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P-T conditions of Pan-African orogeny in southeastern Nigeria

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Different rock types from the area northeast of Obudu, southeastern Nigeria were investigated in order to place constraints on their metamorphic conditions. Detailed petrographic studies indicate four main rock groups in the studied area, namely migmatitic gneiss, migmatitic schist, granite gneiss and a minor amount of amphibolite, metagabbro and dolerite. The chemistry of minerals in these rocks is used to estimate metamorphic pressure and temperature (P-T) using appropriate geothermometers and geobarometers. The estimated temperature for migmatitic gneiss of the area is ~600–625 °C and 600–650 °C for migmatitic schist; the pressure is ~ 8 kbar. For amphibolite the temperature is ~600–700 °C and pressure is 8–12 kbar. The estimated pressures and temperatures for the northeast Obudu rocks correspond to upper amphibolite to lower granulite facies metamorphism. The metamorphism occurred due to continent-continent collision during the Pan-African orogeny, most likely during the D1 deformational phase of the area. The recorded high pressures possibly resulted from crustal thickening in the area. P-T conditions for Pan-African orogeny in northeast Obudu area are in good agreement with P-T estimations for the Pan-African event in adjacent areas.

Key words: Pan-African orogeny, Nigeria, Obudu, upper amphibolite-lower granulite facies

Introduction

The Precambrian basement terrane in Nigeria is located in the Neo-Proterozoic to Early Phanerozoic Pan-African Trans-Saharan mobile belt that stretches from North Africa to Brazil, and has boundaries with the West African Craton to the

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west and the Gabon-Congo Craton to the southeast (Torquato and Cordani 1981; Caby et al. 1981; Boullier 1991; Attoh 1998). Basement rocks occurring in Nigeria are collectively referred to as the 'basement complex', and are exposed in three main regions, namely the southwestern region (Annor 1981; De Swardt 1953; Rahaman 1973; Odeyemi 1976, 1977), the southeastern region (Rahaman et al. 1981; Ekwueme and Ekwere 1989; Ekwueme 1990) and the north-central region (Olarewaju and Rahaman 1982) (Fig. 1a, b). Four episodes of deformation that are prior to, contemporaneous with, or even post-dating metamorphism within the complex have been established on the basis of a wealth of isotopic age data acquired over the years from the basement rocks (Grant et al. 1972; Oversby 1975; Pidgeon et al. 1976; Ogezi 1977; Van Breemen et al. 1977; Grant 1978; Mullan 1979; Ajibade 1980; Fitches et al. 1985; Ekwueme 1987; Ajibade 1988; Ekwueme and Caen-Vachette 1992; Dada et al. 1993; Ferré et al. 1995; Kroener et al. 2001; Ekwueme and Kröner 2006). Accordingly, the deformation and metamorphism that have affected the basement complex are products of four thermotectonic/ orogenic events that include the Liberian (2,700 Ma), the Eburnean (2,200 Ma), the Kibaran (1,300–1,400 Ma), and the Pan-African (450–1,100 Ma) ones. Each of these events has left structural imprints on the basement rocks of the complex (Ekwueme 1994). Many workers on the Nigerian basement, including McCurry (1971) and Rahaman (1976), are of the view that the Pan-African orogenic event was the latest, most pervasive and penetrative deformation episode, and that it completely obliterated earlier structures, primary fabrics and metamorphic assemblages of the complex. On the other hand, others, including Grant (1978), Onyeagocha and Ekwueme (1982), Ekwueme (1987), Oluyide (1988) and Ekwueme (1994) favor the view that although it was pervasive, the Pan-African event did not completely homogenize the rocks of the basement, so that traces of earlier structures still remain within the complex.

In southeastern Nigeria, published works on P-T evaluation of Pan-African metamorphism are scarce. Ferré et al. (2002) observed a predominantly granulite facies metamorphism for eastern Nigeria based on mineral paragenesis. However, details of the P-T estimation method is lacking in their paper. Mvondo et al. (2003) have calculated temperatures of 550 °C to 800 °C and pressures of 4 to 12 kbar for Pan-African metamorphism of schist and gneiss from Yaounde, Cameroon. The present research focused on pelitic and basic rocks, which experienced the Pan-African metamorphic event in the Obudu Plateau area of southeastern Nigeria.

Petrographic features and mineral chemistry of the rocks are used to put constraints on the P-T conditions of the Pan-African orogeny in this area.

Regional geologic setting

Most parts of southeastern Nigeria are underlain by high-grade metamorphic rocks (Wright 1971; Ekwueme 1990, 2003; Ferré et al. 2002; Ejimofor et al. 1996).

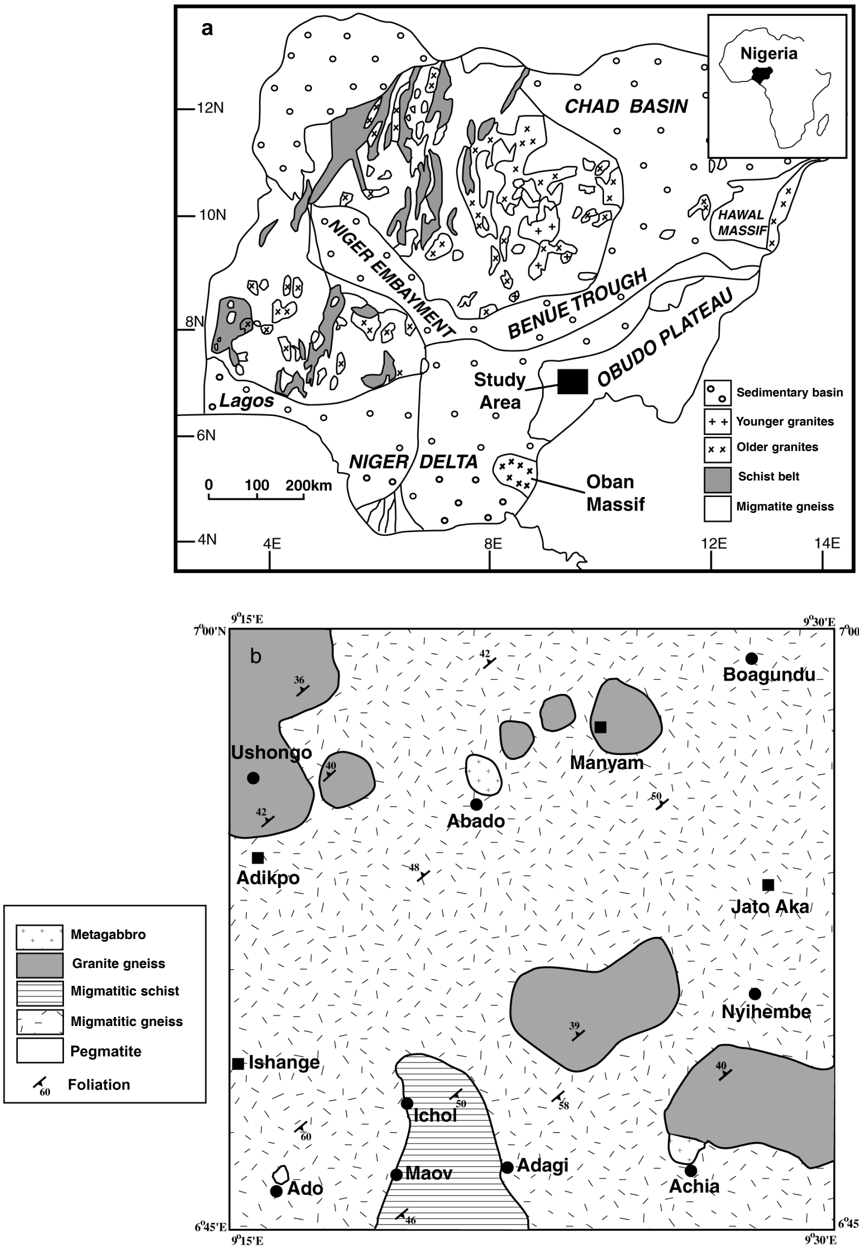


Fig. 1
a) Geologic map of Nigeria. The studied area is shown by a rectangle. b) Simplified geologic map of the northeast Obudu area

The region is also often characterized by the preponderance of Pan-African granitic rocks, which account for more than 80% of the exposed bedrock, and by the general absence of well-developed schist belts similar to the ones in the southwestern and north-central regions of Nigeria. In fact, southeastern Nigeria appears to have more in common with Cameroon and the Central African fold belt than with the north-central and southwestern regions of the basement complex of Nigeria (Ekwueme 2003; Ephraim 2005). Consequently its evolutionary history is currently linked with that of the Pan-Africa mobile belt in Central Africa, north of the Congo Craton (Central African Foldbelt), also known as the Oubanguide or North Equatorial Foldbelt (Toteu et al. 2001; Toteu et al. 2004), and not with the Pan-Africa mobile belt at the margin of the West African Craton, known as the Dahomeyide Orogen. Accordingly, southeastern Nigeria has in recent times been associated with the continent–continent collision involving the northern edge of the Congo Craton as the passive margin and the Adamawa–Yadé and West Cameroon northern block as the active margin (Ephraim 2005; Toteu et al. 2004), instead of the continent–continent collision involving the passive continental margin of the West African Craton and the active continental margin of the Tuareg–Nigerian Shield/ Hoggar Craton (about 600 Ma).

Field relations and petrography

The area of investigation, northeast Obudu, constitutes part of the Bamenda Massif extensions into southeastern Nigeria (Fig. 1a). It is a high-grade metamorphic terrane that consists predominantly of quartzofeldspathic schist and gneiss that have been variably migmatized and intruded by rocks of acidic-intermediate-basic compositions. These rocks form parts of the chains of major intrusions that extend from the Republic of Cameroon to the margin of the Benue Trough. The chains are structurally controlled by existing North-South Pan-African trend within the basement. Rock types mapped within the northeast Obudu area, together with their structural orientations, are presented in Fig. 1b. The field/megascopic observations and the microscopic features of these rocks have been found to be consistent with its classification into four subgroups, namely:

1) Migmatitic gneiss
2) Migmatitic schist
3) Granite gneiss
4) Minor rocks (mainly amphibolite, metagabbro and dolerite)

Detailed descriptions of the field and petrographic characteristics of each rock type are provided below:

Migmatitic gneiss

Quartzofeldspathic gneissic rocks that often display migmatitic characteristics constitute the dominant rock type occurring within the northeast Obudu area. The occurrence and structural orientation (the main foliation) of these rocks are shown in Fig. 1b. The migmatitic gneiss commonly occurs in intimate association with granite gneiss of the area. The heterogeneous deformation and migmatization that may have affected the migmatitic rock group resulted in the occurrence and intimate associations of the banded, semibanded and homogeneous types in such a manner that mapping each of these varieties as distinct units become almost impossible. Megascopically, the rock generally consists of the metamorphic host rock (paleosome) and leucocratic acid injections (leucosome).

The mineralogical modal composition of the migmatitic gneiss is presented in Table 1. The leucocratic mineral-rich phases are predominantly composed of variable proportion of quartz (23–33%), plagioclase (21–35%), orthoclase (7–24%) and sometimes thin selvages of biotite. On the other hand, biotite (3–33%), garnet (1–13%), sillimanite (~1%) and sericite (1–2%) occur as replacements/alteration products. From the petrographic observations it is clear that sillimanite probably replaced a former aluminosilicate (i.e. kyanite, andalusite), most likely kyanite. No kyanite was found in the studied rocks. Other mineral components of the

Table 1
Representative modal composition of the studied rocks

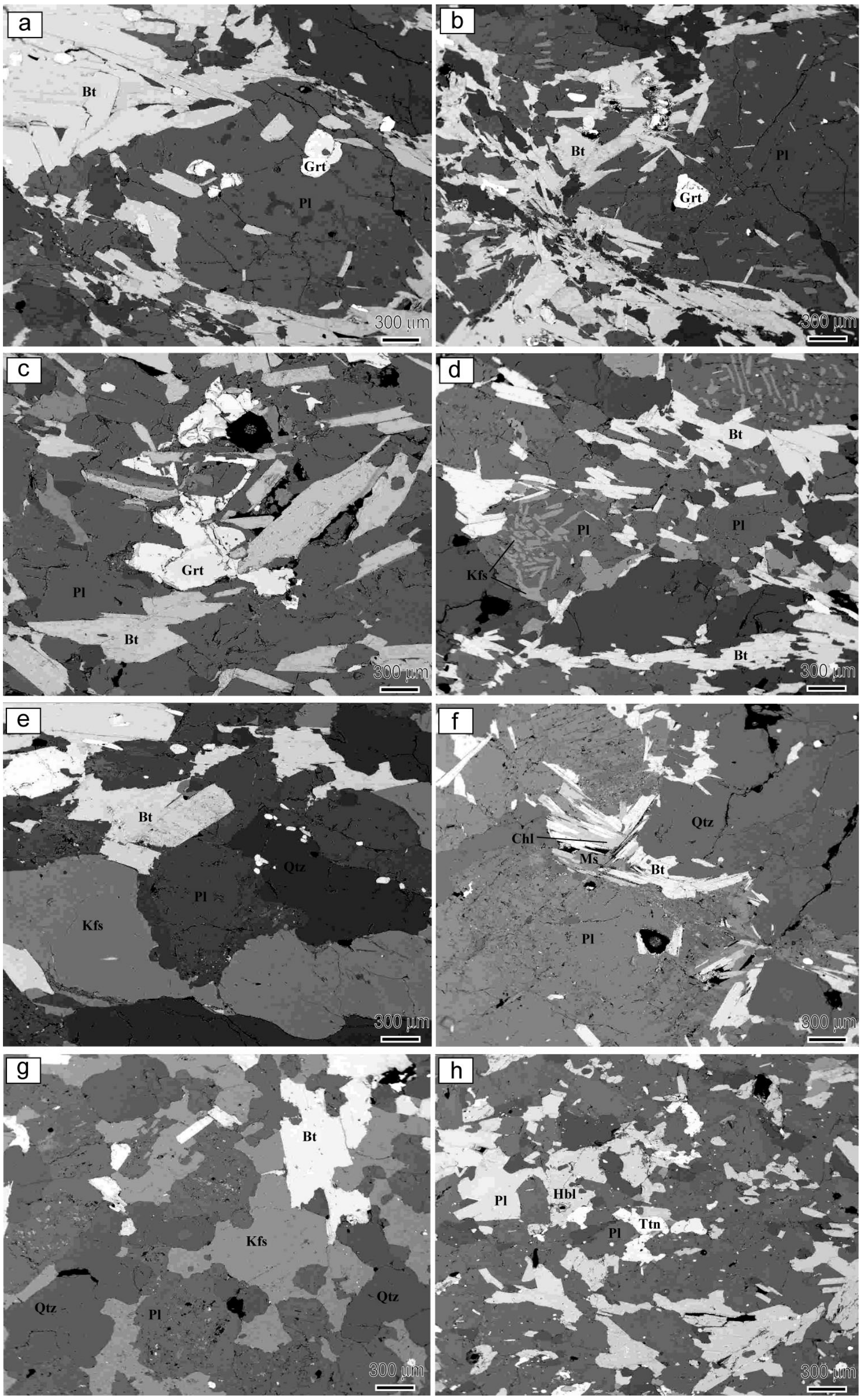
	Migmatitic gneiss	**Migmatitic schist**	**Granite gneiss**	**Amphibolite & metagabbro**
Quartz	30	28	27	6
Plagioclase	35	25	23	26
K-feldspar	20	12	35	3
Biotite	5	21	12	9
Garnet	1	10		
Sillimanite	1	<1		
Hornblende		<1		51
Orthopyroxene	1			
Clinopyroxene				
Olivine				
Chlorite		<1	2	
Titanite	<1	<1	<1	1
Epidote	6	1	<1	2
Zircon	<1	<1	<1	
Allanite			<1	
Apatite	<1		<1	
Sericite		2	<1	
Opaque	<1		<1	2
Total	99	99	99	100

rock include orthopyroxene, titanite, epidote, apatite, zircon and opaque oxide. The quartz, consisting of irregularly shaped crystals with their lenticular outlines parallel to the fabric of the rock, often contains inclusions of biotite, plagioclase and opaque oxides. Interstitial quartz is also present and together with the plagioclase minerals constitute the groundmass mosaic of most of the thin sections examined. The migmatitic gneiss contains both plagioclase and K-feldspar. Plagioclase dominates with an average modal percentage of about 27%. Sericitization of the plagioclase minerals is rampant and is obvious from the rimming and inclusions of sericite minerals within the plagioclase minerals. K-feldspars are subordinate to both plagioclase and quartz (see Table 1), and they are dominantly orthoclase with very little or no microcline. Biotite makes up about 5% of the migmatitic gneiss volume as is discernible from Table 1. It appears to be of two generations. The early or first generation biotites display anhedral, slender and prismatic habit with occasional stumpy laths that may sometimes be kinked, whereas the late or second generation biotite is mainly made up of isolated subhedral crystals that are tabular in form as well as randomly distributed, sometimes cross-cutting each other. The biotite, especially the first generation, occasionally contains inclusions of apatite. Garnet crystals make up about 1% of the rock mode (Table 1) and are commonly wrapped around the foliation of the first generation biotite (Fig. 2a to 2d). Sillimanite crystals also occur within the rock as a minor constituent of about 1% (see Table 1). They are generally observable as finely felted fibroid aggregate of acicular fibrolite that form contorted lenses. Sometimes they appear to be growing on biotite crystals. In addition, traces of orthopyroxene occur in textural equilibrium with the already mentioned assemblages.

Migmatitic schist

Banded schist and locally homogeneous varieties constitute one of the major rock types occurring within northeast Obudu (Fig. 1b). Like the gneissic rocks, the schist is frequently migmatitic and forms part of the basement rocks into which the felsic and mafic plutons are intruded. Most outcrops of migmatitic schist within northeast Obudu are extensively weathered. In the southern Obudu area, Ekwueme (1991) observed interbanding on a megascopic scale of garnet sillimanite gneiss with quartzitic units, and explained such occurrence to be indicative of the sedimentary origin of these rocks. No contact relationships were observed in the field between the migmatitic gneiss and schist but spatial configurations of both rock types suggest that the schist may be relatively younger and was probably supracrustal on the gneissic rocks of the area.

Fig. 2 →
Back-scattered images from different rock types in northeast Obudu. Mineral name abbreviations are after Kretz (1983). a to d, migmatite gneiss; e and f, migmatite schist; g, granite gneiss and h, amphibolite


a
Bt
Grt
Pl
300 µm
b
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c
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f
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Chl
Ms
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g
Bt
Kfs
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Pl
Qtz
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h
Pl
Hbl
Pl
Ttn
300 µm

However, only geochronological data can lead to a better conclusion on the chronology and structural relationship between these two types of rocks within the area.

The modal composition of the migmatitic schist is presented in Table 1. The leucocratic minerals of the migmatitic schist include quartz (26–28%), plagioclase (20–27%) and K-feldspar (12–17%), whereas the mesocratic parts are commonly made up of biotite (20–22%) and garnet (4–18%). In addition, sillimanite (~1%), epidote (1–2%) and sericite (1–3%) occur in minor concentrations, while chlorite, hornblende, titanite and zircon constitute the accessory mineral phase. Plagioclase has a modal average proportion of about 20% (Table 1). Plagioclase occurs in a matrix of interlocking grains with quartz and subordinate K-feldspar. K-feldspar is subordinate to plagioclase and in some samples orthoclase dominates, while in others microcline is the dominant K-feldspar mineral. Biotite is the dominant mafic mineral present and is often associated with garnet. Garnet occurs consistently in all the samples of migmatitic schist examined.

The grains are mostly porphyroblastic with subhedral outline. Sometimes the garnet grains exhibit embayed boundaries and often harbor many inclusions, mostly of quartz, mica and opaque oxides (Fig. 2e to 2f). Sillimanite occurs in some thin sections as a minor component of the rock. Where these occur they often appear to be growing on biotite grains.

Granite gneiss

Several intrusive granitoid bodies of obvious plutonic character are well exposed as oval or dome-shaped bodies sporadically distributed in the basement complex rocks at both the northern edge and the southeastern regions of the study area (Fig. 1b). These granitoid bodies are completely surrounded by the migmatitic gneiss. With very few exceptions, outcrops of the rock generally exhibit similar features and are typically made up of fine- to medium-grained porphyritic granite gneiss near the marginal areas where it is difficult to separate from the surrounding migmatite gneiss complex rocks, due to the presence of narrow contact aureoles with the country rock. The granite gneiss of the area is generally homogeneous, weakly to strongly foliated and massive. The mean of the modal composition of the granite gneiss of northeast Obudu presented in Table 1 indicates that the feldspar minerals altogether constitute more than 50% of the rock volume, followed by quartz and biotite, while chlorite and epidote taken together constitute barely 3% of the rock mode (Fig. 2g). Quartz ranks next to K-feldspar with an average modal proportion of about 27%, and generally exhibits a porphyroblastic habit. Biotite appears to be the major mafic mineral and it constitutes about 12% of the rock volume. Chlorite, epidote and sericite are alteration products in all the samples of the rock studied. The accessory-mineral phase comprising allanite, sericite, sphene, zircon apatite and opaque oxides make up less than 1% of the rock volume.

Minor rocks with basic composition

The minor rocks include amphibolite, metagabbro and dolerite. While metagabbro and amphibolite occur in the migmatitic gneiss of the area, dolerite occurs as enclaves within the granite gneiss. Amphibolite and metagabbro occur within the migmatitic gneiss of northeast Obudu as basic lenses of variable dimension and orientations. Sometimes the lenses are sheared and deformed to produce dismembered enclaves within the host rock.

Amphibolites and metagabbros of the area are mineralogically similar. Metagabbros are coarser grained and lack preferred orientation of the minerals. The modal composition of representative samples of the amphibolitic rock, also presented in Table 1, show that the rock is generally made up of 48–51% hornblende, 24–26% plagioclase, 9–10% biotite and less than 10% of quartz, K-feldspars, opaque oxide, epidote and titanite (Fig. 2h). The dolerites of the area are fine- to medium-grained. The modal compositions in Table 1 show that the dolerites are essentially composed of plagioclase (40–42%), orthopyroxene (38–39%), clinopyroxene (7–9%) and olivine (9%). The accessory mineral phases are mainly made up of opaque oxides (1–4%).

Mineral chemistry

Minerals in optically well-defined, otherwise representative samples from schist, gneiss and amphibolite were analyzed by means of electron microprobe analysis. A JEOL JXA-8900A microprobe in the Indiana University was used. Operating conditions were maintained at an accelerating voltage of 15 kv and a beam current of 10 nA. The raw data were analyzed by the built-in program, which is based on the ZAF procedure.

Mineral and synthetic reference standards were used as standard calibrations. Results are summarized in Table 2.

Garnet: Garnets were analyzed in migmatitic schist and gneiss; in both rock types the garnets are rich in almandine. The composition of garnets in migmatitic gneiss is $Alm_{62-64}Pyp_{7-7.6}Grs_{19.3-23.2}Sps_{7.5-10.5}$ and $Alm_{69-77}Pyp_{10-17}Grs_{6.6-10}$ $Sps_{2.7-9}$ in migmatitic schist. Garnets in these rocks do not exhibit distinct chemical zoning but they are slightly depleted in pyrope content at the rims of the crystals. This feature is considered in thermobarometrical calculations.

Feldspars: The composition of plagioclases in amphibolite and migmatitic gneiss is similar, and corresponds to an andesine-oligoclase ($Ab6_{3-71}An_{29-37}$) composition, while plagioclase in the migmatitic schist is slightly richer in albite ($Ab_{67-77}An_{23-33}$). The composition of plagioclases in granite gneiss is close to the albite end-member ($Ab_{84-96}An_{4-16}$). K-feldspars were analyzed in the migmatitic schist. They are very close to orthoclase end-member.

Mica: The formula unit of mica is calculated on the basis of 22 oxygens, considering all Fe as Fe^{2+}. Biotites are rich in Fe, and Mg# (Mg/Mg+Fe) is 0.3. Al^{IV} in biotites from migmatitic gneiss is 1.225–1.271, 1.175–1.203 in biotites from

Table 2

Representative microprobe analyses of different minerals in the studied rocks. The formula unit of mica is calculated on the basis of 22 oxygens, garnet 12 oxygens, feldspar 8 oxygens and amphibole 23 oxygens. MG = migmatitic gneiss, MS = migmatitic schist, GG = granite gneiss and AM = amphibolite

	Bt				Grt		Pl				Kfs		Amph
	MG	MS	GG	AM	MG	MS	MG	MS	GG	AM	MS	GG	AM
SiO_2	34.97	35.77	34.80	34.91	37.25	38.11	57.75	62.04	63.50	56.79	64.88	65.54	41.60
TiO_2	3.53	3.17	3.44	2.32	0.00	0.00	0.00	0.01	0.05	0.00	0.06	0.02	0.95
Al_2O_3	16.99	15.87	16.28	16.38	21.52	21.78	25.70	23.91	22.27	25.71	18.74	18.28	11.04
Fe_2O_3	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.09	0.00	0.00	0.00	0.04	4.47
FeO	22.14	24.16	24.54	21.28	27.36	33.12	0.00	0.00	0.00	0.00	0.00	0.00	16.43
MnO	0.21	0.06	0.13	0.27	3.28	1.95	0.00	0.00	0.00	0.01	0.04	0.00	0.36
MgO	7.20	6.95	6.18	9.10	1.76	3.81	0.00	0.00	0.01	0.00	0.01	0.00	7.92
CaO	0.03	0.07	0.00	0.01	7.97	2.62	7.29	4.98	3.38	7.76	0.00	0.03	11.76
Na_2O	0.03	0.02	0.02	0.07	0.01	0.02	7.66	9.10	9.89	7.75	1.19	0.09	1.17
K_2O	8.89	8.80	9.28	9.03	0.01	0.00	0.11	0.20	0.02	0.08	14.22	14.80	1.13
F	0.31	0.84	0.70	0.65	0.11	0.05	0.00	0.15	0.13	0.00	0.00	0.00	0.46
Total	94.00	94.88	94.69	93.38	99.16	101.40	98.58	100.32	99.11	98.09	99.22	98.81	96.82
Si	2.739	2.797	2.747	2.749	2.992	2.997	2.620	2.746	2.827	2.597	2.995	3.030	6.400
Ti	0.208	0.186	0.204	0.137	0.000	0.000	0.000	0.000	0.002	0.000	0.002	0.001	0.110
Al	1.569	1.463	1.515	1.520	2.038	2.019	1.375	1.248	1.169	1.386	1.020	0.996	2.002
Fe^{3+}	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.003	0.000	0.000	0.000	0.001	0.518
Fe^{2+}	1.450	1.580	1.620	1.401	1.838	2.179	0.000	0.000	0.000	0.000	0.000	0.000	2.114
Mn	0.014	0.004	0.008	0.018	0.223	0.130	0.000	0.000	0.000	0.000	0.002	0.000	0.047
Mg	0.840	0.810	0.727	1.068	0.211	0.446	0.000	0.000	0.001	0.000	0.001	0.000	1.816
Ca	0.003	0.006	0.000	0.001	0.686	0.221	0.354	0.236	0.161	0.380	0.000	0.001	1.939
Na	0.005	0.003	0.004	0.010	0.001	0.003	0.673	0.781	0.854	0.687	0.107	0.008	0.349
K	0.889	0.879	0.935	0.908	0.001	0.000	0.006	0.011	0.001	0.005	0.893	0.874	0.222
Total	7.716	7.727	7.761	7.812	7.990	7.995	5.031	5.025	5.014	5.055	4.965	4.912	15.516
Alm%	-	-	-	-	62.10	73.20	-	-	-	-	-	-	-
Prp%	-	-	-	-	7.10	15.00	-	-	-	-	-	-	-
Sps%	-	-	-	-	7.50	4.40	-	-	-	-	-	-	-
Grs%	-	-	-	-	23.20	7.40							
a_{Ann}	0.214	0.261	0.287	0.193	-	-	-	-	-	-	-	-	-
a_{An}	-	-	-	-	-	-	0.658	0.770	0.841	0.645	-	-	-
a_{Ab}	-	-	-	-	-	-	0.377	0.249	0.169	0.393	0.020	0.00	-
a_{Or}	-	-	-	-	-	-					0.887	0.989	-

migmatitic schist, 1.217–1.253 in biotites from granite gneiss, and 1.228–1.251 in biotites from amphibolite. The highest Ti content belongs to biotites from migmatitic gneiss and granite gneiss (~0.2 atom per formula unit, apfu) and the lowest content belongs to biotites from amphibolite (0.137–0.145). F content of biotites in the migmatitic schist is about 0.9, which is higher than the biotite F-content in the other rocks (0.028–0.789 apfu).

Amphibole: Amphiboles were analyzed in amphibolite from the Obudu area. Representative microprobe data are provided in Table 2. Cations are calculated based on 23 atoms of oxygen and the Fe^{2+}/Fe^{3+} ratio is estimated using the stoichiometric approach (Droop 1987). The studied amphiboles have values of $NaM4<0.67$ and $(Ca+Na)M4>1.34$ and are calcic amphiboles according to the classification of Leake (1978). Mg# is 0.462–0.502 for the studied amphiboles. They show a ferrohornblende and hastingsite composition on the Mg#/Si diagram (Fig. 3) and magnesiohornblende to tschermakite composition on the Ti/Al^{IV} diagram of Leake et al. (1997) (Fig. 4a). Amphiboles plot between the hornblende and pargasite substitution vectors in Fig. 4b (Hietanen 1974). The F content of the amphiboles is 0.038–0.464.

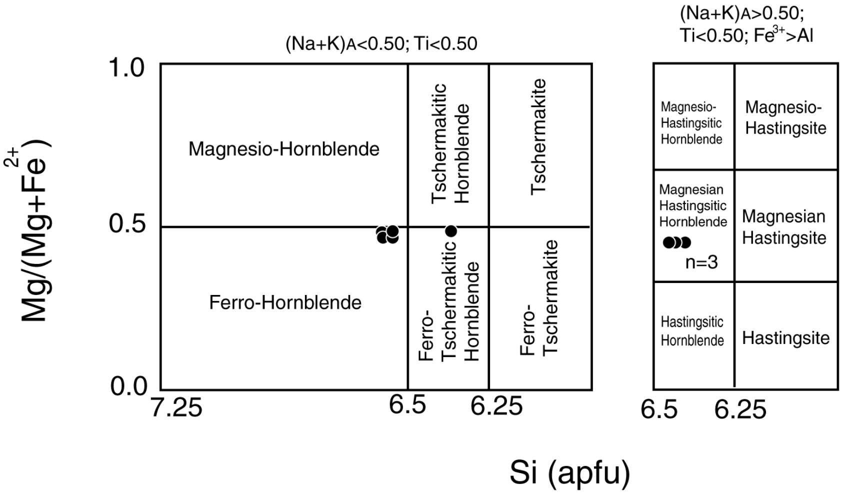

Fig. 3
$Mg/(Mg+Fe^{2+})$ versus Si diagram for amphiboles indicates a ferrohornblende to hastingsite composition for the studied amphiboles

Pressure and temperature estimation

Pressure and temperature of formation of the studied rocks were estimated using conventional geothermobarometric methods. Fe-Mg exchange between garnet and biotite thermometer using calibrations of Bhattacharya et al. (1992)

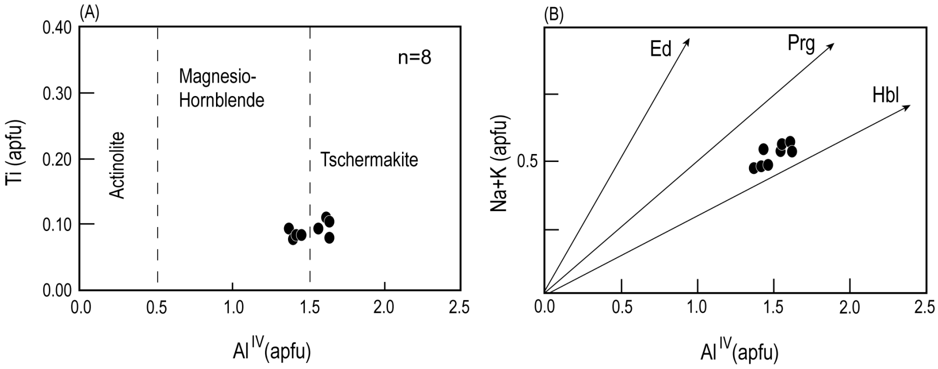

Fig. 4
Ti versus Al(IV) and Na+K versus Al(IV) (after Hietanen 1974) for the studied amphiboles which show magnesio-hornblende to tschermakite composition. Amphiboles from amphibolite in northeast Obudu plot along the pargasite-hornblende exchange vector

and Thompson (1976) was applied to migmatitic schist and migmatitic gneiss. Solution models of Helffrich and Wood (1989) and Ganguly and Saxena (1984) are used for garnets. A temperature of 600–625 °C was calculated for migmatitic gneiss and 700–860 °C for migmatitic schist. Temperatures estimated using calibrations by Ferry and Spear (1978), Pigage and Greenwood (1982) and Hodges and Spear (1982) are higher than those from calibrations of Bhattacharya et al. (1992) and Thompson (1976), while temperatures from the calibration of Indares and Martignole (1985) are systematically lower than the results from the other calibrations. The higher temperatures are an artifact of the high Ti content in biotite (Indares and Martignole 1985). The lower temperatures are due to the introduction of interaction parameters for Ti and Al^{vi} in biotite and Mn and Ca in garnet, into the original calibration of Ferry and Spear (1978). The calibration of Indares and Martignole (1985) possibly over-corrects the effect of the minor components. The temperatures given by the Bhattacharya et al. (1992) calibration, which uses the mixing parameters for pyrope-almandine asymmetric regular solution after Hackler and Wood (1984), is intermediate to those of Indares and Martignole (1985) and Ferry and Spear (1978). These temperatures are taken to best estimate the temperatures of garnet-biotite-bearing rocks of the Obudu area. The behavior of sillimanite is not well understood in the studied rocks. It replaces other minerals (mainly biotite) and appears as a fibrous aggregate, making up less than 1% of the rocks (Table 1). Therefore the GASP (garnet-sillimanite-quartz-plagioclase) barometer cannot be used to estimate the pressure unequivocally. However, the Koziol and Newton (1988) calibration was also attempted. Garnets with highest Mg contents and biotites with highest Ti content were used to find the possible peak metamorphic pressure. Migmatite gneiss gives a pressure of 7.6–10.9 kbar and migmatite schist of 9.5–14 kbar.

Because of the uncertain status of sillimanite in the studied rocks these pressures were not used to constrain the P-T condition of northeast Obudu. For amphibolite the hornblende-plagioclase thermometer of Holland and Blundy (1994) and the thermometer of Colombi (1989) were used. The hornblende-plagioclase thermometer calibrated by Blundy and Holland (1990) and Holland and Blundy (1994) is constructed by using the Al^{iv} content of amphibole coexisting with plagioclase in silica-saturated rocks. The overall standard error for this thermometer is 38 °C. Considering the complex chemical composition of amphiboles and possibility of several miscibility gaps among amphibole end-members and an uncertain Fe^{3+}/Fe_{total} ratio using microprobe data, temperatures obtained from plagioclase-hornblende thermometer are not very precise.

Considering the presence of quartz in amphibolites the edenite-tschermakite calibration of the thermometer was used, which gives temperatures of 680 °C for amphibolite. Using the semi-quantitative thermobarometer of Ernst and Liu (1998) a temperature of 600 °C and pressure of 8–12 kbar can be considered for these rocks (Fig. 5). The thermometer of Colombi gives a temperature of ~700 °C for the amphibolite, which is in good agreement with temperatures from the hornblende-plagioclase thermometer. The P-T condition for migmatitic schist was estimated using multi-equilibria calculations and THERMOCALC v.2.4. (Powell and Holland 1988). There is no suitable mineral paragenesis in granite gneiss to estimate P-T conditions of their formation, but since amphibolite appears in the form of lenses within these rocks, more likely the P-T conditions estimated for amphibolite can also be considered for granite gneiss. The P-T results are summarized in Table 3.

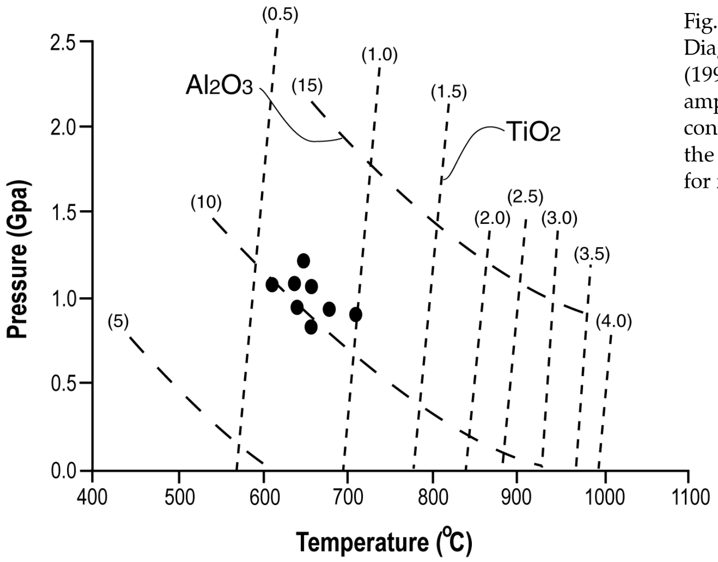

Fig. 5
Diagram of Ernst and Liu (1998) for the studied amphiboles to estimate P-T condition of formation of the amphibolite (see text for more explanations)

Table 3
Summary of P-T estimation for the southeastern Nigeria rocks

	Amphibolite	Migmatitic schist	Migmatitic gneiss
Thermometry			
Grt-Bt (Bhattacharya et al. 1992)		790 °C	615 °C
Hbl-Pl (Holland and Blundy 1994)	700 °C		
Amph (Colombi 1989)	710 °C		
Barometry			
Al in hornblende (Johnson and Rutherford 1989)	5 kbar		
Thermobarometry			
THERMOCALC v.2.4. (Powell and Holland 1988)		P=7±2 kbar T=615±50 °C	
Al-Na in hornblende (Ernst and Liu, 1998)	8–12 kbar		
Mineral component activity values used in THERMOCALC calculations		ann=0.12, phl=0.0161, east=0.014 alm=0.37, py=0.0058, gr=0.00074 or=0.90, an=0.38, ab=0.67	

Discussion and Conclusions

The studied area in northeast Obudu, the Bamenda Massif, is a part of the Eastern Nigeria Terrane. The existence of two main terranes in Nigeria, i.e. the Western and Eastern Terranes, was proposed by Ferré et al. (1995, 2002). Eastern Nigeria was intruded by several Proterozoic plutons (e.g. Snelling 1964; Tougarinov et al. 1968; Caen-Vachette and Umeji 1983; Umeji and Caen-Vachette 1984; Ferré et al. 2002). Two main deformational phases, D1 and D2, are recognized in the Eastern Nigeria Terrane and in other Pan-African terranes (e.g. Ferré et al. 2002; Mvondo et al. 2003). Ferré et al. (2002) consider a possible monocyclic tectonometamorphic evolution for Eastern Nigeria with granulite facies conditions. They consider the peak of metamorphism contemporaneous with D1 deformation (ca. 64 Ma), which occurred due to the easterly displacement of an early nappe. Ephraim et al. (2006) also have reported a possible granulite facies metamorphism for these rocks. Mvondo et al. (2003) consider D1 deformation phase as a compressional phase due to collision and D2 phase as an extensional phase. The metamorphic rocks in the Eastern Nigeria Terrane and the Obudu area are considered to reach metamorphic grades up to upper amphibolite facies by Onyeagocha and Ekwueme (1990), while Ferré et al. (2002) and Ukwang et al. (2003) concluded that metamorphism in the Eastern Nigeria Terrane extended to granulite facies. Ekwueme and Kröner (2006) have calculated a single zircon age of 574±10 Ma for gneiss of the Obudu Plateau. They conclude that the Pan-African high-grade event in the area was coeval with the formation of granulites in Cameroon, Togo and Ghana. This study indicates a formation temperature for migmatite gneiss of the area of 600–625 °C. P-T conditions for migmatite schist are 600–800 °C and 4–9 kbar and 600–700 °C and 8–12 kbar for amphibolite. Probably lower temperatures show re-equilibration during thermal relaxation; therefore low temperatures were not used to estimate the peak of metamorphic conditions. It can be seen that amphibolite shows higher temperatures than migmatitic gneiss. Most likely, migmatitic gneiss has experienced a later re-equilibrium during solidification of the generated partial melts and during thermal relaxation or exhumation. The estimated pressures and temperatures for northeast Obudu rocks correspond to upper amphibolite to lower granulite facies metamorphism. These results are in agreement with the P-T conditions estimated for Pan-African orogeny from other areas (e.g. Yaounde Nappe, Cameroon – Mvondo et al. 2003; Ukwortug area of Obudu - Ukwang et al. 2003; Agou Massif of southern Togo – Agbossoumonde et al. 2004; Ghana, Togo and Benin – Castaing et al. 1993; Dahomeyide – Attoh 1998a, b). Estimated P-T conditions for migmatitic schist and amphibolite (where both P and T estimates

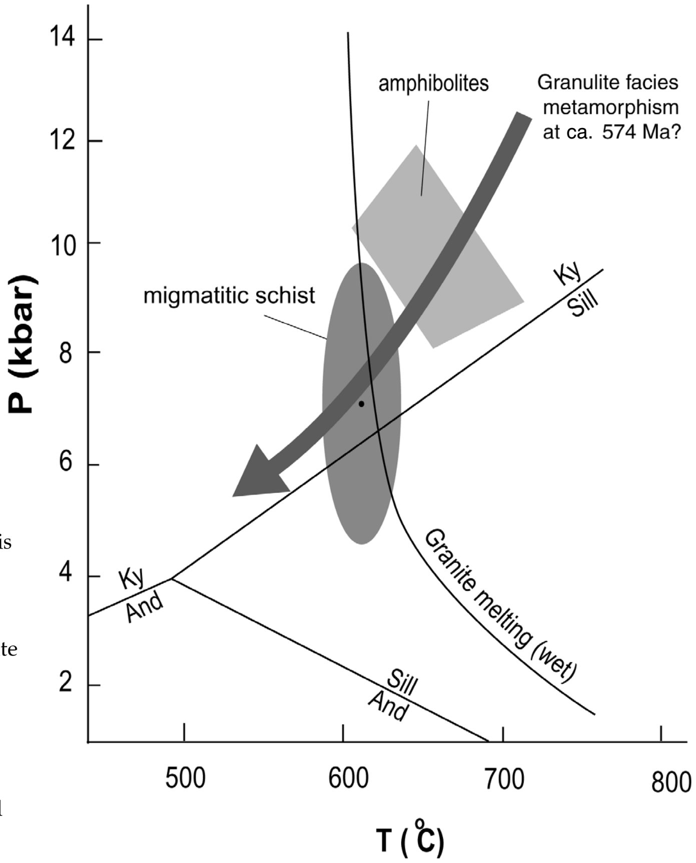

Fig. 6
P-T conditions of formation of the studied rocks. The schematic P-T path is modified after Affaton et al. (2000) Aluminosilicates equilibria and granite melting curves are provided for comparison. Granulite facies metamorphic age (ca. 574 Ma) is from Ekwueme and Kröner (2006)

are available) are plotted on the P-T diagram of Fig. 6. Although the P-T path for the Obudu area is not very certain; probably these rocks have experienced the same P-T evolution as granulite facies rocks from Kabye Massif of northern Togo during the Pan-African orogeny (Affaton et al. 2000). A pressure of about 8 kbar (average of pressures calculated in this contribution, considering P estimation uncertainties) corresponds to a depth of 30 km (assuming an average crustal density of ~2700 kg/m^3). This shows a possible crustal thickening probably similar to Phanerozoic continent-continent collision of the Himalaya type (e.g. Maboko 1977).

The main conclusions that may be made from this study are:

- Metamorphic rocks from northeast Obudu have undergone upper amphibolite to granulite facies metamorphism;
- This metamorphism occurred due to continent-continent collision;
- High pressures estimated show a possible crustal thickening due to collision;
- The P-T results provided here are in good agreement with P-T condition estimated for Pan-African orogeny in other areas.

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