims may indicate that crystallization probably occurred rapidly during a single magmatic episode. During analysis, 24 evaluations were made giving Uranium contents that range between 92.858 to 1506.932 ppm while Th concentrations vary between 61.902 to 476.611 ppm. The ratio Th/U for the zircons has values which range between 0.316 and 0.835.

U-Pb Geochronology

The $^{206}Pb/^{207}Pb$ ages range between 569 and 613 Ma, the spot ages concentrated around 585−595 Ma (Table 2). The ages yielded a mean value 590.3 ± 5.3 Ma (MSWD = 0.82), which symbolized emplacement age of Idanre charnockite. Concordia diagram for the rock (Fig. 7), the mean and age range (Fig. 8) and normalized probability histogram (Fig. 9) for the U-Pb age is shown.

Lu-Hf Isotopic Composition

Fifteen (15) grains of zircon yielded $^{176}Lu/^{177}Hf$ isotopic composition with values which range between 0.000416 to 0.000935 (Table 3). Initial $^{176}Hf/^{177}Hf$ ratios range from 0.281957 to 0.281984. Hf isotope initial $^{176}Hf/^{177}Hf$ range between 0.281951 to 0.281996. εHf(t) falls between -14.6 to -16.8. The two-stage model age tDM2 range from 2395 to 2504 but are mainly concentrated between 2400-2500.

Table 1: Mineralogical features of Idanre charnockite

Rock Type Minerals	Ch Slide 1	Ch Slide 2	Ch Slide 3	Ch Slide 4	Ch Slide 5	Mean
Quartz	17	24	21	15	19	19.3
Plagioclase (Albite)	31	34	28	37	33	32.5
Orthoclase	-	-	3	-	5	0.8
Biotite	29	24	24	21	25	24.5
Hornblende	13	13	10	16	13	13
Muscovite	-	1	-	-	-	0.2
Pyroxene	8	3	9	6	6	6.5
Magnetite	-	-	-	4	-	1
Opaque	2	1	5	1		2.2
Others	100	100	100	100	100	100

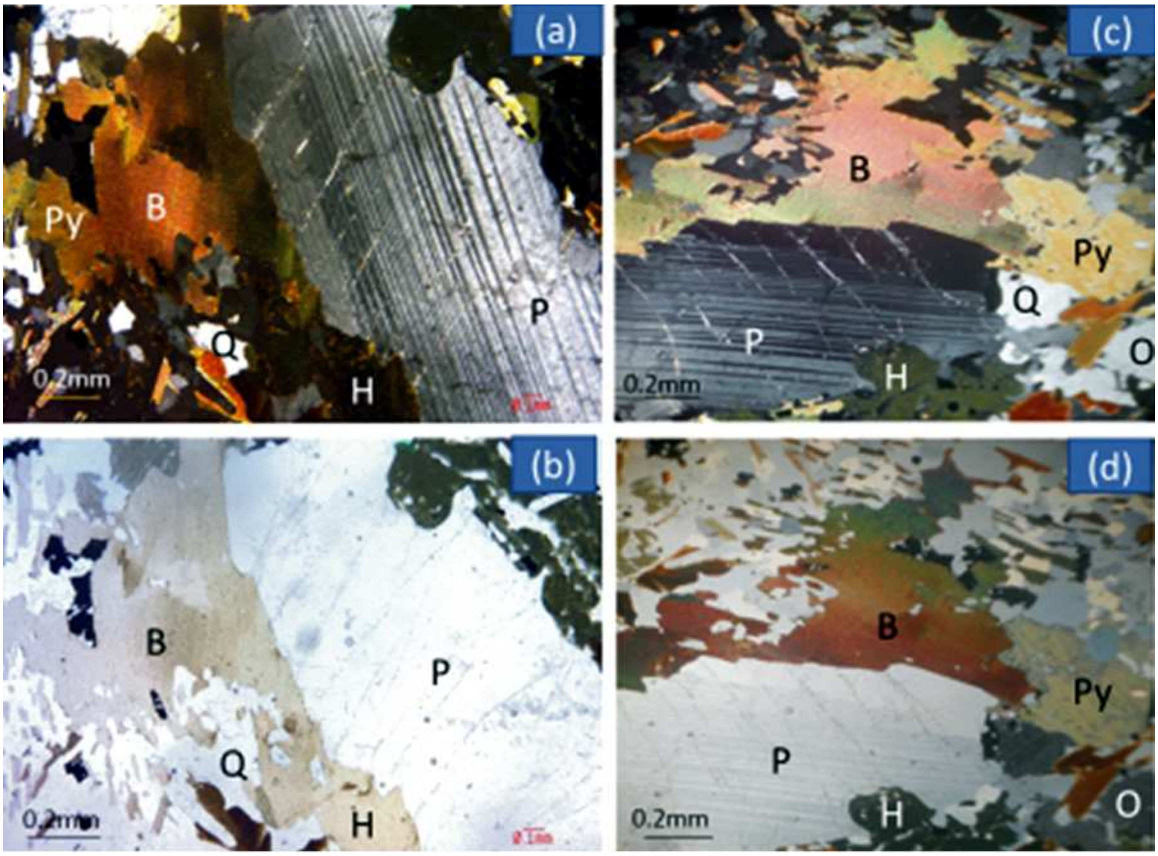

Fig. 5: Photomicrograph of Idanre charnockite in transmitted light showing the component minerals (a, c) cross polarised light (b, d) plane polarised light; P (plagioclase), H (hornblende), B (biotite), Q (quartz), Py (pyroxene).

Table. 2: *Zircon isotopic composition and age of charnockite from Idanre area*

Spot	U(ppm)	Th(ppm)	Th/U	$^{207}Pb/^{206}Pb$ ratios		$^{207}Pb/^{206}Pb$ Age		Discordance		Inferred Age (Ma)	1σ
				$^{207}Pb/^{206}pb$	1σ	$^{207}Pb/^{206}Pb$	1σ	<1000 Ma	>1000 Ma		
D29-01	200.142345	89.0082336	0.44472465	0.06188	0.00101	670	35	-3.7	-17.8	569	13
D29-02	649.904826	330.937854	0.50920972	0.06015	0.00069	609	25	-0.5	-3.0	591	13
D29-03	989.535922	343.946286	0.34758343	0.06116	0.00064	645	23	-1.3	-6.3	607	13
D29-04	248.739196	117.278163	0.47149048	0.06131	0.00073	650	26	-2.0	-10.0	591	13
D29-05	148.119176	96.0811771	0.6486748	0.06197	0.00125	673	44	-2.7	-12.7	597	14
D29-06	160.895785	98.7104788	0.61350569	0.05963	0.00084	590	31	0.7	2.8	607	13
D29-07	115.588041	70.4892861	0.609832	0.0597	0.00116	593	43	0.2	0.7	597	13
D29-08	249.811039	169.608279	0.67894629	0.06151	0.00083	657	29	-2.2	-10.4	595	13
D29-09	342.516521	256.489326	0.74883782	0.06159	0.00087	660	31	-3.0	-15.0	574	13
D29-10	262.591625	208.92845	0.79564019	0.06344	0.00095	723	32	-5.1	-24.0	583	13
D29-11	1506.9319	476.611411	0.31627933	0.06062	0.00062	626	22	-1.4	-7.0	585	12
D29-12	266.059704	148.065778	0.55651336	0.05998	0.00089	603	32	-0.3	-1.7	593	13
D29-13	143.674706	116.127868	0.8082694	0.06208	0.00117	677	41	-2.7	-12.3	603	14
D29-14	176.254289	106.845711	0.60620205	0.06469	0.00106	764	35	-6.7	-31.5	581	13
D29-15C	179.873609	124.616857	0.69280234	0.06122	0.00099	647	35	-2.4	-11.7	579	13
D29-15R	277.402822	147.912265	0.5332039	0.06136	0.00072	652	25	-2.8	-13.6	574	12
D29-16	178.765654	87.5280851	0.48962473	0.06125	0.0009	648	32	-1.8	-8.7	596	13
D29-17	192.508186	84.5060684	0.4389739	0.06034	0.00102	616	37	0.0	-0.5	613	14
D29-18	92.8583074	77.5153323	0.83477003	0.0612	0.00192	646	68	-2.1	-10.4	585	15
D29-19	128.950434	82.5947348	0.64051537	0.05974	0.00117	594	43	0.0	0.0	594	14
D29-21	198.176251	97.9740518	0.49437837	0.06001	0.00086	604	31	-0.2	-0.8	599	13
D29-22	95.4279859	61.9017299	0.6486748	0.06071	0.00152	629	54	-0.8	-4.0	605	14
D29-23	107.895397	83.2445229	0.77152988	0.06069	0.0013	628	47	-1.7	-7.9	582	14
D29-24	297.425711	174.082831	0.58529853	0.06132	0.00082	650	29	-2.8	-12.8	576	13

Table. 3. *Zircon age, Lu-Hf, $^{176}Hf/^{177}Hf$ isotopic composition, εHf(t) and tDM2 age of the charnockite*

Sample	Point	Zr. Age (Ma)	$^{176}Hf/^{177}Hf$	±2σ	$^{176}Lu/^{177}Hf$	$(^{176}Hf/^{177}Hf)_i$	εHf(t)	tDM (1) Ma	tDM(2) Ma
D29	D29-04	569	0.281955	1.40E-05	0.000416	0.281951	-16.8	1777	2504
D29	D29-01	591	0.282001	1.20E-05	0.000522	0.281995	-14.8	1720	2395
D29	D29-02	607	0.281958	1.40E-05	0.0006	0.281951	-16	1782	2480
D29	D29-03	591	0.281964	1.20E-05	0.000639	0.281957	-16.1	1775	2477
D29	D29-05	597	0.281984	1.20E-05	0.000848	0.281974	-15.4	1758	2436
D29	D29-06	607	0.28198	1.60E-05	0.000537	0.281974	-15.2	1749	2431
D29	D29-07	597	0.281966	1.30E-05	0.000564	0.28196	-15.9	1769	2468
D29	D29-08	595	0.282006	1.40E-05	0.000866	0.281996	-14.6	1728	2390
D29	D29-09	574	0.281962	1.40E-05	0.000726	0.281954	-16.6	1782	2494
D29	D29-10	583	0.281961	1.60E-05	0.000883	0.281951	-16.5	1791	2494
D29	D29-11	585	0.281964	6.50E-06	0.000935	0.281954	-16.4	1789	2488
D29	D29-12	593	0.281957	1.50E-05	0.000462	0.281952	-16.3	1777	2487
D29	D29-13	603	0.281972	1.20E-05	0.000677	0.281964	-15.6	1766	2454
D29	D29-14	581	0.281978	1.10E-05	0.000455	0.281973	-15.8	1748	2449
D29	D29-15	579	0.281971	1.10E-05	0.00046	0.281966	-16.1	1758	2465

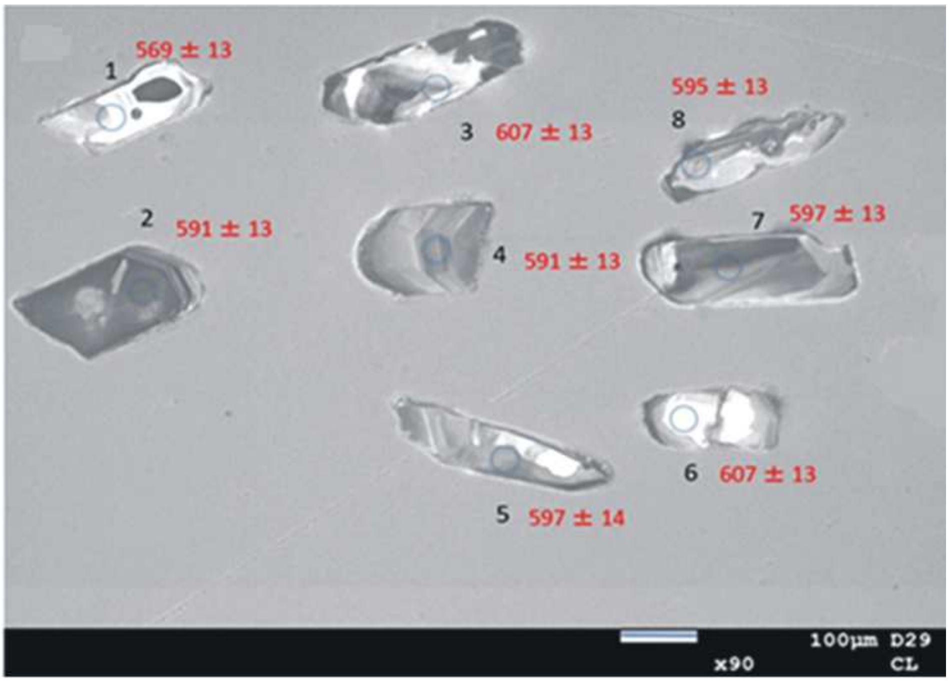

Fig. 6: Cathodoluminescence images and age of dated spots in zircon from Idanre Charnockite

Discussion

In an earlier study, Olarewaju (1988) reported at Ikere Ekiti, (50km NE of Idanre), based on field relationship, occurrence of an outcrop containing intermix of charnockite and porphyritic granite and suggested such relationship revealed that the two rocks occurred contemporaneously. A visit to this locality shows unequivocal and compelling evidence that charnockite and granite in southwestern Nigeria apart from been closely associated are both igneous in origin. Geological principles suggest that if this granitoid is igneous like every others in the basement and the associated charnockite is metamorphic, then their ages should be different; either the charnockite is older, otherwise, the granite must have been metamorphosed to granite gneiss. However, this was not the case for this charnockite-granite outcrop. The absence of diagnostic index metamorphic mineral assemblages like garnet, chlorite, epidote, staurolite or sillimanite in Idanre charnockite but minerals that are common in igneous rocks may point to igneous origin.

Zircon Morphology

In earlier works, Alexandrov et al. (2000) and Wang et al. (2002, 2007) reported that morphology of zircon grains holds great promises when deciphering zircon source. Zircon grain with pronounced and well-formed oscillatory zoning has been traced to igneous origin while those with indiscernible zonation are metamorphic in origin. According to Belousova et al. (2002), geochemical features of zircon could equally decipher whether it is from a magmatic or metamorphic source. The ability of zircon to resist alteration during weathering makes it reliable for detrital and tectonic studies (Chapman et al., 2016). According to Roberts et al. (2015) the resistance of zircon to wear and its ability to host numerous isotopic information that borders on petrogenesis makes it reliable source of information concerning evolution of crust and mantle-crust petrology. Igneous zircon can precisely fingerprint sources of magma or document evolution of the continental crust locally or regionally. For this reason, zircon is the most frequently analysed accessory mineral and is regularly used in U–Pb dating and tracking thermal history (Reiners 2005; Chapman et al., 2016), radiogenic isotope studies (Valley et al., 1994; Kinny and Maas 2003), temperature of crystallization (Watson and Harrison 2005), and trace element

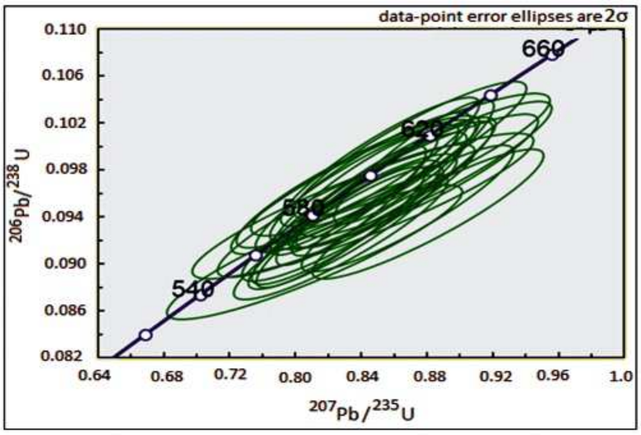

Fig. 7: Concordia diagram of zircon U-Pb age of charnockite from Idanre area

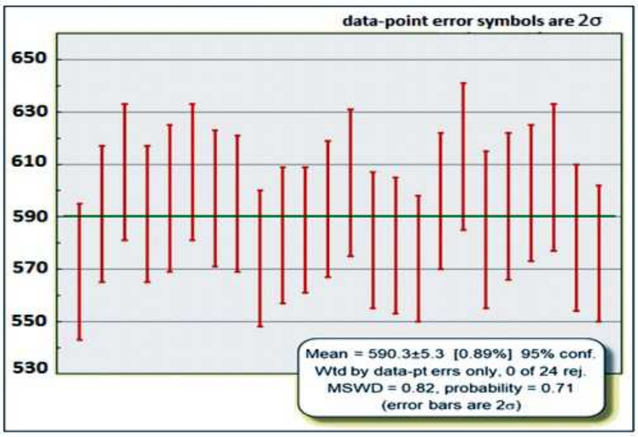

Fig. 8: Mean and age range of 24 Laser Ablation points for zircon in the charnockite

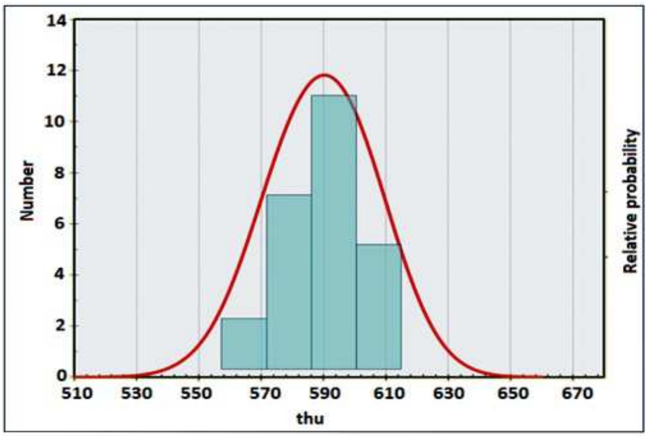

Fig. 9: Normalized probability plot and histogram for zircon U-Pb age of Idanre charnockite

evaluations (Belousova et al., 2002).

Zircon Geochemistry and Age

Th/U ratio of zircon which have been commonly used to assess their origins largely fall above the threshold value that distinguishes magmatic zircons (> 0.3) from metamorphic types which are usually < 0.1. The ratios (0.316-0.835) indicate that Idanre charnockite has igneous origin. The age of formation of Idanre charnockite at 590.3 ± 5.3 Ma as revealed in this study agrees with ages earlier determined from several areas of Nigeria. The age agrees with mineral age of hornblende from Bauchi charnockite with K/Ar age of 535±35 Ma (Snelling 1966); U-Pb on zircons age of 634±30 Ma from charnockite in Ipinsa (Tubosun 1981) among others. Tubosun (1981) also reported that the massive charnockite from Ikere-Ekiti has an age of 620 ± 20 Ma. It is also comparable to those beyond the border of Nigeria. For instance, Cameroon (Toteu et al., 1994, 2001), Akuse Massif, SE Ghana (Attoh 1998), Kabye Massif of northern Togo (Affaton et al., 2000) which was interpreted as the climax of regional granulite-facies metamorphism that accompanied continental collision between West African and Benin-Nigerian plates during the Pan-African episode. These ages correlated well with the Oban Massif charnockite, and 574.1±1.0 Ma age of charnockite in the Obudu area (Ekwueme and Kroner 2006). All these charnockite have ages that fall within Pan-African age. Even apart from charnockite units in other parts of Nigeria basement, the age of Idanre charnockite is consistent with U-Pb evaporation zircon age (589±11 Ma) (Dada et al., 1989) for amphibole-biotite granite in Toro, and (598±11 Ma) (Ferre et al., 1998) biotite-hornblende granite of Solli Hills in south eastern Nigeria. Different dating methods including Rb-Sr, K-Ar, U-Pb; and mineral dating using U-Pb evaporation techniques on zircon and Ar-Ar have been adopted in previous studies to show the exact period of magma plutonism in Nigeria. All indicated that granite plutonism and formation of charnockite in Nigeria generally fall within time frame of Pan-African orogeny.

Lu-Hf Isotopic Composition

Geodynamic evolution of the earth's continental crust has been linked to interplay of multiple geological processes. These activities can be picked by U-Pb-Lu-Hf isotopic study of zircon which can act as a paleo-geophysical tool relating crust-mantle interaction through time (Hartnady et al., 2018). Lu-Hf isotopic composition in this study reveals $^{176}Lu/^{177}Hf$ value of 4.16 ~ 9.53 x 10^{-4}, initial $^{176}Hf/^{177}Hf$ values of 2.81951~2.81996 x 10^{-1} and εHf(t) values of -14.8 ~ -16.6 suggesting derivation of the charnockite magma from melting of crustal components. The two-stage model age tDM2 of 2395 to 2504 which clustered around 2400-2500 suggests the magmatic fluid contain components separated from the primitive mantle during Neoarchean.

Conclusion

Field study revealed that charnockite in Idanre intruded into a migmatite basement. The Charnockite is of medium grained size with rounded masses of average elevation. Major minerals in the charnockites are quartz, orthoclase, plagioclase, biotite and hornblende.

Zircon morphology and chemical composition revealed magmatic origin while the U-Pb age 590.3 ± 5.3 Ma (MSWD = 0.82) signified emplacement age of the Idanre charnockite coinciding with the Pan-African orogeny. Lu-Hf isotopic composition and εHf(t) indicated that the charnockite was derived from anatexis of an ancient crustal protolith that was contaminated by mantle material. The two-stage model age suggested that the magma liquid was detached from the primitive mantle during Archean.

Acknowledgements

The authors are grateful to Mr. Abiodun Akinola and David Omogba who assisted during the fieldwork. The anonymous reviewers whose suggestions improved the quality of the paper are appreciated with thanks.

Conflict of interest

There are no conflicts of interest with regard to this manuscript.

Funding

This research was self sponsored and not supported by any Funding Institution.

Authors' Contributions

First Author (Mr. Oluwatoyin O. Akinola) designed the research plan, organized the study, co-ordinated the data analysis and was a major contributor to the writing of the manuscript. Second Author (Prof. Azman A. Ghani) provided leadership role in all the stages of the research. He reviewed the manuscript critically for significant intellectual content. Third Author (Dr. Abel O. Talabi) participated in the data acquisition, drafting of the article and served as the corresponding Author.

References

Ademeso, O.A. (2009). Deformation traits in charnockitic rocks of Akure area, Southwestern Nigeria. Asian Journal of Earth Sciences, 4, 112–120.

Adetunji, A., Olarewaju, V.O., Ocan, O.O., Ganev, V.Y. and Macheva, L. (2016). Geochemistry and U-Pb zircon geochronology of the pegmatites in Ede area, Southwestern Nigeria: A newly discovered oldest Pan African rock in Southwestern Nigeria. Journal of African Earth Science, 115, 177–190.

Ajibade, A.C. (1976). Provisional classification and correlation of the schist belts of north western Nigeria. In: C.A. Kogbe (ed.), Geology of Nigeria, Elizabethan Publishing Company, Lagos. pp. 85–90.

Ajibade, A.C. (1980). Geotectonic evolution of the Zungeru region Nigeria. Unpublished Ph. D Thesis. University of Wales, 303p.

Alexandrov, P., Cheilletz, A., Deloule, E. and Cuney, M. (2000). 319±7 Ma crystallization age for the Blond granite (northwest Limousin, French Massif Central) obtained by U/Pb ion-probe dating of zircons. C.R. Academic Science, Series IIA, Earth and Planetary Science, 330, 617–622.

Annor AE (1998) Structural and chronological relationship between the low-grade Igarra schist and its adjoining Okene migmatite-gneiss terrain in the Precambrian exposure of southwestern Nigeria. Journal of Mining Geology, 34, 187–196.

Belousova, E.A., Griffin, W.L., O'Reilly, S. and Fisher, N.J. (2002). Igneous zircon: trace element composition as an indicator of source rock type. Contributions to Mineralogy and Petrology, 143, 602–622.

Bessoles, B. and Trompette, R. (1980). Géologie de l'Afrique — La chaîne Pan-Africaine (zone mobile d'Afrique centrale (partie sud) et zone mobile soudanaise). Mémoire du Bureau de recherché Géologiques et Minières Orléans, Volume 92, p.397.

Black, R., Caby, R., Moussine-Pouchkine, A., Bayer, R., Bertrand, J.M., Boullier, A.M., Fabre, J. and Lesquer, A. (1979). Evidence for late Precambrian plate tectonics in West Africa. Nature, 278, 223–227.

Burke, K.C. and Dewey, J.F. (1972). Orogeny in Africa. Orogeny in Africa, 583-608.

Burke, K., Dewey, J.F. and Kidd, W.S.F. (1977). World distribution of sutures—the sites of former oceans. Tectonophysics, 40, 69–99.

Caby, R., Bertrand, J.M.L. and Black, R. (1981). Pan-African ocean closure and continental collision in the Hoggar-Iforas segment, central Sahara. In Developments in Precambrian Geology, 4, 407–434. Elsevier.

Hapman, J.B., Gehrels, G.E., Ducea, M.N., Giesler, N. and Pullen, A. (2016). A new method for estimating parent rock trace element concentrations from zircon, Chemical Geology, 430, 59–70.

Cooray, P.G. (1977). Classification of charnockite rocks of Nigeria. Journal of Mining and Geology, 14, 1–6.

Dada, S.S., Brick, J.L., Lancelot, J.R. and Rahaman, M.A. (1993). Archaean Migmatite- Gneiss Complex of North-central Nigeria: Its Geochemistry, Petrogenesis and Crustal evolution. In 16th colloquium of African Geology, 14th-16th Sept.,1993, Mbabane, Swaziland, pp. 97–102.

Dada, S.S., Lancelot, J.R. and Briqueu, L. (1989). Age and origin of the annular charnockitic complex at Toro, Northern Nigeria: U-Pb and Rb-Sr evidence, Journal of African Earth Sciences, 9, 227–234.

Ekwueme, B.N. (1990). Rb-Sr ages and petrologic features of Precambrian rocks from the Oban Massif, south-eastern Nigeria. Precambrian Research, 47, 271–286.

Ekwueme, B.N. and Kröner, A. (1992). Preliminary zircon evaporation ages from migmatitic gneisses in Kaduna, northern Nigeria: evidence for an early Archaean (Pre-Leonian) event in the Nigerian basement complex. In: International Geological Correlation Programmes 280 International Conference, Salvador, Brazil.

Ekwueme, B.N. and Kröner, A. (1998). Single zircon evaporation ages from the Oban Massif, south eastern Nigeria. Journal of African Earth Sciences, 26, 195–205.

Ekwueme, B.N. and Kröner, A. (2006). Single zircon ages of migmatitic gneisses and granulites in Obudu Plateau: Timing of granulite facies metamorphism in southeastern Nigeria. Journal of African Earth Sciences, 44, 459–469.

Elueze, A.A. (1982). Geochemistry of the Ilesha granite gneiss in the basement complex of southwestern Nigeria. Precambrian Research, 19, 167–177.

Elueze, A.A. (1992). Rift system for Proterozoic schist belts in Nigeria. Tectonophysics, 209, 167–169.

Fabre, J. (2005). Géologie du Sahara occidental et central Tervuren. Africain Geoscience Colloquia. 108, 572.

Ferré, E., Gleizes, G. and Caby, R. (2002). Obliquely convergent tectonics and granite emplacement in the Trans-Saharan belt of Eastern Nigeria: a synthesis. Precambrian Research, 114, 199–219.

Fitches, W.R., Ajibade, A.C., Egbuniwe, I.G., Holt, R.W. and Wright, J.B. (1985). Late Proterozoic schist belts and plutonism in NW Nigeria. Journal of the Geological Society of London 142, 319–337.

Gasquet, D., Ennih, N., Liégeois, J.P., Soulaimani, A. and Michard, A. (2008). The Pan-African belt. In Continental evolution: the geology of Morocco (pp. 33–64). Springer, Berlin, Heidelberg.

Grant, N.K. (1970). Geochronology of Precambrian basement rocks from Ibadan, southwestern Nigeria; Earth and Planetary Science Letters, 10, p. 29–38.

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. In Coompana Drilling and Geochemistry Workshop 2018 extended abstracts, Report Book, 19, 132–144.

Hockey, R.D., Sacchi, R., De Graff, W.P.F.H. and Muotoh, E.O.G. (1986), The geology of Lokoja-Auchi area. Geological Survey of Nigeria Bulletin, 39, 71pp.

Key, R.M., Johnson, C.C., Horstwood, M.S.A., Lapworth, D.J., Knights, K.V., Kemp, S., Watts, M.J., Gillespie, M., Adekanmi, M.A. and Arisekola, T.M. (2012). Investigating high zircon concentrations in the fine fraction of stream sediments draining the Pan-African Dahomeyan Terrane in Nigeria. Applied Geochemistry 27, 1525–1539.

Kilpatrick, J.A. and Ellis, D.J. (1992). C-Type magmas: Igneous charnockites and their extrusive equivalents. Transactions of Royal Society of Edinburg, Earth Sciences, 83, 151–164.

Kinny, P.D. and Maas, R. (2003). Lu–Hf and Sm–Nd isotope systems in zircon. Rev. Mineral. Geochem. 53, 327–341.

Kroner, A. and Stern, R.J. (2005). Pan-African Orogeny. Encyclopedia of Geology, 1, A-E, 1–12.

Leblanc, M. (1976). Proterozoic oceanic crust at Bou Azzer. Nature, 261, 34–35.

Liégeois, J.P., Latouche, L., Boughrara, M., Navez, J. and Guiraud, M. (2003). The LATEA metacraton Central Hoggar, Tuareg shield, Algeria): behaviour of an old passive margin during the Pan-African orogeny. Journal of African Earth Sciences, 37, 161–190.

Liégeois, J.P., Benhallou, A., Azzouni-Sekkal, A., Yahiaoni, R. and Bonin, B. (2005). The Hoggar swell and volcanism: Reactivation of the Precambrian Tuareg shield during Alpine convergence and West African Cenozoic volcanism. Geological Society of America, Special Paper 388, 379–400.

Matheis, G. and Caen-Vachette, M. (1983). Rb–Sr isotopic study of rare-metal bearing and barren pegmatites in the Pan-African reactivation zone of Nigeria. Journal of African Earth Sciences, 1, 35–40.

Mccurry, P. (1976). The Geology of the Precambrian to Lower Paleozoic rocks of northern Nigeria - a review of Geology of Nigeria, C.A. Kogbe (ed.) Elizabethan Publishing Company, Lagos. P.15–39.

Olarewaju, V.O. (1987). Charonockite-granite association in SW Nigeria, Rapakivi granite type and charnockite plutonism in Nigeria. Journal of Africa Earth Sciences, 6: 67–77

Olarewaju, V.O. (1988). Petrology and Geochemistry of the charnockitic and associated granitic rocks of Ado-Ekiti, Akure, SW Nigeria, Geological Survey of Nigeria Publication, p 231–239.

Oluyide, P.O. (1988). Structural trends in the Nigerian Basement Complex. *In* P.O. Oluyide (Coordinator) Precambrian Geology of Nigeria. Geological Survey of Nigeria Publication. 93–97.

Orajaka, S. (1971). The petrogenesis of the Obudu-type enderbite. Journal of Mines, Metals, Fuels (Calcutta) (April), 94–98.

Oyawoye, M.O. (1962). The petrology of the district around Bauchi, Northern Nigeria, Journal of Geology, 70, 604–615.

Oyawoye, M.O. (1964). The contact relationship of charnockite and biotite gneiss at Bauchi, Northern Nigeria, Geology Magazine, 10, 138–144.

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.

Rahaman, M.A., Van Breemen, O., Bowden, P. and Bennett, J.N. (1984). Age migrations of anorogenic ring complexes in Northern Nigeria. Journal of Geology, 92, 173–184.

Rahaman, M.A., Ajayi, T.R., Oshin, I. and Asubiojo, F. (1988). Trace-element Geochemistry and Geo-tectonic setting of ile-ife schist belt. Precambrian Geology of Nigeria, Publication of the Geological Survey of Nigeria. 248–255.

Rahaman, M.A. (1988). Recent advances in the study of the basement complex of Nigeria. In Precambrian Geol. of Nigeria, (Oluyide, P.O., Mbonu, W.C., Ogezi, A.E., Egbuniwe, I. G., Ajibade, A.C., and Umeji, A.C.) (*Eds*.), a publication of Geological Survey of Nigeria. pp 11–41.

Reiners, P.W. (2005). Zircon (U–Th)/He thermochronometry. Reviews in Mineralogy and Geochemistry, 58, 151–179.

Roberts, N.M.W., Van Kranendonk, M., Parman, S., Shirey, S, and Clift, P.D. (*eds*) (2015). Continent Formation Through Time. Geological Society, London, Special Publications, 389, 197–225.

Snelling, N.J. (1966). Geochronology. *In* Overseas Geological Survey Annual Report. HMSO, London.

Toteu, S.F., Van Schmus, R.W., Penaye, J. And Michard, A. (2001). New U– Pb and Sm–Nd data from north central Cameroon and its bearing on the pre-Pan-African history of central Africa. Precambrian Research, 108, 45–73.

Toteu, S.F., Van Schmus, W.R., Penaye J. and Nyobé, .J.B (1994). U/Pb and Sm/Nd evidence for Eburnean and Pan-African high-grade metamorphism in cratonic rocks of southern Cameroon. Precambrian Research, 67, 321–347.

Tubosun, I.A. (1981). Chronologie U/Pb évènements magmatiques du socle précambrien du sud-ouest du Nigeria. Unpublished D.E.A Dissertation, 1–17.

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

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.

Valley, J.W., Chiarenzelli, J.R. and McLelland, J.M. (1994). Oxygen isotope geochemistry of zircon. Earth Plan. Sci. Lett. 126, 187–206.

Wang, X., Griffin, W.L., O'Reilly, S.Y., Zhou, X.M., Xu, X.S., Jackson, S.E. and Pearson, N.J. (2002). Morphology and geochemistry of zircons from late Mesozoic igneous complexes in coastal SE China: implications for petrogenesis. Mineralogical Magazine, 66, 235–251.

Wang, X., Griffin, W.L., O'Reilly, S.Y. and Li, W.X. (2007). Three stages of zircon growth in magmatic rocks from the Pingtan Complex, eastern China. Acta Geologica Sinica 81, 68–80.

Watson, E.B. and Harrison, T.M. (2005). Zircon thermometer reveals minimum melting conditions on earliest Earth. Science, 308, 841–844.