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Research Article

ON THE CHEMISTRY AND GEOTHERMOBAROMETRY OF AMPHIBOLES OF CHARNOCKITES FROM BAUCHI AND SAMINAKA, NORTHCENTRAL NIGERIA: GENETIC IMPLICATIONS

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ABSTRACT
Amphibole compositions of the charnockites from Bauchi and Saminaka, North-central Nigeria have been studied by electron probe micro analysis. Generally, the amphiboles are all calcic, silica and magnesia poor, ferroan rich weakly titaniferous and have most of their aluminum in tetrahedral site. Si contents average 6.35 apfu (Bauchi) and 6.42 apfu (Saminaka). Ca is always above 1.7 apfu for both areas. Na^{A} is always > Na^{M4}. K_2O contents are high. All samples exhibit low Al^{VI} and high Al^{IV} contents equate to more than 90% of Al to the tetrahedrical site. TiO_2 contents average 1.60% (Bauchi) and 1.65% (Saminaka). FeO^{T} contents are high. Most of the amphiboles are characterized by low Fe^{3+} and high Fe^{2+} contents. Xmg ratio varies between 0.18 and 0.64 (Bauchi) and 0.26 to 0.37 (Saminaka). They may be divided into two sub-groups: On the one hand the magnesio-hastingsite - hastingsite and pargasite group and on the other hand the tschermakite group. The amphiboles from Bauchi and Saminaka charnockites plot in the igneous field of the diagram. From thermobarometric investigations, Amphiboles in the charnockites solidified between 4.4 to 7.2 kbar (Bauchi) and 5.3 to 5.6 kbar as estimated by its Al contents, while temperature of crystallization range from 826º to 599º C (Bauchi) and 826º to 650º C (Saminaka). Nevertheless, Bauchi charnockite's amphibole-core temperatures decrease continuously from 826º C for hastingsite to magnesio-hornblende 599º C. These conditions correspond to a shallow crustal chamber (15-20 km depth).

Key Words: *Geothermobarometry, Petrogenesis, Amphibole, Charnockite, Bauchi, Saminaka, Northcentral Nigeria*

INTRODUCTION

Charnockitic rocks are generally known to have various origins, ranging from metamorphic to igneous derivations (Kilpatrick and Ellis, 1992). Various models of origin have been presented by different workers in the field, on the charnockites of the study area.

According to Oyawoye (1962, 1964), the metasomatic model presents a hydrothermal fluid rich in Fe^{2+}, soaking and depositing its Fe^{2+} in a pre-existing granite converting them to charnockites. In the geochemical model, Olarewaju (1988) posited that fractional crystallization of dacitic-andesitic magma at depth will produce massive fine-grained charnockitic rocks and subsequent partial melting of the crustal rock by the residual melt phase will produce acidic magma, which when emplaced produces coarse grained charnockitic rock.

Based on the tectonic model by Rahaman *et al.,* (1988), the evolution of granites and charnockitic rocks were caused by the opening and closing of the ocean with the attendant deposition of large volumes of sediment followed by metamorphism of the sediments. The igneous model involves the melting of the lower crustal rocks during the Pan African orogenic event leading to the production and upward rise of granitic magma to higher levels and eventually charnockitic magma will be produced and emplaced by fusion under dry granulite facies conditions Dada *et al.,* (1989).

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The aim of this study is to evaluate the chemical composition, pressure and temperature at which charnockites from part of northcentral Nigeria are emplaced, using electron microprobe data of amphiboles from studied areas.

General Geology

The Study areas (Saminaka and Bauchi) are located in the Basement Complex of north central, Nigeria. They form part of the Precambrian to mid Cambrian northern Nigeria crystalline shield. Macleod *et al.*, (1971) have summarized the general geology of the areas as consisting of migmatite, granite gneiss, granulite gneisses and the granite series which include granites sensuo stricto, diorites, charnokites and bauchites.

The rocks of the Basement Complex range in age from the Pan African (about 500-600 milion years) to Archean (over 2,500million years). They extend from the east of Nigeria and into the Cameroon Republic and from the western part to the Benin Republic. The rocks have a complex geology and structure because of several metamorphic and thermotectonic cycles of deformations, shearing, folding and faulting. The structures are deep seated, with the dominant trend being essentially N-S. Subordinate trends which may be locally dominant include east-west and variation from NE-SW to NW-SE. The dominance of transcurrent faulting and shearing produce fractures with NE-SW, NW-SE, NNE-SSW and NNW-SSE trends. Some of these fractures host minerals especially the schist belts.

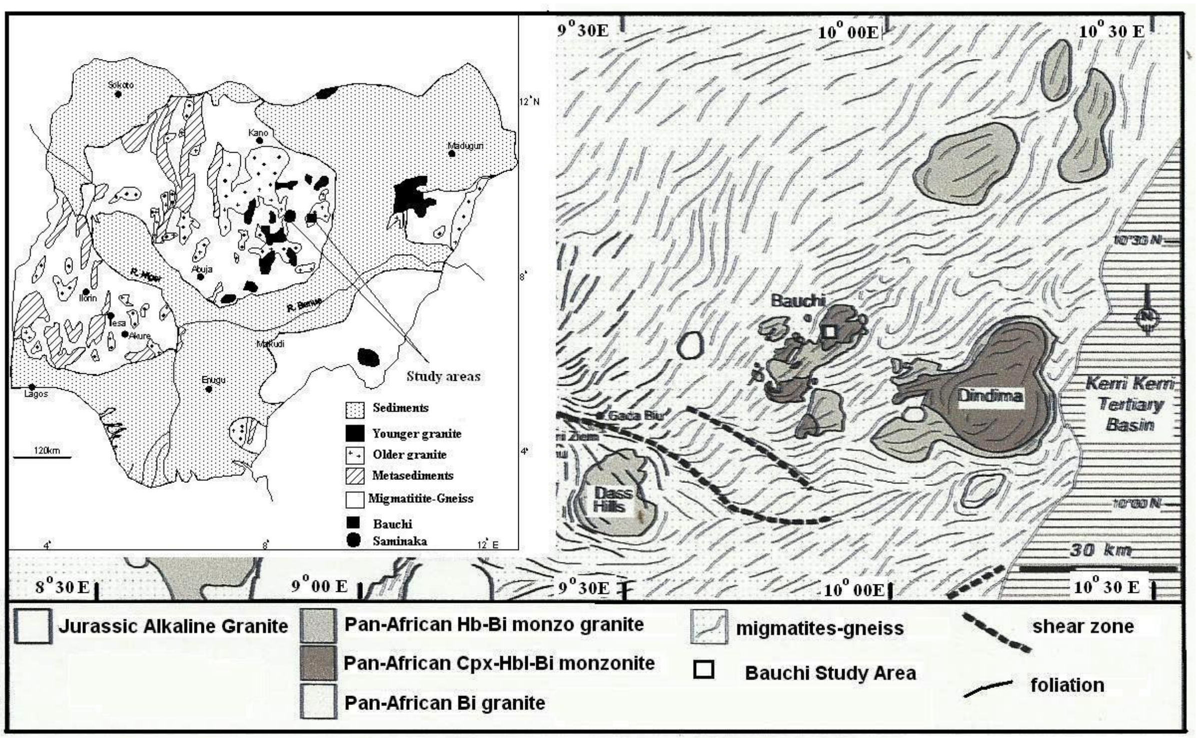

Figure 1: Geological map of the Bauchi area. Foliations compiled from field data, SLAR images and previous maps (Modified from Ferre *et al.*, 2002). Inset: Generalized geological map of Nigeria.

MATERIALS AND METHODS

Polished thin sections were made from selected fresh surface samples taken from both Complexes.

Mineral chemistry was determined with JXA JEOL- 8900L electron probe micro analyzer at the Electron Microprobe Laboratory, McGill University, and Montreal, Canada. The analysis was conducted with a 15Kv accelerating voltage, 20nA beam current and a 10um beam diameter. Natural minerals were used as standards and counting times at each peak was 20seconds and background for all elements.

Table 1: Representative amphibole compositions of the investigated Bauchi charnockite.

Sample	B091	B092	B093	B094	B095	B096	B097	S101	S102	S103	S104	S105	S106
SiO_2	43.33	39.91	49.69	39.97	39.93	41.60	43.68	41.47	41.60	42.07	42.32	41.13	41.08
TiO_2	1.57	1.89	0.40	1.98	1.87	1.75	0.93	1.89	2.01	1.56	0.75	1.97	1.72
Al_2O_3	9.69	11.57	4.73	11.23	11.67	8.92	8.52	9.90	9.91	9.62	9.91	9.84	9.60
Cr_2O_3	0.06	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.03	0.00
Fe_2O_3	6.04	4.35	7.41	4.61	4.19	7.65	3.98	5.19	5.65	6.28	6.73	5.83	6.80
FeO	16.31	24.13	12.02	23.84	24.18	19.35	22.42	22.32	21.22	19.93	18.66	20.92	20.55
MnO	0.29	0.23	0.25	0.25	0.23	0.38	0.32	0.42	0.36	0.40	0.43	0.38	0.39
MgO	7.78	2.92	11.94	3.15	2.89	5.60	5.17	4.31	4.97	5.63	6.20	5.14	4.98
CaO	10.89	10.93	11.50	10.88	10.90	10.88	11.40	10.61	10.79	10.73	10.97	10.62	10.53
Na_2O	1.23	1.30	0.54	1.39	1.32	1.25	0.72	1.78	1.60	1.72	1.60	1.91	1.84
K_2O	1.22	1.67	0.33	1.63	1.68	1.14	1.44	1.22	1.27	1.13	1.10	1.33	1.20
F	0.13	0.04	0.19	0.00	0.04	0.17	0.13	0.02	0.15	0.14	0.17	0.06	0.09
Cl	0.02	0.08	0.02	0.05	0.07	0.09	0.07	0.06	0.06	0.06	0.05	0.08	0.05
H_2O*	1.92	1.88	1.96	1.90	1.88	1.83	1.86	1.91	1.86	1.87	1.86	1.89	1.88
O=F,Cl	0.06	0.03	0.08	0.01	0.03	0.09	0.07	0.02	0.08	0.07	0.08	0.04	0.05
Total	**100.41**	**100.86**	**100.90**	**100.87**	**100.81**	**100.53**	**100.59**	**101.08**	**101.37**	**101.07**	**100.68**	**101.09**	**100.66**
Si	6.550	6.253	7.241	6.259	6.257	6.435	6.747	6.425	6.400	6.457	6.484	6.358	6.377
Al^{IV}	1.450	1.747	0.759	1.741	1.743	1.565	1.253	1.575	1.600	1.543	1.516	1.642	1.623
Al^{VI}	0.276	0.390	0.053	0.332	0.412	0.061	0.298	0.232	0.197	0.197	0.274	0.150	0.133
Ti	0.179	0.223	0.044	0.233	0.220	0.204	0.108	0.220	0.233	0.180	0.087	0.229	0.201
Cr	0.007	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.003	0.000
Fe^{3+}	0.687	0.513	0.813	0.543	0.495	0.891	0.463	0.605	0.654	0.725	0.776	0.678	0.795
Fe^{2+}	2.061	3.162	1.465	3.122	3.168	2.503	2.896	2.892	2.730	2.558	2.391	2.705	2.668
Mn	0.037	0.030	0.031	0.034	0.031	0.050	0.042	0.055	0.047	0.052	0.056	0.050	0.052
Mg	1.753	0.682	2.594	0.735	0.675	1.291	1.191	0.995	1.140	1.288	1.416	1.184	1.152
Ca	1.764	1.835	1.795	1.826	1.830	1.803	1.887	1.761	1.779	1.764	1.801	1.795	1.751
Na	0.360	0.395	0.152	0.422	0.401	0.375	0.216	0.535	0.477	0.512	0.475	0.572	0.554
K	0.235	0.334	0.061	0.326	0.336	0.225	0.284	0.241	0.249	0.221	0.215	0.262	0.238
F	0.061	0.018	0.086	0.000	0.020	0.083	0.064	0.010	0.072	0.066	0.081	0.027	0.042
Cl	0.006	0.021	0.004	0.012	0.019	0.024	0.018	0.015	0.015	0.015	0.014	0.020	0.012
OH*	1.934	1.960	1.909	1.988	1.962	1.893	1.918	1.975	1.913	1.919	1.905	1.953	1.945
Total	**17.359**	**17.564**	**17.009**	**17.573**	**17.567**	**17.403**	**17.386**	**17.537**	**17.505**	**17.497**	**17.491**	**17.594**	**17.543**
$(Ca+Na)^B$	2.000	2.000	1.948	2.000	2.000	2.000	2.000	2.000	2.000	1.948	2.000	2.000	2.000
Na^B	0.236	0.165	0.152	0.174	0.170	0.197	0.113	0.239	0.221	0.236	0.199	0.241	0.249
$(Na+K)^A$	0.359	0.564	0.061	0.573	0.567	0.403	0.386	0.537	0.505	0.497	0.491	0.594	0.543
$Mg/(Mg+Fe^{+2})$	0.460	0.177	0.639	0.191	0.176	0.340	0.291	0.256	0.295	0.335	0.372	0.305	0.302

Mineral Chemistry

Structural formulae of amphiboles from Bauchi and Saminaka charnockites are calculated on an anhydrous basis assuming 23 Oxygens atoms per half unit cell, with the general form $A_{0-1}B_2C_5T_8O_{22}$ $(OH)_2$ representing one formula unit. According to the IMA classification and Fe^{3+} calculation proposed by Leake *et al.*, (1997), all the amphiboles from Bauchi and Saminaka charnockites are calcic (^BCa>1 apfu; Figure 2; Table 1) and belong to two sub groups. Group 1 is defined by $^{A}(Na+K) < 0.5$ apfu (Figure 2), and mostly contain high Si contents ($^{T}Si>6.5$ apfu Bauchi only) characteristic of ferro-hornblendes, with minor magnesio-hornblende (B3). Group 2, defined by $^{A}(Na+K) > 0.5$ apfu (Figure 2). This group mostly contains low Si contents ($^{T}Si<6.5$ apfu both Bauchi and Saminaka) characteristic of hastingsite. The calcic nature is further confirmed by $(Ca+Na)^{B} \geq 1.948$ for Bauchi and Saminaka amphiboles and the $Na_B> 0.113$ for Bauchi and $Na_B> 0.199$ for Saminaka (Table 1; Figure 2).

From the Si vs Mg/(Mg+Fe) diagram after Leake (1997) used to classify the calcic amphibole, it is observed that the amphiboles are hastingsitic (Bauchi and Saminaka), ferrohornblendes and magnesiohornblende (Bauchi) (Figure 2).

TiO_2 contents range from 0.4 to 1.98% (Bauchi) and 1.56 to 2.01% (Saminaka). FeO^T contents are high, from 18.69 to 28.05% (Bauchi) and 24.72 to 26.99% (Saminaka). Most of the amphiboles are characterized by a low Fe^{3+} and a high Fe^{2+} contents. The amphiboles on average are rich in total FeO_T and MgO while the TiO_2 content is relatively low.

Al_2O_3 is around 10% and all samples exhibit low Al^{VI} and high Al^{IV} contents which equates to more than 90% of Al in the tetrahedral site. All the analysed amphiboles contain sufficient Al to balance the Si deficiency in the tetrahedral sites. Na and K contents are low, with Na ranging between 0.152-0.401 apfu (Bauchi) and 0.477-0.572 apfu (Saminaka). Na^{A} is always greater than Na^{M4}. The K content ranges from 0.061-0.336 apfu (Bauchi) and 0.215-0.262 apfu (Saminaka). Ca ranges from 1.801 to 1.887 and Ti is very low, < 0.25 apfu.

Regardless of the amount of Na+K in the A site, the Xmg [=Mg/ (Mg+Fe^{2+})] of Bauchi and Saminaka charnockites range from 0.18 to 0.46 (Bauchi) and 0.256 to 0.372 (Saminaka), making them all ferroan except a sample from Bauchi, (B3=0.64) which is magnesian. The magnesiohornblende found within the mineral grains of the Bauchi charnockite record the lowest pressure and temperature (P: 0.9 kbar and T: 714º C; Table 2 and 3) of the studied amphiboles.

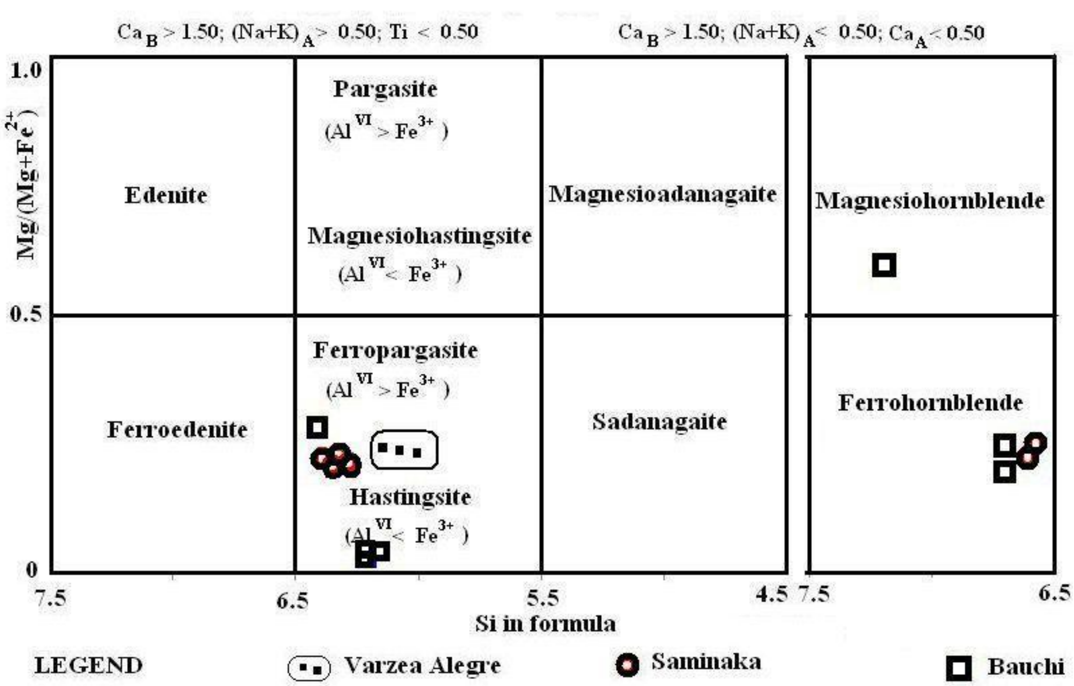

Figure 2: Compositional variations of calcic-amphibole from the Bauchi and Saminaka charnockites, North-central Nigeria. Cation proportions are per formula unit. Amphibole classification after Leake *et al.*, (1997). Note: The encircled samples are from charnockitic magmatic rocks from the Várzea Alegre Massif, Espírito Santo, Southeastern Brazil (After Mendes *et al.*, 1992).

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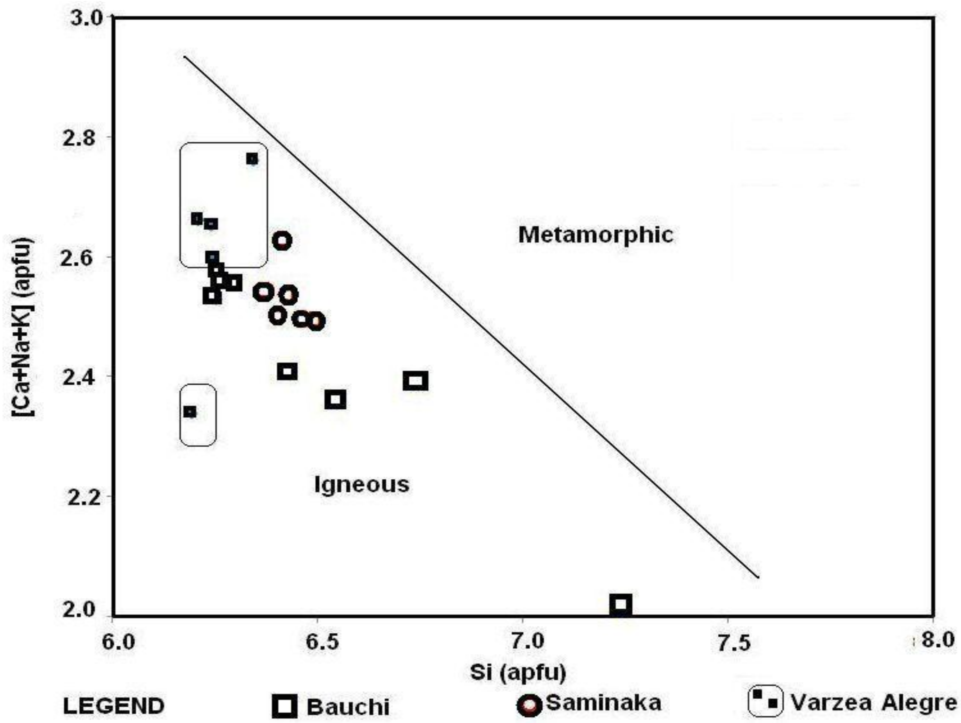

Figure 3: Compositional variations of amphibole from Bauchi and Saminaka charnockites plotted in terms of cations (Ca+Na+K) vs Si (apfu) diagram after Giret *et al.*, (1980). Note: The encircled samples are from charnockitic magmatic rocks from the Várzea Alegre Massif, Espírito Santo, Southeastern Brazil (After Mendes *et al.*, 1992).

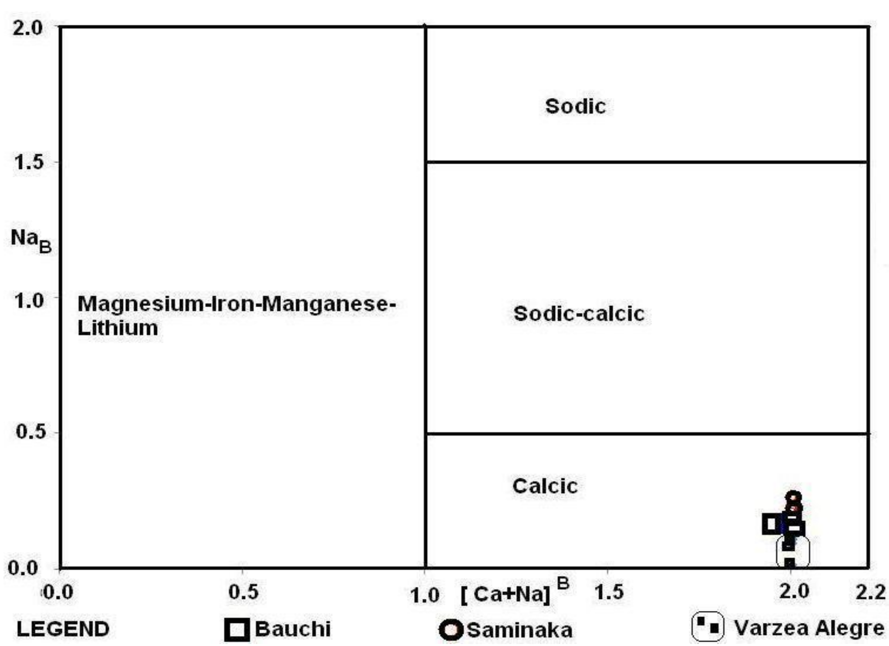

Figure 4: Composition and classification of amphiboles. After Leake *et al.*, (1997). Note: The encircled samples are from charnockitic magmatic rocks from the Várzea Alegre Massif, Espírito Santo, Southeastern Brazil (After Mendes *et al.*, 1992).

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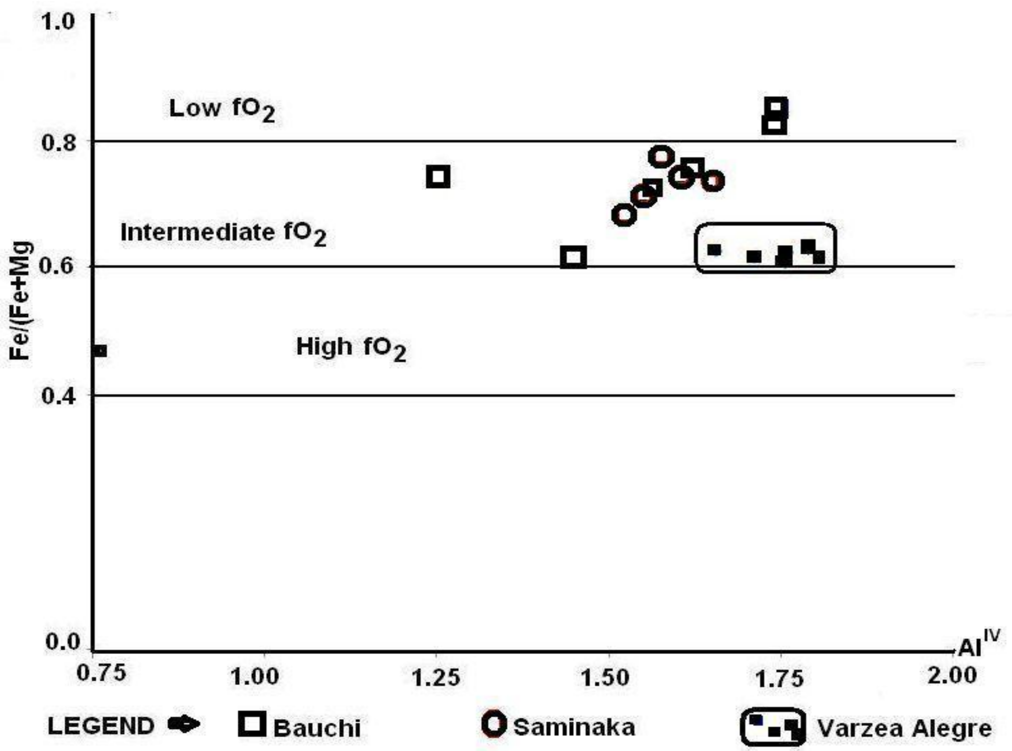

Figure 5: Composition of amphiboles from the Bauchi and Saminaka charnockites in term of Fe/(Fe+Mg) versus Al^{IV}. Fields of fO_2 and composition of hornblende from Bauchi charnockite Northcentral Nigeria after Anderson and Smith (1995). Note: The encircled samples are from charnockitic magmatic rocks from the Várzea Alegre Massif, Espírito Santo, Southeastern Brazil (After Mendes *et al.*, 1992).

Amphibole Geothermobarometry

Numerous studies have dealt with parageneses of calcic amphibole in mafic (meta-) igneous rocks (Spear, 1981; Mader and Berman, 1992; Ague and Brandon, 1992; Ague 1997; Ernst and Liu, 1998; Tulloch and Challis, 2000). These studies make it clear that, with increasing *P-T* conditions, calcic amphiboles exhibit increases in Mg/(Mg + Fe) and in K, Al, Na, and Ti contents and commensurate decreases in Si and total Fe + Mg + Mn + Ca.

Pressure conditions of crystallization, deduced from contact aureoles or experimentally controlled runs have been observed to be correlated linearly with the Al-content in amphibole, and, many calibrations of the Al-in-amphibole barometer have been published (Hammarstrom and Zen, 1986; Hollister *et al.*, 1987; Johnson and Rutherford, 1988; Rutter, 1989; Blundy and Holland, 1990; Schmidt, 1992; Anderson and Smith, 1995; Ernst and Liu, 1998). Pressure for the mineral assemblages used in the temperature calculations were calculated using Al-in-hornblende method. A-H barometer calibration proposed by Schmidt (1992) is chosen and results are compared to those obtained using others experimental calibration published by Hammarstrom and Zen (1986) and Hollister *et al.*, (1987).

In these formulations P is pressure in Kbar and Al_T is the total amphiboles that are calibrated at about the same pressure: P_1 [Hammarstrom and Zen (1986)] = (Max=6.9 kbar, Min=3.9 kbar); P_2 [Hollister *et al.*, (1987)] = (Max= 7.4 kbar, Min= 4.0); P_3 [Schmidt (1992)] = (Max=7.2 kbar, Min=4.4 kbar).

Determined pressures of this study are similar with an average of 5.6 kbar ±0.2 (Table 2). However, a pressure estimate for the sample B093 is abnormally low (P_1=0.2; P_2=-0.2; P_3=0.9) and may be justified by the fact that its electron probe analysis (up to 49.69% SiO_2) is out of the silica range of calibration.

Table 2: Results of geobarometry, Amph-Al (Total) of samples from Bauchi and Saminaka charnockites, North-central and Varza Alegre charnockitic rock, Brazil (Mendes *et al.*, 1999). The table shows Pressure Calculations using Hammarstrom and Zen (1986), Hollister *et al.*, (1987) and Schmidt (1992).

Pressure	Hammarstrom and Zen (1986)P1	Hollister *et al.*, (1987)P2	Schmidt (1992) P3
	Bauchi Area		
Max (Kbar)	6.9	7.4	7.2
Min (Kbar)	3.9	4.0	4.4
Average (Kbar)	5.5	5.8	5.9
	Saminaka Area		
Max (Kbar)	5.2	5.4	5.6
Min (Kbar)	4.8	5.1	5.3
Average (Kbar)	5.0	5.3	5.5
	Varzea Alegre Brazil		
Max (Kbar)	6.4	6.8	6.7
Min (Kbar)	5.7	6.0	6.1

Table 3: Calculated temperature using amphibole population in charnockites from Bauchi and Saminaka areas, north central Nigeria (Amp-TB geothermometer of Ridolfi *et al.*, 2009). Zr and P_2O_5 saturation levels for the Varza Alegre massif using the calibration curves of Watson and Harrison (1983 and 1984; Mendes *et al.*, 1999).

Temperature	Max (°C)	Min (°C)
Bauchi Area	826	599
Saminaka Area	826	650
Varza Alegre	950	550

Geothermometry

Geothermometers are reactions that can be used to calculate or estimate temperature of formation of minerals. Electron microprobe data for the amphiboles from Bauchi charnockite was used to calculate temperatures using temperature calibration based on Ti content in hornblende by Otten (1984). Temperature of formation estimates varies from 599º to 826º C (Bauchi) and 650º to 826º C (Saminaka). The temperatures difference may indicate a long interval of crystallization of the Bauchi and Saminaka charnockites. Figure 3 adapted from Giret *et al.*, (1980) shows that all samples analyzed have high temperature igneous amphiboles and no low temperature metamorphic amphiboles, indicating a formation as a result of igneous processes.

These computations are confirmed from Wendlandt (1981) the estimates of pressures and temperatures for the formation or crystallization of charnockites by igneous processes. He defined a window from about 4 kbar to 12 kbar and 750º C to 1000º C for charnockites of igneous origins while those by metamorphic processes may be formed at somewhat lower temperatures. The P-T got from amphiboles of Bauchi and Saminaka charnockites (Bauchi: av. Pressure = 5.26 kbar and av. temperature = 754º C;

Saminaka: average pressure= 5.47 kbar and average temperature = 777º C) falls within Wendtlandt (1981)'s estimates for the crystallization of charnockites by igneous processes.

DISCUSSIONS

The amphiboles in the Bauchi charnockite cluster between Mg-hornblende-Ferrohornblende-Hastingsite, while those in the Saminaka charnockite are mainly hastingsites in the ($Mg/Mg+Fe^{2+}$) vs Si diagram (Figure 2; Leake *et al.*, 1997). Compositional limit for igneous amphibole is shown in Figure 3 with respect to (Ca+Na+K) versus (Si) formula unit (Giret *et al.*, 1980). According to IMA classification proposed by Leake *et al.*, (1997), the amphiboles of Bauchi and Saminaka charnockites are calcic amphiboles (Figure 4; Leake *et al.*, 1997), but represent a wide compositional range. The (Mg/Mg+Fe) ratios (Bauchi: 0.176 to 0.639 and Saminaka: 0.256 to 0.372) is in accordance with the ranges for calc-alkaline amphiboles (Mason, 1985), while the Fe/(Fe+Mg) ratios suggest crystallization of these rocks in environments of intermediate fO_2 with contributions from a minor low fO_2 situation, except for sample B093 that falls within the high fO_2 phase (Figure 5).

The amphiboles from Bauchi and Saminaka charnockites plot in the igneous field of the diagram. This behavior is interpreted as an indication that the amphiboles are igneous and this further confirms that the charnockites of Bauchi and Saminaka areas could not have been formed by metasomatic processes as suggested by the metasomatic model of Oyawoye (1962, 1964). Rather, the process of magmatic intrusion into the pre-existing older rocks as suggested by the Dada *et al*., (1989) model must have been responsible for the emplacement.

Looking at the chemical compositions of the amphiboles from Bauchi and Saminaka charnockites, it is observed that it has a close genetic similarity with those of Varzea Alegre charnockitic rocks from Brazil (Tables 1-2; Figures 2 and 3). The calculated P-T results, 0.9 kbar to 7.2 kbar (from Schmidt, 1992; Table 2) and 599º C to 826º C for Bauchi charnockite and 5.3 to 5.6 kbar (from Schmidt, 1992; Table 3) and 650º to 826º C for Saminaka charnockite are similar to those obtained from the amphiboles from the Varzea Alegre charnockitic rocks with temperatures between 550º and 950º C and pressure between 6.1 and 6.7 kbar (Table 3).

Most of the calcic amphiboles in the Bauchi and Saminaka charnockites crystallized at relatively medium pressures (Table 2: ~99% of analyses yield pressures between 4.4 to 7.2 kbar at Bauchi and 5.3 to 5.6 kbar at Saminaka) regardless of the crystal size, the location of the analysis (i.e. core or rim), or the nature of the amphibole (hastingsite, ferro-hornblende and magnesio-hornblende). In contrast, magnesio-hornblende from a sample (B093) shows a lower value for temperature (599º C) and pressure (0.9 kbar). This may reasonably represent a late phase amphibole formed during the progressive cooling of the rock.

The values shown in Tables 2 and 3 are within the range given by Olarewaju (2006). Olarewaju (2006) stated that crystallization temperatures for charnockitic intrusions of Nigeria range from 718º C to 958º C and that a model of origin involving melting in the lower crust under granulite facies conditions of low water pressure or high CO_2 contents (PCO2 >> H2O) during the Pan-African episode is favoured for the genesis of the charnockitic magma.

CONCLUSIONS

Following the amphibole characteristics displayed by the Saminaka and Bauchi amphiboles and the discussions, it can be inferred that the charnockites from Bauchi and Saminaka in the Basement terrain of North Central Nigeria have an igneous origin, and were emplaced during the Pan-African orogeny. Using three different calibration of Al-in-hornblende (A-H barometry), pressure at the time of formation are similar and averaging 5-6 kbar which corresponds to a shallow crustal chamber. Temperature estimates vary from 599º to 846º C (Bauchi area) and 650º to 826º C (Saminaka area). From amphibole thermometry, one might deduce that magmatic charnockites should be situated at the upper parts of the mantle, or at the lower parts of the crust (70-100km deep). However, it is possible that having originated from the upper mantle, there could be short resident storage in shallow crustal chambers (15-20km)

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before the commencement of crystallization. This would synchronize very well with the pressure estimates found in this work.

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REFERENCES

Ague JJ (1997). Thermodynamic calculation of emplacement pressures for batholitic rocks, California: implications for the aluminum-in-hornblende barometer. *Geology* **25** 563-566.

Ague JJ and Brandon MT (1992). Tilt and northward offset of Cordilleran batholiths resolved using igneous barometry. *Nature* **360** 146-149.

Anderson JL and Smith DR (1995). The effects of temperature and O_2 on the Al-in-hornblende barometer. *American Mineralogist* **80** 549-559.

Blundy JD and Holland TJB (1990). Calcic amphibole equilibria and a new amphibole-plagioclase geothermometer. *Contribution to Mineralogy and Petrology* **104** 208-224.

Dada SS, Lancelot JR 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**(2) 227-234.

Daif Menana and Arafa Ahmed (2007). Mineralogy and Geochemistry of Neogene Andesites from Annaba's Area (North east Algeria) - Calcic Amphibole Thermobarometry. *Medwell Online Journal of Earth Sciences* **1**(2) 101-107.

Ernst WG and Liu J (1998). Experimental phase-equilibrium study of Al- and Ti- Contents of calcic-amphibole in MORB-A semi-quantitative thermobarometer. *American Mineralogist* **83** 952-969.

Ferre E, Gleize G and Caby R (2002). Oblique convergent tectonics and granite emplacement in the Trans-Saharan belt of Eastern Nigeria; a synthesis. Precambrian Research, 114, pp 199-219.

Frost BR and Frost CD (2008). On Charnockites. *Gondwana Research* **13** 30-44.

Giret A, Bonin B and Léger JM (1980). Amphibole compositional trends in oversaturated and undersaturated alkaline plutonic ring complexes. *Canadian Mineralogist* **18** 481-495.

Hammarstrom JM and Zen E (1986). Aluminum in hornblende: An empirical igneous geobarometer. *American Mineralogy* **71** 1297-1313.

Hollister LS, Grissom GC, Peters EK, Stowell HH and Sisson VB (1987). Confirmation of the empirical correlation of Al in hornblende with pressure of solidification of calc-alkaline plutons. *American Mineralogy* **72** 231-239.

Johnson MC and Rutherford MJ (1988). Experimental calibration of Aluminium-in-hornblende geobarometer applicable to calc-alkaline rocks. *EOS* **69** 1511.

Kilpatrick JA and Ellis DJ (1992). C-type magmas: igneous charnockites and their extrusive equivalents. Proc. 2nd Hutton Symposium on the Origin of Granites and Related Rocks, edited by Brown PE and Chappell BW. *Trans Roy Soc Edinburgh, Earth Sciences* **83**(1-2) 155-164.

Leake BE, Woolley AR, Arps CES, Birch WD, Gilbert MC, Grice JD, Hawthorne FC, Kato A, Kisch HJ, Krivovichev VG, Linthout K, Laird J, Mandarino J, Maresch WV, Nickel EH, Rock NMS, Schumacher JC, Smith DC, Stephenson NCN, Ungaretti L, Whittaker EJW and Youzhi G (1997). Nomenclature of amphiboles: Report of the subcommittee on amphiboles of the International Mineralogical Association Commission on New Minerals and Mineral Names. *Canadian Mineral*ogy **35** 219-246.

Mader UK and Berman RG (1993). Amphibole thermobarometry, a thermodynamic approach, Current Research - Part E. *Geological Survey of Canada Paper* **92**(1E) 393-400.

Masoudi F and Jamshidi Badr M (2008). Biotite and Hornblende Composition Used to Investigate the Nature and Thermobarometry of Pichagchi Pluton, Northwest Sanandaj Sirjan Metamorphic Belt, Iran. *Journal of Sciences, Islamic Republic of Iran* **19**(4) 329-338.

Mendes JC, Wiedemann CM and Mcreath I (1999). Conditions Of formation of charnockitic magmatic rocks from the Várzea Alegre Massif, Espírito Santo, Southeastern Brazil. *Revista Brasileira de Geociências* **29**(l) 47-54.

Olarewaju VO (1988). Petrology and geochemistry of the charnockitic and associated granitic rocks of Ado-Ekiti, Akure, SW Nigeria. In: *Precambrian Geology Nigeria*, *Geological Survey of Nigeria Publication* pp 231-239.

Otten MT (1984). The origin of brown hornblende in Artfjallet gabbro and dolerites. *Contribution to Mineralogy and Petrology* **86** 189-199.

Rahaman MA, Ajayi TR, Oshin IO and Asubiojo FOI (1988). Trace element geochemistry and geotechnic setting of Ife-Ilesha schist belt, edited by Oluyide PO, Mbonu WC, Ogezi AE, Egbuniwe IG, Ajibade AC and Umeji AC, In: *Precambrian Geology of Nigeria*. *Geological Survey of Nigeria*, *Publicatio*n 241-256.

Rutter MJ (1989). Experimental data for a proposed empirical igneous geobarometer: Aluminium in hornblende at 10 kbar pressure. *Geology* **17** 897-900.

Spear FS (1981). An experimental study of hornblende stability and compositional variability in amphibolite. *American Journal of Science* **281** 697-734.

Schmidt MW (1992). Amphibole composition in tonalite as a function of pressure: An experimental calibration of the Al-in-hornblende barometer. *Contrib Mineral Petrol* **110** 304-310.

Tuloch AJ and Challis GA (2000). Emplacement depths of Palezoic-Mesozoic plutons from western New Zealand estimated by hornblende-Al geobarometry. *New Zealand Journal of Geology and Geophysics* **43** 555-567.

Watson EB and Harrison TM (1983). Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types. *Earth Planet Science Letters* **64** 295-304.

Wendlandt RF (1981). Influence of CO_2 on melting of model granulite facies assemblages: a model for the genesis of charnockites. *American Mineralogist* **66** 1164-1174.

Wones D and Gilbert MC (1982). Amphiboles in the igneous environment. In: Amphiboles, Petrology and Phase Relations, edited by Veblen DR and Ribbe PH. *Mineralogical Society of America*, *Reviews in Mineralogy* **9B** 355–389.