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ORIGINAL PAPER

Petrography and geochemistry of Neoproterozoic charnockite–granite association and metasedimentary rocks around Okpella, southwestern Nigeria

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Abstract

The Neoproterozoic charnockite–granite association of Okpella intrudes metasedimentary and migmatite-gneiss complex rocks in the eastern Igarra Schist Belt, southwestern Nigeria. In order to unravel the complex processes involved in the formation and tectonic evolution of the Igarra Schist Belt during the Neoproterozoic, detailed field, petrographic and whole-rock geochemical study of the charnockite–granite association and metasedimentary rocks around Okpella was conducted. Published data on the metasedimentary rocks and Pan-African granitoids in different sectors of the belt were also compiled for detailed interpretations. The charnockites and granites of Okpella show primary magmatic mineralogy and geochemical characteristics. They are silicic (> 63 wt% SiO_2), metaluminous to peraluminous, high-K calc-alkaline, ferroan, post-collisional granitoids. The garnet-biotite schist, calc-silicate gneiss and quartzite in the area are low–medium grade metasedimentary rocks. The mineralogy and geochemistry of the charnockites suggest that the charnockitic melt was derived from mafic lower continental crust through partial melting and assimilation-fractionation processes. The granites probably originated from mixed melts derived from lower- to mid-crustal tonalites-trondhjemites-granodiorites and/or subducted metagreywackes and mantle-derived magmas (probably the charnockitic melt and/or its progenitor). The granites and charnockites are coeval and were presumably emplaced during the post-collisional stages of the Pan-African Orogeny. The garnet-biotite schist, calc-silicate gneiss and quartzite represent metamorphosed immature to slightly mature sedimentary rocks, probably greywacke, marl and subarkose, respectively, that were sourced from intermediate–acid rocks which underwent low–moderate chemical weathering with minor contribution from recycled sediment sources and deposited in active continental environments. The Neoproterozoic evolution of the Igarra Schist Belt, therefore, involved deposition and infolding of sediments in active continental margin during the early Pan-African followed by upwelling of basaltic magma from the mantle which underplated and crystallized in the lower continental crust and was subsequently partially melted to generate the charnockitic and granitic melts through mantle-crust interaction during the late Pan-African.

Keywords Charnockite–granite association · Metasedimentary rocks · Mafic lower continental crust · Tonalites-trondhjemites-granodiorites · Active continental environments · Neoproterozoic

Introduction

The association of charnockite–granite igneous rocks is widely recognized worldwide, commonly interpreted as the results of mantle-crust interaction during late orogenic stages (Hubbard 1968, 1988; Hubbard and Whitley 1978, 1979; Thomas et al. 1993; Rajesh 2004, 2008; McLelland et al. 2010; Harlov et al. 2012; Sekaran et al. 2016; Kumar et al. 2020). In Nigeria, the close association of charnockites and granites with respect to field relations is well documented in different parts of the Basement Complex, especially around Ado-Ekiti–Ikerre–Akure, Idanre and Toro (Hubbard 1968;

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Cooray 1972; Tubosun et al. 1984; Olarewaju 1987; Dada et al. 1989; Ocan 1990; Ademeso 2010). The charnockite–granite associations of Nigeria commonly occur in two modes: (i) charnockites as the cores of aureoles in Older Granite bodies and (ii) charnockites along the margins of texturally similar Older Granites (Tubosun et al. 1984; Olarewaju 2006).

Tubosun et al. (1984), Rahaman et al. (1988), Dada et al. (1989) and Olarewaju (2006) on the basis of detailed field, geochemical, isotopic and geochronological data on some charnockite–granite associations of Nigeria have suggested that charnockitic, dioritic and granitic magmas were present together and were emplaced contemporaneously or soon after one another during the Pan-African Orogeny. Hence, owing to the field relationships, similar radiometric ages and structural features of the granites and charnockites, Dada (2006) in his re-classification of the Nigerian Basement Complex grouped these granitoids together and simply referred to them as "Pan-African granitoids". A number of petrogenetic processes have been proposed for the charnockite–granite associations of Nigeria, prominent among which are: (i) fractionation of basic magma emplaced under high-grade conditions (Olarewaju 1987, 2006) and (ii) fusion of tonalitic restite under dry granulite facies conditions and magma mixing (Dada et al. 1989). Magma generation by partial melting of the lower continental crust and/or upper mantle and the dominant role of crustal-derived melts with small amounts of juvenile mantle magma is generally accepted by researchers working on the charnockite–granite associations of Nigeria.

Within the Nigerian basement terrain, charnockites and granites mainly intrude migmatite-gneiss rocks of upper amphibolite to granulite facies (Dada et al. 1989; Olarewaju 2006; Ogunyele et al. 2019; Oyawale and Ocan 2020). However, in some areas such as the Igarra Schist Belt, the association of these granitoids intrudes metasedimentary rocks of greenschist to lower amphibolite facies (Odeyemi 1988; Olarewaju 1999). The deposition of these younger metasedimentary rocks in Nigeria predates the emplacement of the Pan-African granitoids and hence, the former could possibly have played significant roles in the formation of the latter, more especially in areas where they outcrop together (Fitches et al. 1985). For example, Goodenough et al. (2014) suggested the contribution of metasedimentary rocks in the origin of the post-collisional granites from western Nigeria. Geochemical studies of the metasedimentary rocks from the Nigerian schist belts have also been used to evaluate the nature of their provenance and weathering processes, as well as to identify the corresponding tectonic setting and understand crust–mantle evolution (Olobaniyi 2003; Okunlola and Okoroafor 2009).

However, in spite of the numerous research on the charnockite–granite associations and metasedimentary rocks of Nigeria and the Nigerian basement terrane in general, the geology, tectonic settings and evolution of a large areal extent of the terrane, including the Igarra Schist Belt where Okpella is located, are still poorly understood. The Okpella charnockite–granite association is largely unknown and geologic data on the association as well as the metasedimentary rocks in the area are scanty (Odeyemi 1988; Olarewaju 1999; Jimoh et al. 2016; Ogunyele et al. 2018). In light of the above, detailed field, petrographic and whole-rock geochemical study of the charnockite–granite association and metasedimentary rocks around Okpella was conducted to unravel the complex processes involved in their formation and tectonic evolution. This paper, therefore, presents new geologic data on the Okpella charnockite–granite association and metasedimentary rocks and compiles published geochemical data on the metasedimentary rocks and Pan-African granitoids in different sectors of the Igarra Schist Belt from literature for the purpose of comparison and unravelling the evolution of the belt during the Neoproterozoic.

Regional geology

The study area is part of the Precambrian Basement Complex of Nigeria (Odeyemi 1988; Olarewaju 1999; Ogunyele et al. 2018). The Nigerian Basement Complex is located within the Pan-African Trans-Saharan mobile belt between the West African and Congo Cratons and to the south of the Tuareg Shield (Woakes et al. 1987; Goodenough et al. 2014) (Fig. 1a). The complex is composed of three major rock groups: the Migmatite-Gneiss Complex with ages ranging from Neoproterozoic to Paleoproterozoic and Archean (Grant 1970; Rahaman 1976, 1988; Dada 1998; Kröner et al. 2001; Ekwueme 2003a; Okonkwo and Ganev 2012, 2015); low-grade, younger metasedimentary and metavolcanic rocks which formed the Schist Belts considered to be of Neoproterozoic age with most dates varying between 690 and 489 Ma (Turner 1983; Elueze 1988; Odeyemi 1988; Rahaman 1988; Omitogun et al. 1991; Caby and Boessé 2001; Danbatta 2008; Fagbohun et al. 2020); and the Older Granite suite which intrude the two earlier lithologies and have Pan-African ages (Ferré et al. 1998, 2002; Ekwueme 2003b; Adetunji et al. 2016, 2018; Girei et al. 2019; Ibe and Obiora 2019; Bute et al. 2019). The available ages of the Pan-African granites in Nigeria are bracketed between 650 and 580 Ma (Tubosun et al. 1984; Rahaman et al. 1991; Dada et al. 1993; Dada 1998; Goodenough et al. 2014; Bute et al. 2019). However, some early magmatic phases at ca. 790–709 Ma have been recognized (Fitches et al. 1985; Goodenough et al. 2014; Adetunji et al. 2016). Mesozoic anorogenic calc-alkaline ring complexes known as the Younger Granites intruded the eastern terrane of the Nigerian basement prior to the development of seven

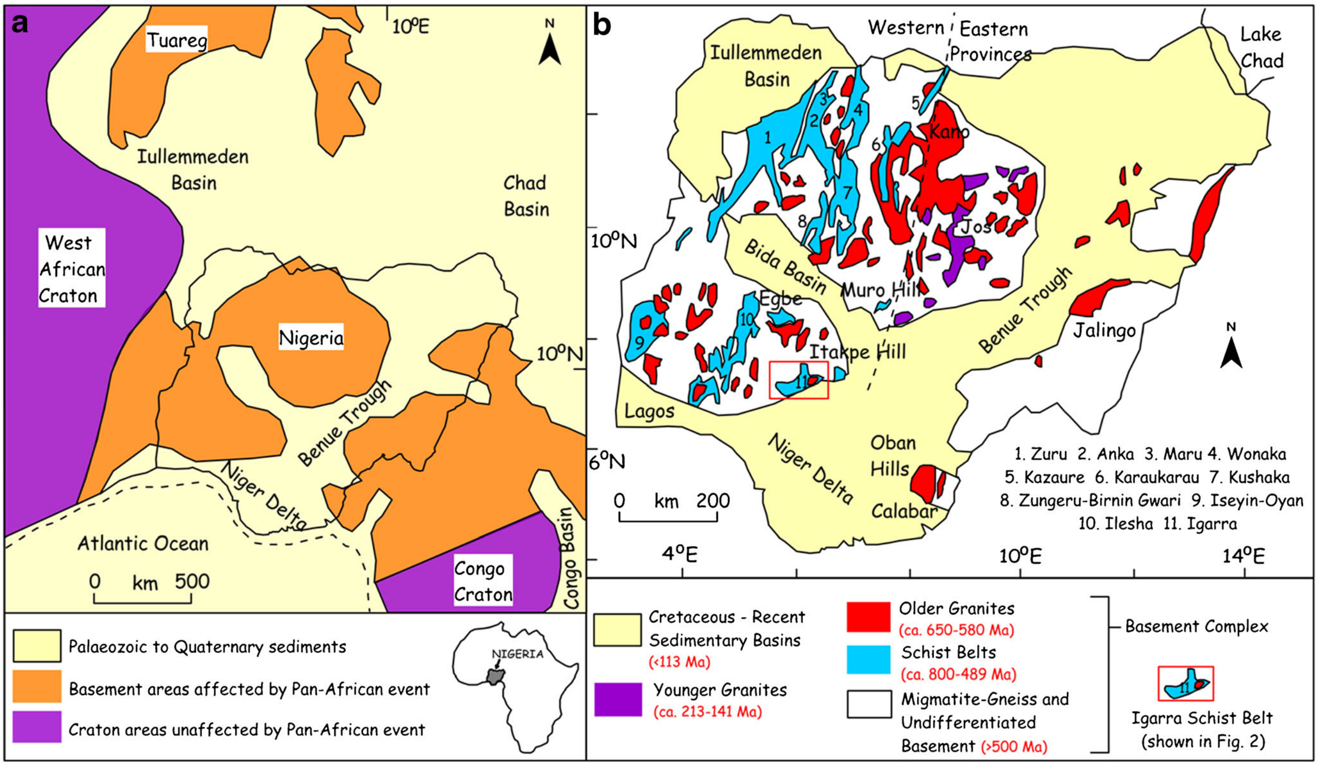


Fig. 1 **a** Regional geological map of Nigeria within the Pan-African Trans-Saharan mobile belt between the West African and Congo Cratons. **b** Outline geological map of Nigeria showing the Basement Complex, Younger Granites and Sedimentary Basins (modified after Woakes et al. 1987)

sedimentary basins in both the eastern and western terranes which were filled by Cretaceous to recent sediments (Fig. 1b).

The Nigerian basement records polycyclic tectonic evolution and polyphase deformations during the Precambrian (Rahaman 1976, 1988; Odeyemi 1981; Ajibade et al. 1987; Ekwueme and Kalsbeek 2014). As a result of these deformations, complex structures are associated with the basement rocks (Ekwueme 1987; Oluyide 1988; Kolawole et al. 2017). The last and most penetrative orogenic event (Pan-African orogeny) that affected the Nigerian basement produced an approximately NS structural trend in the rocks (Rahaman 1988; Ferré et al. 1996; Obaje 2009).

The study area constitutes the eastern part of the Igarra Schist Belt in southwestern Nigeria (Fig. 2). Three major rock groups constitute the Igarra Schist Belt, the observed sequence of which is as follows: (i) the Migmatite-Gneiss Complex, (ii) the Igarra metasedimentary rocks, and (iii) the Pan-African granitoids (Odeyemi 1988; Omitogun et al. 1991). The Migmatite-Gneiss Complex comprising migmatites, biotite- and biotite-hornblende gneisses, granite gneisses and relics of an ancient metasedimentary sequence constitute the basement (sensu stricto) in the area. It is the oldest rock group (Archean to Neoproterozoic age) on which the Igarra metasedimentary rocks occur as supracrustals. The contacts between the migmatite-gneiss and the metasedimentary rocks are fault-bounded in most places (Odeyemi 1988; Jimoh et al. 2016).

The Igarra metasedimentary rocks cover an area of approximately 3000 km^2 and is predominated by low-grade rocks of sedimentary origin (schists, calc-silicate gneisses, marbles, metaconglomerates, quartzite and banded iron formation) overlying the Migmatite-Gneiss Complex (Okeke and Meju 1985; Odeyemi 1988; Adegbuyi et al. 2017) (Fig. 2). On the basis of lithologic and structural complexity, as well as abundance and configuration of intrusive rocks in the Igarra Schist Belt, Turner (1983) assigned a Kibaran age to the belt. Rahaman et al. (1988) however disagreed with Turner (1983) and with reference to available radiometric data argued that the Nigerian schist belts including the Igarra belt are essentially of Neoproterozoic age with most dates varying between 690 and 489 Ma and also suggested the possibility of early Pan-African sedimentation and volcanism at ca. 800 Ma. Odeyemi (1988) suggested that the Igarra and Egbe Schist Belts could have evolved as a paired metamorphic belt with the latter belt being a volcano-sedimentary complex consisting of abundant metavolcanics (amphibolites, amphibole schists) (Olobaniyi and Annor 2003). The complete absence of metavolcanics and the occurrence of conglomeratic horizons in the Igarra Schist Belt suggest a clastic sedimentary environment of deposition and tectonic instability of the basin throughout the depositional period, respectively (Odeyemi

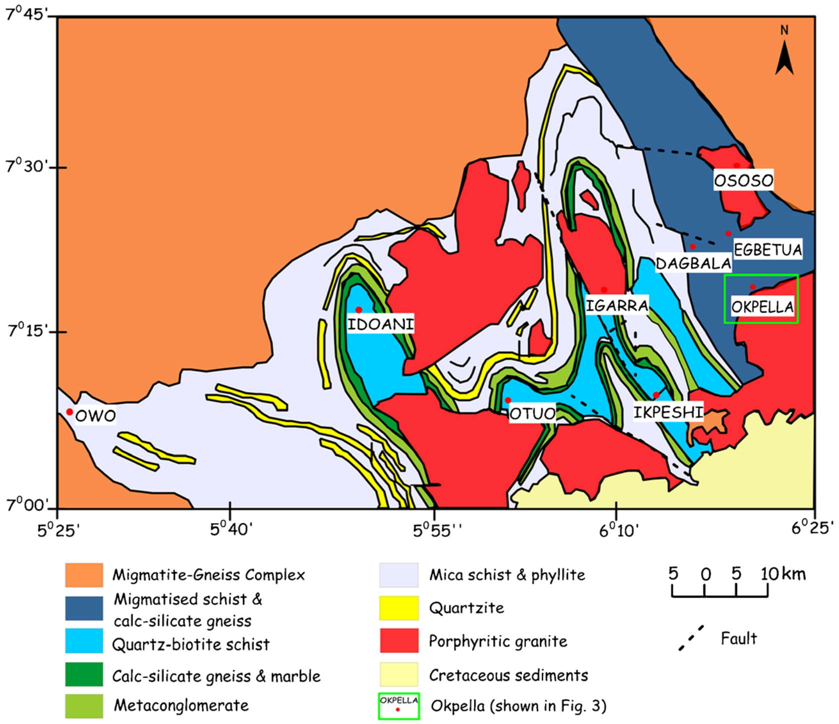


Fig. 2 Geological map of Igarra Schist Belt showing Okpella area (modified after Odeyemi 1988)

1988; Omitogun et al. 1991). At least four antiformal and four complimentary synformal folds with roughly NS axis, and four major fault zones have been mapped in the Igarra Schist Belt. Metamorphism in most parts of the belt is of low grade (greenschist facies) and locally higher (up to lower amphibolite facies) in the eastern part (Omitogun et al. 1991). The pre-Mesozoic drift reconstruction of the West Gondwana revealed that the Igarra Schist Belt matches the Seridó Schist Belt of northern Borborema Province, northeast Brazil, and have essentially similar lithologies, structural history and metamorphism (Caby 1989; Dada 2008; Archanjo et al. 2013).

The Migmatite-Gneiss Complex and the Igarra metasedimentary rocks were intruded by Pan-African granitoids comprising syn- to late-tectonic porphyritic, biotite- and biotite-hornblende granites, granodiorites, syenites and adamellites; charnockites and gabbros; unmetamorphosed dolerite, pegmatite, aplite and syenite dykes. These Pan-African intrusives represent the youngest group of rocks of Precambrian age in the area. Field evidence indicates that most of the granitic activity took place during the waning stage of the Pan-African Orogeny (Odeyemi and Rahaman 1992).

Methodology

The study involved geological mapping of the Okpella area on a scale of 1:30,000 during which various lithologies in the area were studied and sampled for petrographic and whole-rock geochemical analyses. Twenty-two representative samples were collected from the main outcrops comprising six granite [three porphyritic granite (PG) and three medium- to coarse-grained granite (MCG)], six charnockite [three medium-grained charnockite (MCh) and three coarse-grained charnockite (CCh)], four garnet-biotite schist (GBS), five calc-silicate gneiss (CGN) and one quartzite (Qtz).

Thin sections of 10 samples were prepared and studied under a petrographic microscope. Mineral contents (in volume percent) of the rocks were determined and their photomicrographs were captured. The major and trace elements concentrations of all the samples were also determined using an Energy Dispersive X-Ray Fluorescence (ED-XRF) machine (PANalytical model). These analyses were carried out at the National Geosciences Research Laboratory, Kaduna, Nigeria.

All the samples were crushed and pulverized to < 63 μm (230 mesh) using a jaw crusher and pulveriser, respectively. After pulverization of each sample, the pulveriser was cleaned using acetone. The pulverized samples were homogenized using a homogenizer, after which glass beads used for the major elemental analyses (Si, Al, Mn, Fe, Ti, Mg, Ca, Na, K and P) expressed in oxide weight percent were prepared by first drying the sample powder in an oven at 100 °C for 24 h to remove the moisture in the rock powder. About 5 g of the dry powdered rock sample was weighed into a silica crucible and ignited in the furnace at 800–900 °C for 2 to 3 h to calcinate the impurities. The samples were then removed from the furnace and allowed to cool to room temperature in desiccators. Each ignited powdered rock sample was weighed again to determine the weights of the calcinated impurities (or loss on ignition) which were H_2O and CO_2. One gram of the stored ignited rock powder was weighed and thoroughly mixed with exactly five times of flux (spectroflux 100B) and then heated to temperatures of 1100 °C in a platinum crucible to form a molten mixture. The molten mixture was then cast into a mould, cooled and removed, over a compressed stream of air, tapping the edge with a small iron slab until the glass bead formed was separated. Each glass bead was labelled and slotted into the computerized XRF machine for major elemental analysis.

Trace elemental analysis was carried out using compressed pellets. These pellets were prepared by weighing 5 g of oven-dried powdered rock samples and 5 g flux (cellulose-powder) was added to it as a binding and dispersive agent. This mixture was shaken in small plastic containers for about 10 min. The mixture was then compressed using a manual compressor (pelletizer) at a pressure of l500 kgm^{-2}. The prepared pellets were thereafter placed in the computer-programmed XRF machine for trace elemental analysis. The accuracy of the analytical results was verified through the analysis of duplicate samples and standards. The relative systematic error of the analyses is <3% compared to certified standards/reference materials.

Results

Local geology—Okpella area

The geology of the Okpella area in the eastern part of the Igarra Schist Belt comprises largely of strongly deformed, low- to medium-grade metasedimentary rocks underlaid by granitic gneiss, both of which were intruded by granites, charnockites, pegmatites, quartz veins and dolerite dykes (Figs. 3 and 4). The granitic gneiss of probable Paleoproterozoic age outcrops in the northeastern part of the area; it is medium- to coarse-grained, light grey, granoblastic to weakly foliated with moderately thick (0.5–2 cm) mineralogical bands of light and dark colours (Fig. 4a). The light bands are composed of felsic minerals such as quartz, K-feldspars and plagioclase feldspars while biotite, hornblende and opaque minerals constitute the dark bands. The granite gneiss trends NW-SE with moderate dips to the west (av. 68°).

The Neoproterozoic metasedimentary rocks in the area include garnet-biotite schist, calc-silicate gneiss and marble, quartzite and banded iron formation (BIF) (Fig. 4b, c, f). These majorly trend NS to NW-SE with some of the lithologies, particularly the garnet-biotite schist and calc-silicate gneiss also showing a minor older ENE-WSW to EW trend. The garnet-biotite schist outcrops extensively as low-lying rocks in the central and northwestern part of the area; it is schistose, dark grey to black in colour and medium-grained to porphyroblastic. It contains abundant quartz, biotite, plagioclase feldspar, K-feldspar and porphyroblasts of red garnets. The garnet porphyroblasts sometimes exceed 3 cm in size. The schist probably covers more area in the past than it presently outcrops. This is evident by the abundance of the rock as both small and giant xenoliths within charnockites and granites which occur to its south. Calc-silicate gneiss and marble occur in the central part of Okpella, with the former being more abundant, foliated, folded, medium-grained, colour varying from dark green to dark grey, and often associated with marble and granitic bands, pegmatites and quartz veins (Fig. 4c, h). In hand specimen, the marble is composed essentially of calcite with minor amounts of graphite while the calc-silicate gneiss is composed mainly of calcite, quartz, biotite and opaques. Quartzite and BIF outcrop as ridges in the northern part of the area and are composed essentially of quartz and iron minerals, respectively.

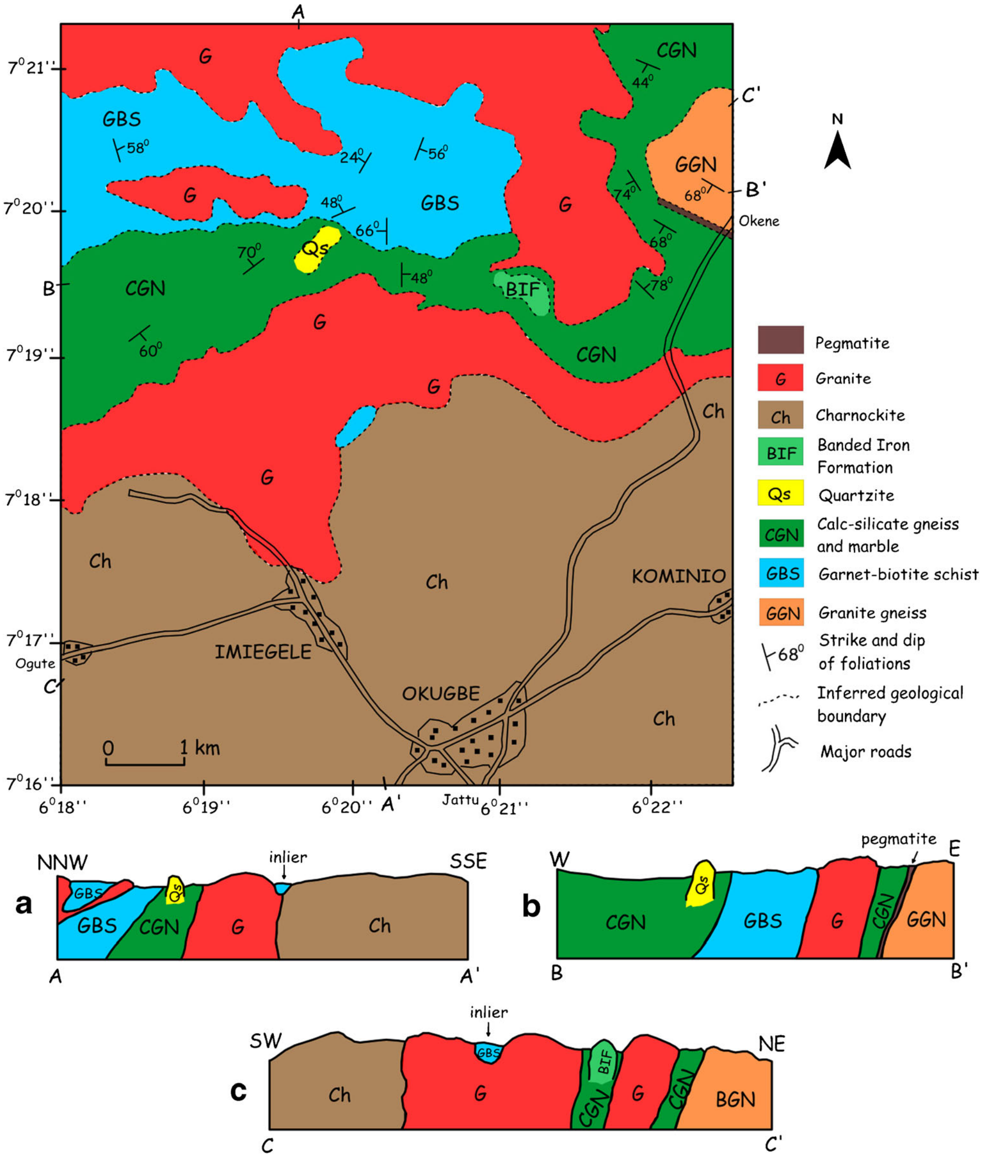
Granites and charnockites form batholiths as well as low-lying outcrops with numerous boulders and constitute the larger proportion of the area (>70%). They are closely associated in the field and sometimes contain xenoliths of their host rocks (mainly garnet-biotite schist and calc-silicate gneiss) especially at their contacts (Fig. 4d, g). Where observed, the contacts between these granitoids and their host rocks are usually sharp and sometimes marked by the mixing of the granitoids and host rocks as a result of the assimilation of the latter by the intruding magmas. The charnockites are of two textural varieties: coarse-grained to porphyritic and fine- to medium-grained, with the former being more abundant and containing xenoliths of the latter, hence, is probably younger than the latter (Fig. 4e). Both varieties of charnockite are dark-grey to dark-green in colour. Granites in the area are light coloured (light grey to pinkish) and of two varieties: coarse-grained to porphyritic (Fig. 4d) and medium- to coarse-grained (Fig. 4g). The granites occur prominently in the central and northern part of the area forming ridges. The granites and charnockites are coeval as they show evidence of magma mingling forming a hybrid rock (charnockite-granite hybrid) at their contacts. The charnockite–granite association of Okpella, although not yet dated, may be correlated to the charnockite–granite associations of Ado-Ekiti–Ikerre–Akure and Idanre in southwestern Nigeria which have yielded Pan-African (Neoproterozoic) emplacement ages of 631 ± 18 Ma and 586 ± 5 Ma, respectively (Tubosun et al. 1984).

The gneisses and metasedimentary rocks around Okpella are complexly and strongly deformed and show geological structures such as foliations, folds, faults, joints, shears, boudinages and lineations in outcrops (Fig. 4). Detailed field study and structural analysis revealed the presence of two major folds in the central and northeastern part of the area.

Petrography

Modal compositions and photomicrographs of the analysed rock samples are shown in Table 1 and Fig. 5, respectively.

Fig. 3 Geological map and schematic cross sections (**a**-**c**) of Okpella area, eastern Igarra Schist Belt, southwestern Nigeria (Ogunyele et al. 2018)



The modal analysis (Table 1) revealed that the granites have high quartz contents varying between 40 and 45 vol.%, and contain more K-feldspar (21–22 vol.%) than plagioclase feldspar (10–15 vol.%). Biotite in the granites range between 10 and 15 vol.%; hornblende and muscovite occur in small amounts in these rocks. The charnockites are characterized by relatively anhydrous mineral assemblages as indicated by the presence of orthopyroxene (7–8 vol.%) in them, with quartz contents ranging between 25 and 33 vol.%. They contain more plagioclase (18–25 vol.%) than K-feldspar (av. 6 vol.%). Biotite, hornblende, garnet and opaques also occur as essential minerals in the charnockites. Classification of the granitoids using the combined QAP discrimination diagrams of Streckeisen (1974, 1976) and Rajesh and Santosh (2012) (Fig. 6) revealed that the granites are granites sensu stricto while the charnockites are charnoenderbites (or opdalites).

The garnet-biotite schist and calc-silicate gneiss have high quartz (35–45 vol.%), biotite (15–30 vol.%) and plagioclase (10–15 vol.%) contents and subordinate amounts of K-feldspar (2–10 vol.%). The garnet-biotite schist and calc-silicate gneiss also contain garnets porphyroblasts (13–25 vol.%) and calcite (10–15 vol.%), respectively. From hand specimen, the quartzite is composed largely of quartz with minor amounts of muscovite, chlorite and feldspars. The mineral assemblages of the garnet-biotite schist, calc-silicate gneiss and quartzite are indicative of low-medium grade metamorphism in the area probably from greenschist to lower amphibolite facies. The strong

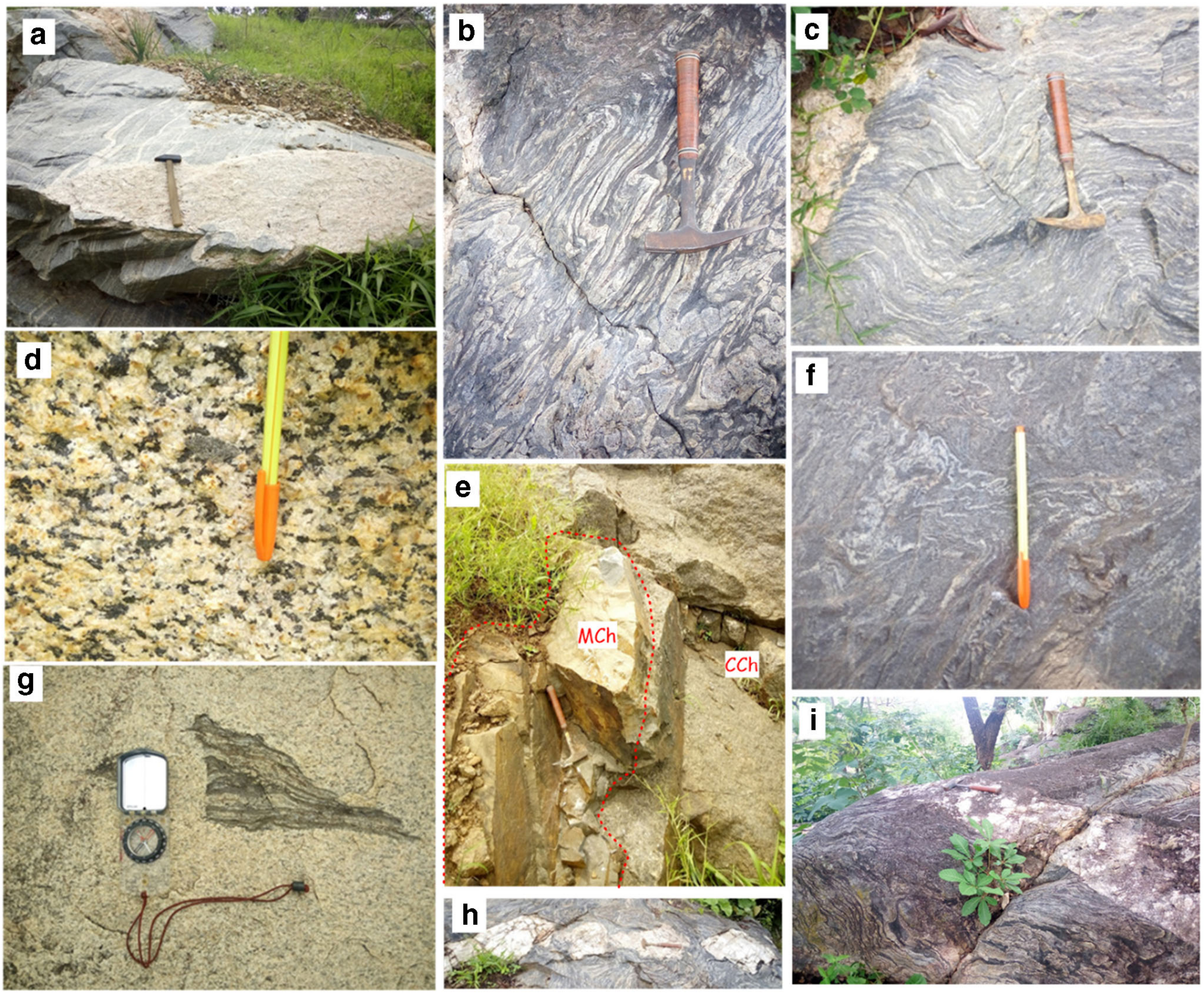


Fig. 4 Field photographs (mesoscopic aspects) of some lithologies around Okpella, southwestern Nigeria. **a** Coarse-grained (granoblastic) granitic gneiss intruded by pegmatites. **b** Garnet-biotite schist showing strong foliation and tight folds. **c** Calc-silicate gneiss with open folds and intruded by pegmatites. **d** Coarse-grained to porphyritic granite with phenocrysts of K-feldspar and quartz. **e** Coarse-grained charnockite containing xenoliths of fine- to medium-grained charnockite. **f** Ptygmatic folds in garnet-biotite schist. **g** Medium- to coarse-grained granite containing xenoliths of calc-silicate gneiss. **h** NS trending boudinage structure in calc-silicate gneiss, the boudins are composed of quartz. **i** Joint cutting a pegmatite sill and garnet-biotite schist

deformation of the schist and calc-silicate gneiss in this area in comparison to other parts of the Igarra Schist Belt corroborated that the grade of metamorphism of Okpella metasedimentary rocks is locally higher.

The microstructures identified in the rocks around Okpella include foliations, microfolds, microfractures, twinning, myrmekite and reaction rims (Fig. 5a–l). The formation of rim- and wart-like myrmekite around plagioclase feldspar in the coarse-grained charnockite (Fig. 5d, e) is suggestive of K-metasomatism and/or progressive sub-magmatic deformation in the rock. Folded foliations, microfault and microcracks in the studied rocks indicate deeply penetrative deformation in the area; these further confirm the structures and textures observed in the field (Fig. 4).

Whole-rock geochemistry

Charnockite–granite association

Major and trace elements geochemical data of the charnockite–granite association of Okpella are presented in Table 2. Published limited geochemical data on the Idoani (Adegbuyi et al. 2017) and Igarra (Okeke et al. 1988) granites in the western and central parts of the Igarra Schist Belt, respectively, are also presented in Table 2 for comparison and detailed interpretations on the schist belt. The occurrence of charnockites has not been reported elsewhere in the Igarra Schist Belt; hence, no geochemical data is available.

Table 1 Modal compositions (in vol.%) of the studied charnockite–granite association and metasedimentary rocks

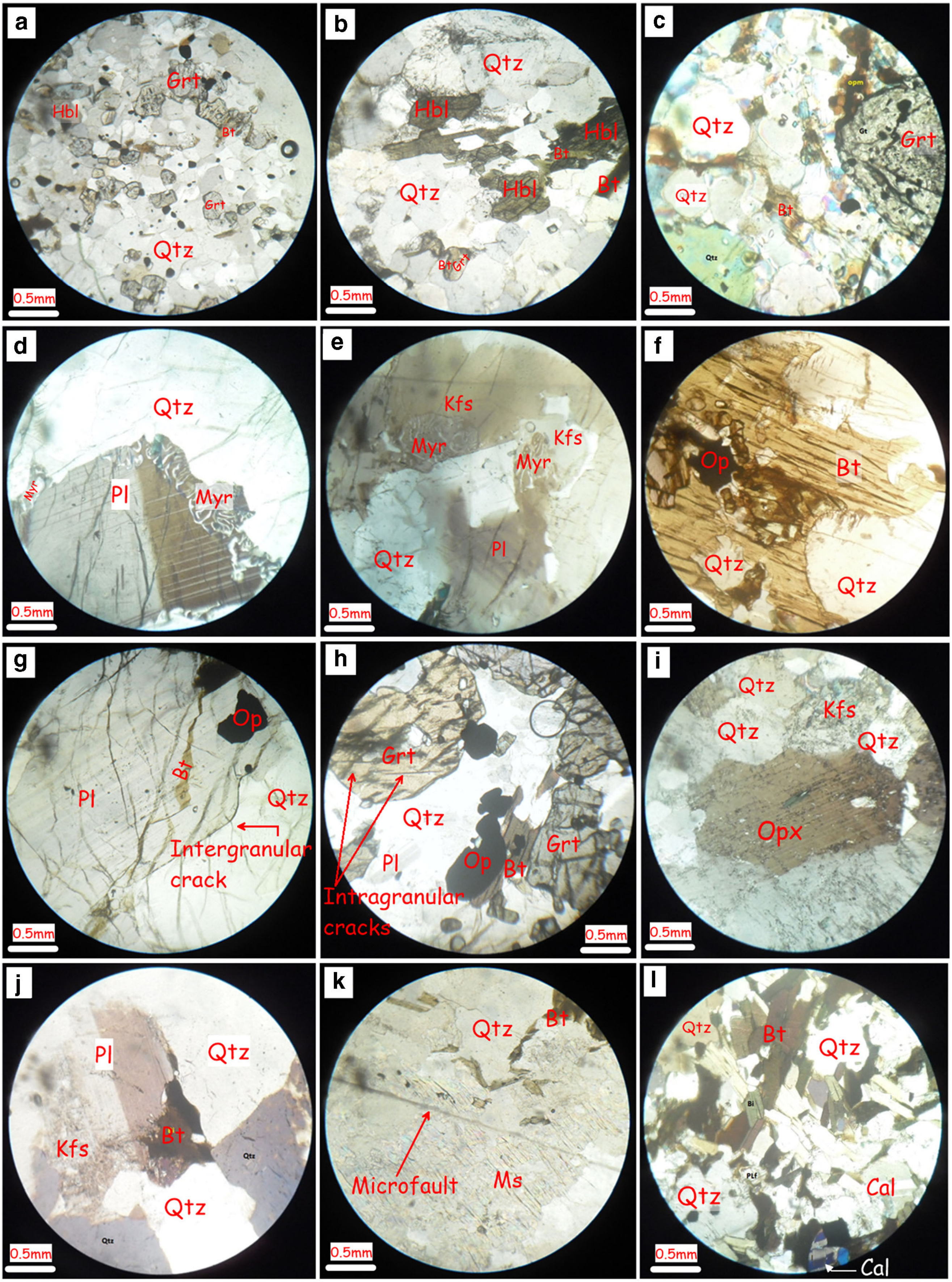
Rock	Granite		Charnockite		Garnet-biotite schist		Calc-silicate gneiss	
Sample	MCG1	PG1	CCh1	MCh3	GBS1	GBS2	CGN5	CGN4
Quartz	40	45	25	33	35	40	40	45
K-feldspar	21	22	6	6	5	10	4	2
Plag. feldspar	10	15	25	18	12	10	10	15
Biotite	10	15	28	10	15	18	30	29
Calcite							15	10
Muscovite	8							
Hornblende	2	3	5	4		8		
Garnet				12	25	13		
Orthopyroxene			8	7				
Opaque			3	9	7		5	
Total	99	100	100	99	99	99	99	99

The granites of Okpella show whole-rock high SiO_2 (70.53–76.6 wt%) and $Na_2O + K_2O$ (4.51–7.93 wt%), and low MgO (< 1.07 wt% in most samples) and Fe_2O_3t (< 3.69 wt%) contents, typical of granites sensu stricto and similar to the post-collisional granites of western Nigeria (Goodenough et al. 2014). The charnockites also have high SiO_2 (63.4–72.42 wt%) and $Na_2O + K_2O$ (4.64–7.47 wt%) contents similar to the Cardamom Hill silicic igneous charnockites, southern India (Chacko et al. 1992; Rajesh 2004, 2007). Two samples of the charnockites (MCh2 and CCh2), however, show extremely low total alkalis coupled with relatively high LOI, indicating a strong alteration and are therefore excluded from further consideration. In comparison to the granites, the charnockites have relatively higher Fe_2O_3t (4.22–6.68 wt%), MgO (0.94–4.34 wt%) and TiO_2 (0.4–0.86 wt%). The contents of Al_2O_3 (11.9–14.02 wt%) and MnO (<0.13 wt % in most samples) in both the charnockites and granites are similar. The K_2O/Na_2O ratio of the charnockites (0.66–1.72) is, however, slightly lower than that of the granites (1.03–1.97).

In comparison with the granites from Idoani and Igarra, the Okpella granites have higher average SiO_2, Fe_2O_3 and MnO, and lower average Al_2O_3, MgO, CaO and $Na_2O + K_2O$. The Harker diagrams of the granites and charnockites of Okpella and the granites of Idoani and Igarra (Fig. 7) show a more or less coherent negative trend between SiO_2 and TiO_2, Al_2O_3, MgO and Fe_2O_3t. All other major oxides (Na_2O, K_2O, MnO, CaO and P_2O_5), however, show erratic variations with SiO_2.

The total alkalis-silica diagram (Fig. 8a) for the granitoids of Okpella showed that the granites plot as granites; the charnockites as granodiorites and both granitoids are subalkalic. The granites and charnockites are mainly high-K calc-alkaline granitoids (Fig. 8b). All the rock samples plot in the calc-alkalic to alkali-calcic fields on the $K_2O + Na_2O$-CaO versus SiO_2 plot of Frost et al. (2001) (Fig. 8c); metaluminous to peraluminous fields on the Shand's index plot, with most samples plotting within the fields for the post-collisional granites of western Nigeria (Goodenough et al. 2014) (Fig. 8d) and ferroan field on the FeOt/(FeOt + MgO) diagram, with all the samples plotting entirely within the Caledonian post-collisional granite field of Frost et al. (2001) (Fig. 8e). The granites are I- to S-type granitoids while the charnockites are typical I-type granitoids (Fig. 8d). The granites and charnockites have variable but very low contents of Cr, Ni, Co and V pointing to their felsic compositions; similar, high Ba, Sr and moderate to fairly high Rb contents and depleted contents of Nb and Ta. The K/Rb ratios of the granites (127–370) and charnockites (129–342) are within the values for the continental crust (≤462) (Rudnick and Gao 2003), suggesting that they are of crustal sources. Anomalously high K/Rb ratio in one of the samples (MCG1) probably indicates a source more enriched in K and/or hydrothermal alteration. The Rb versus Nb + Y diagram (Pearce et al. 1984) was used to determine the tectonic

Fig. 5 Representative photomicrographs of the studied rocks, mineral ▶ abbreviations used are according to Kretz (1983): **a** garnet-biotite schist composed of mafic bands (garnet + biotite + hornblende + opaques) and felsic bands (quartz + feldspar); **b** detailed view of the association quartz + garnet + biotite + hornblende, oriented along the foliation in garnet-biotite schist; **c** inclusion-rich garnet + biotite + quartz + opaques in medium-grained charnockite; **d**, **e** myrmekite formation in coarse-grained charnockite; **f** fractures in biotite filled by quartz and opaques in coarse-grained charnockite; **g** biotite filling fractures in plagioclase in coarse-grained charnockite, intergranular cracks are abundant; **h** intragranular cracks in garnet in the coarse-grained charnockite in contact with schist; **i** orthopyroxene crystal in coarse-grained charnockite; **j** phenocrysts of plagioclase, quartz and K-feldspar in porphyritic granite, twinning in plagioclase feldspar and saccharoidal pattern in quartz; **k** microfault in muscovite, biotite rim around quartz in medium- to coarse-grained granite; **l** calc-silicate gneiss composed largely of quartz + biotite + calcite + plagioclase feldspar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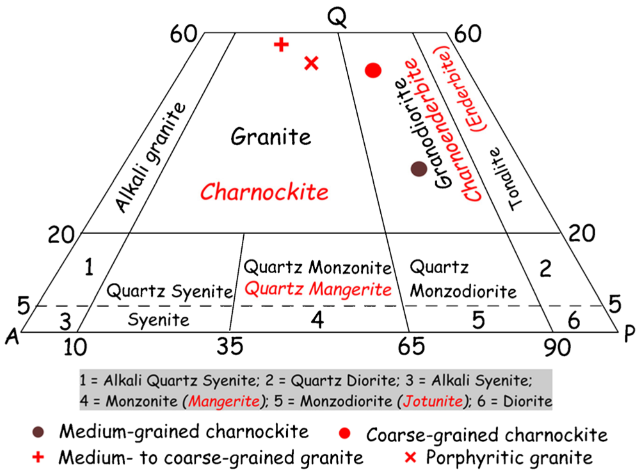


Fig. 6 Classification of the charnockites and granites of the Okpella area using a combined Quartz–Alkali feldspar–Plagioclase (QAP) diagram (the terms in red are used for the classification of charnockitic rocks) (after Streckeisen 1974, 1976; Rajesh and Santosh 2012)

settings of the granitoids (Fig. 8f). The samples plotted mainly in the volcanic-arc field closely overlapping with the field for post-collisional granites.

Metasedimentary rocks

Whole-rock major and trace elements compositions of representative samples of the garnet-biotite schist, calc-silicate gneiss and quartzite of Okpella area are reported in Table 3. The compositions of some metasedimentary rocks in other parts of the Igarra Schist Belt (Okeke and Meju 1985; Ikoro et al. 2012; Adegbuyi et al. 2017) as well as some Precambrian sediments such as PAAS (post-Archean Australian shale; McLennan 1989), PG (Proterozoic greywackes; Condie 1993) and UCC (upper continental crust; Rudnick and Gao 2003) are also presented in Table 3 for comparison with the studied metasedimentary rocks.

The garnet-biotite schist of Okpella have SiO_2 (65.23–71.58 wt%; av. 68.15 wt%), Al_2O_3 (14.02–15 wt%; av. 14.55 wt%), Fe_2O_3 (3.69–6.77 wt%; av. 5.84 wt%), MgO (0.61–4.42 wt%; av. 2.05 wt%) and MnO (0.07–0.22 wt%; av. 0.12 wt%) contents similar to that of PG. However, K_2O (2.77–3.71 wt%; av. 3.14 wt%) and TiO_2 (0.86–1.47 wt%; av. 1.26 wt%) contents are slightly enriched whereas Na_2O (1.74–2.4 wt%; av. 2.22 wt%) and P_2O_5 (0.01–0.03 wt%; av. 0.02 wt%) contents are depleted compared to PG. The average major elements compositions of samples of the schist are very similar to that of PG than to the PAAS, suggesting that the garnet-biotite schist shows more affinity for greywacke than shale. SiO_2/Al_2O_3 and K_2O/Na_2O ratios in the garnet-biotite schist range from 4.46 to 5.12 and 1.23 to 1.59 with averages of 4.7 and 1.43, respectively.

The Okpella calc-silicate gneiss shows wide ranges for almost all major oxides including: SiO_2 (47.2–70.94 wt%), CaO (2.96–11.3 wt%), Fe_2O_3 (4.27–12.2 wt%), Al_2O_3 (13.58–18.1 wt%) and MgO (1.7–4.9 wt%). The contents of Na_2O (1.4–2.83 wt%) and K_2O (1.2–2 wt%) are, however, similar. The calc-silicate gneiss is characterized by SiO_2/Al_2O_3 and K_2O/Na_2O ratios ranging from 2.59 to 5.22 and 0.55 to 1.43 with averages of 3.72 and 0.91, respectively. The composition of the calc-silicate gneiss suggests a shaly/greywacke protolith rich in carbonates. The Okpella quartzite is composed almost entirely of SiO_2 (87.5 wt%) with subordinate amounts of other major oxides.

In terms of major element geochemistry, the garnet-biotite schist of Okpella is very similar to the quartz-mica schists of Idoani and Igarra in the western and central Igarra Schist Belt (Okeke and Meju 1985; Adegbuyi et al. 2017). The calc-silicate gneiss of Okpella, however, have higher SiO_2, TiO_2, Al_2O_3 and Fe_2O_3, and lower CaO and K_2O contents compared to the calc-silicate gneiss from Igarra (Ikoro et al. 2012). MgO and LOI in the calc-silicate gneisses are, however, similar. The quartzite of Okpella is more silica-rich than those from Idoani and Igarra. The Idoani and Igarra quartzites, however, have higher Al_2O_3, Fe_2O_3, MgO and K_2O contents than the Okpella quartzite (Okeke and Meju 1985; Adegbuyi et al. 2017). The SiO_2/Al_2O_3 ratios in the schists and calc-silicate gneisses of the Igarra Schist Belt are very similar, suggesting similar provenance.

All the metasedimentary rocks of Okpella show moderate to high contents of Ba (270–980 ppm), Rb (60–210 ppm), Sr (38–356 ppm) and Zr (64–330 ppm) comparable to the UCC. However, V, Ni, Cr and Sc are depleted while Ta, Ti, Y and Th are enriched relative to the UCC. The average K/Rb ratios of the garnet-biotite schist (181.18), calc-silicate gneiss (143.97) and quartzite (51.37) are less than that for UCC (283), suggesting that these rocks were derived from the upper continental crust.

Discussion

Charnockite–granite association—petrogenetic constraints and tectonic evolution

The charnockites and granites of Okpella area show primary magmatic paragenesis and geochemical features. The charnockites are pyroxene-bearing, metaluminous to slightly peraluminous, ferroan, calc-alkalic to alkali-calcic granodiorites (I-type) with high silica and total alkalis contents, similar to the Cardamom Hill silicic igneous charnockites of southern India (Chacko et al. 1992; Rajesh 2004, 2007; Santosh and Rajesh 2007). The presence of orthopyroxene in the mineral assemblages of the charnockites points toward high-temperature and relatively dry condition of the original magma, similar as interpreted in the charnockites of Ado-Ekiti–Ikerre–Akure, southwestern Nigeria (Olarewaju 1987;

Table 2 Major (wt%) and trace (ppm) elements of the studied charnockite–granite association and granites from other sectors of the Igarra Schist Belt$^{(a)}$

Rock	Granite (porphyritic and medium- to coarse-grained)						Charnockite (coarse- and medium-grained)						Granites$^{(a)}$	
Sample	PG1	MCG1	PG3	MCG3	MCG2	PG2	MCh2	CCh2	MCh3	MCh1	CCh3	CCh1	A(3)	B(8)
(wt%)														
SiO_2	70.53	71.58	72.58	73.57	74	76.6	63.4	65.1	66.25	70.3	70.7	72.42	65.35	66
TiO_2	0.43	0.86	0.38	0.34	0.32	0.17	0.8	0.4	0.7	0.62	0.86	0.6	0.31	
Al_2O_3	13.08	14.02	13.22	13.01	13.24	12.33	16.2	15.31	13.28	13.6	13.92	11.9	16.05	18
Fe_2O_3*	3.44	3.69	2.43	5.10	3.5	2.47	7.7	6.68	5.94	6.68	5.45	4.22	1.72	0.82
MnO	0.05	0.11	0.08	0.06	0.25	0.05	0.21	0.22	0.23	0.11	0.13	0.04	0.07	0.06
MgO	3.9	2.51	1.07	0.64	0.51	0.31	1	0.99	4.34	1.03	0.94	2.01	2.19	2
CaO	0.82	1.77	1.76	1.71	1.64	1.06	5.62	5.5	1.46	3.01	3	2.03	1.89	1.92
Na_2O	3.9	1.74	3.65	2.19	2.3	2.04	0.8	0.78	4.5	1.64	1.8	3.97	3.56	3.66
K_2O	4.03	2.77	3.94	3.1	3.97	4.02	1.09	1	2.97	3	3.09	2.9	4.94	6.2
P_2O_5	0.03	0.01	0.02	0.02		0.05			0.02	0.01	0.02	0.03	0.11	
LOI	0.44	0.42	0.84	0.73	0.71	0.62	2.6	2.84	0.58	0.88	0.96	0.58		
Total	100.65	99.49	99.97	100.47	100.44	99.72	99.42	98.82	100.27	100.88	100.87	100.7		
(ppm)														
Ba	910	1100	810	510	520	470	580	210	1000	480	300	810		
Co	7	5	7	5	5	24	7	9	4	4	2	9		
Cr	5	9	3	0.32	0.27	0.01	2	1	6.1	0.31	0.43	8		
Cu	53	53	37	28	26	59	10	6	34	20	33	37		
Nb	10	16	8	3	4	12	5	2	19	2	2	11		
Ni	1	8	3	4	9	112	16	10	13	9	6	2		
Rb	190	73	120	96	89	262	150	155	190	84	75	140		
Sc	2	3	1	1	1	1	3	3	2.6	1	1	2		
Sr	100	280	290	90	138	150	134	12	180	100	120	241		
Ta	5	4	5	3	3	5	2	1	10	2	5	6		
Th	3	16	16	14	31	53	12	11	32	16	26	4		
V	8	3	5	1	13.7	13	12	12	4.9	2	3	10		
Y	20	29	40	34	13	42	20	14	59	38	37	12		
Zn	23	23	44	22	26	60	38	44	79	42	18	44		
Zr	290	380	122	120	119	130	130	116	270	118	120	270		
mg#	25.2	23.7	46.6	19.93	22.42	19.93	20.48	22.71	58.17	23.42	35.49	48.57	69.42	72.87
K_2O/Na_2O	1.03	1.59	1.07	1.41	1.73	1.97	1.36	1.28	0.66	1.83	1.72	0.73	1.38	1.69
K/Rb	176.02	535.44	272.48	267.98	370.18	127.33	60.3	53.54	129.72	296.38	341.91	171.9		
Rb/Sr	1.9	0.26	0.41	1.07	0.64	1.75	1.12	12.92	1.05	0.84	0.63	0.58		
K/Ba	36.75	35.53	40.37	50.44	63.36	70.98	15.59	39.52	24.65	51.87	85.48	29.71		
Ba/Rb	4.79	15.07	6.75	5.32	5.85	1.79	3.87	1.35	5.26	5.71	4	5.79		
Ba/Sr	9.1	3.93	2.79	5.67	3.77	3.13	4.33	17.5	5.55	4.8	2.5	3.36		

A Porphyritic granite from Idoani, western Igarra Schist Belt (Adegbuyi et al. 2017), *B* Porphyritic granite from Igarra, central Igarra Schist Belt (Okeke et al. 1988)

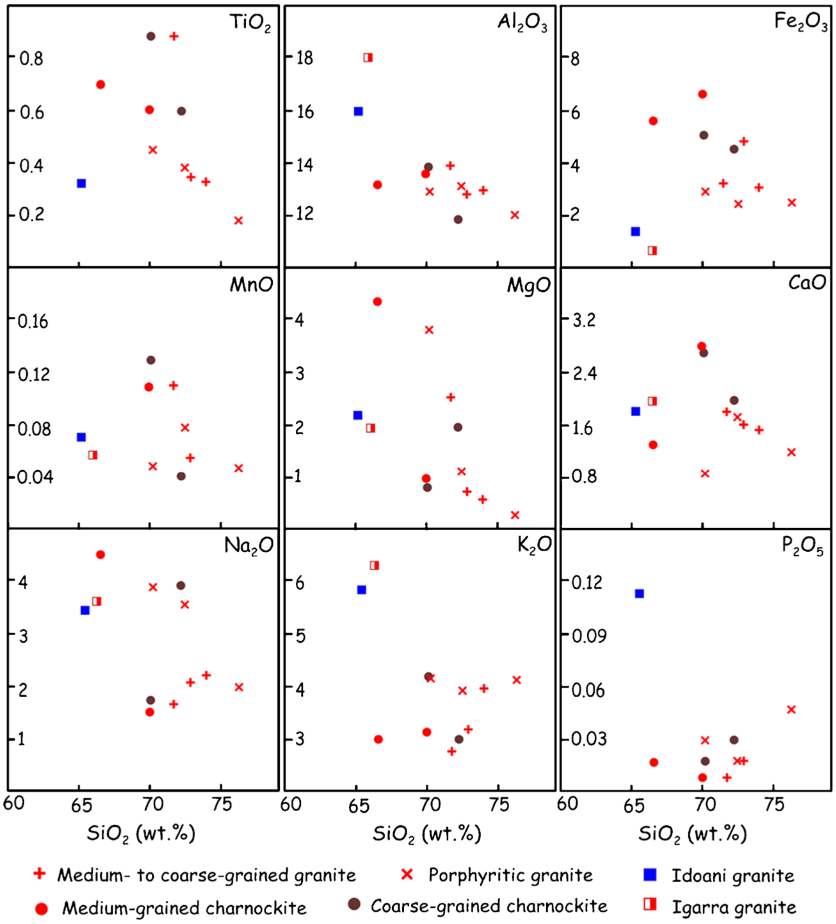
*Total Fe as Fe_2O_3

$^{(a)}$ Data from published literature

$^{(n)}$ Number of analysis

Ademeso 2010) and Venda Nova, SE Brazil (Mendes and De Campos 2012). The occurrence of primary biotite and primary hornblende in the charnockites may, however, be explained by the crystallization of the magma at the late magmatic stage during which H_2O activity is likely to slightly increase as suggested by Martignole (1979), Harlov et al. (2012) and Mendes and De Campos (2012). Availability of sufficient K_2O and MgO (~0.2 wt%) in anhydrous magmas are other important factors that can cause the crystallization of hydrous minerals, especially micas (Hewitt and Wones 1984). Garnets

Fig. 7 Harker plots of some major elements against SiO_2 for Okpella granitoids and the Idoani and Igarra granites



in the fine- to medium-grained charnockites are xenocrysts probably derived from their host rock (garnet-biotite schist) especially at contacts. As suggested by Frost and Frost (1987) and Rajesh (2004), CO_2-rich melt is likely to be enriched in K, Ba and Zr, which is characteristic of igneous charnockites like the Okpella charnockites.

The chemical compositions of the charnockites seem to be broadly compatible with an amphibolitic (basaltic) source when plotted on the CaO/(FeOt + MgO + TiO_2) versus CaO + FeOt + MgO + TiO_2 diagram of Patiño Douce (1999) which shows the compositions of melts produced by experimental dehydration-melting of various lithologies such as amphibolites, greywackes, felsic pelites and mafic pelites (Fig. 9a). On the plot of mg# versus SiO_2 (Fig. 9b), the charnockites plotted mainly within the field of mantle melts interacted with crust. Hence, based on mineralogy, geochemical features and close similarity to the Cardamom Hill silicic igneous charnockites of southern India, the charnockites of the Okpella area are inferred to be formed from high temperature melts of mafic/basaltic source. Following the petrogenetic model of Rajesh (2007) for the Cardamom Hill silicic igneous charnockites and the experimental work of Sisson et al. (2005), we hypothesize that the evolution of the charnockites of the Okpella area involved an initial partial melting of "recently crystallized" mafic lower crustal rocks derived from juvenile basaltic magmas that upwelled from the asthenospheric mantle and underplated the lower continental crust, followed by fractionation to produce silicic charnockitic melts. The fractionation was most probably an open system assimilation-fractional crystallization, and could possibly have increased the water activity of the charnockitic melt. The K/Rb ratios of samples of the charnockites which are similar to that of the continental crust and their plot around tonalitic and trondhjemitic melts on the K_2O versus SiO_2 diagram (Fig. 8b) probably suggest that lower-mid crustal tonalites and trondhjemites (or their metamorphic equivalents) were assimilated by the initial melt. The presence of garnets in the assemblage of the charnockites and their metaluminous to slightly peraluminous nature are other features that suggest the influence of assimilation in the evolution of the charnockitic melt. The plot of the charnockites within the field of mantle melts interacted with crust (Fig. 9b) could alternatively be interpreted as indicating generation of the high temperature charnockitic melt by partial melting of "older" lower crustal mafic rocks which interacted with or had inputs from juvenile mantle magmas, probably during subsequent episodes of underplating. The underplated basaltic magmas as well as the charnockitic melt may have contributed to the heating and melting of the lower to middle crustal rocks,

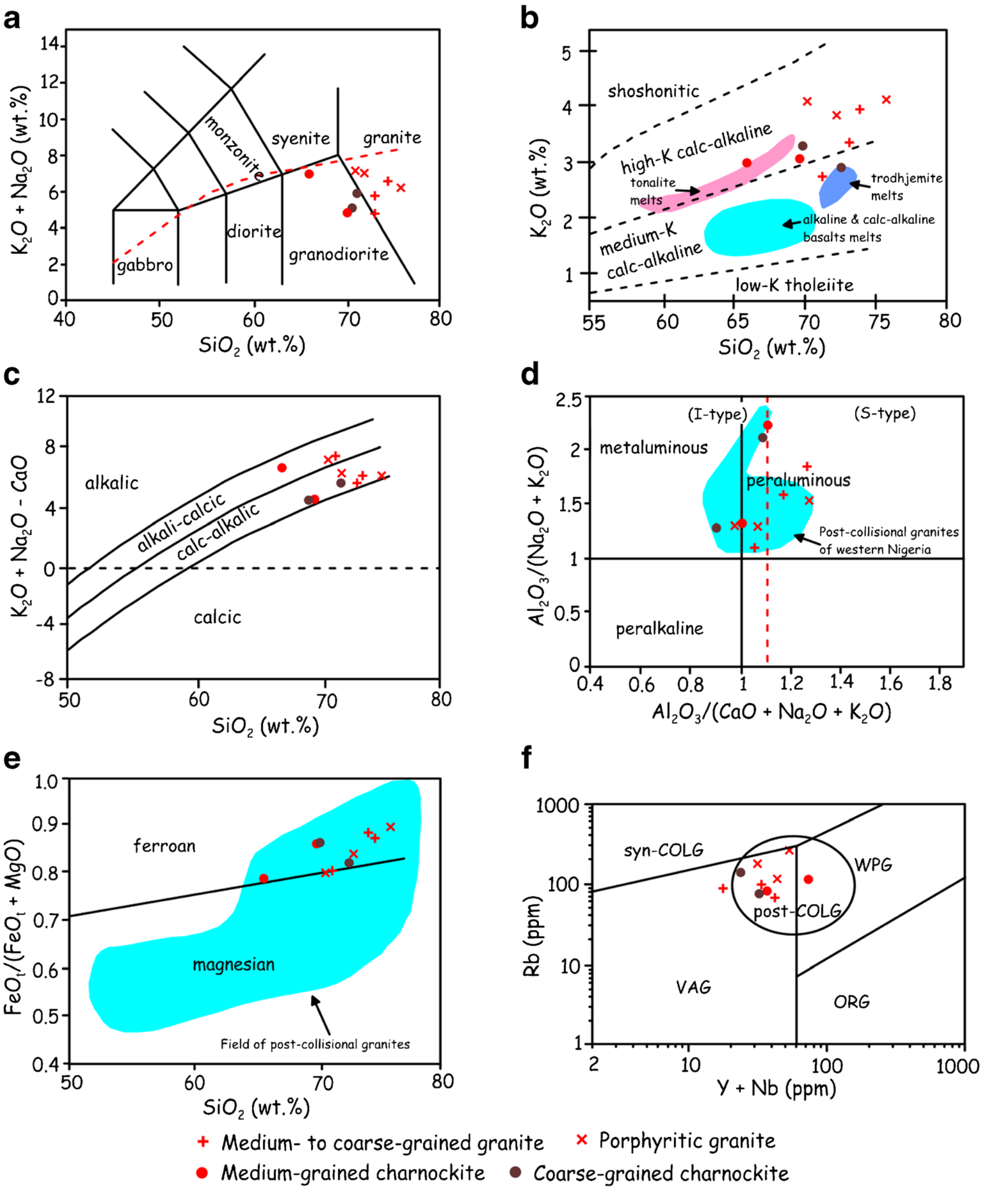


Fig. 8 Petrochemical diagrams for discriminating Okpella charnockites and granites. **a** Total alkalis versus silica (after Gillespie and Styles 1999), red dashed line represents boundary between alkalic rocks above and sub-alkalic rocks below. **b** K$_2$O versus SiO$_2$ plot (after Le Maitre 2002) with fields of compositions of tonalitic, trondhjemitic and basaltic melts from Roberts and Clemens (1993); (**c**) K$_2$O + Na$_2$O-CaO versus SiO$_2$ plot (after Frost et al. 2001). **d** Shand's Al$_2$O$_3$/(Na$_2$O + K$_2$O) versus Al$_2$O$_3$/(CaO + Na$_2$O + K$_2$O) molecular plot (after Maniar and Piccoli 1989), with field for post-collisional granites of western Nigeria (Goodenough et al. 2014) given for comparison. **e** FeO$_{total}$/(FeO$_{total}$ + MgO) versus SiO$_2$, with field for post-collisional granites from Frost et al. (2001). **f** Rb versus Nb + Y tectonic discrimination diagram (after Pearce et al. 1984)

resulting in the generation of high-K calc-alkaline magma that formed the granites.

The partial melting of metaigneous rocks of intermediate compositions (e.g. tonalitic rocks) is a viable model for the genesis of high-K calc-alkaline granites (Roberts and Clemens 1993; Patiño Douce 1999, 2005; Watkins et al. 2007; Laurent et al. 2014; Costa et al. 2018; Peng et al. 2019; Yakymchuk 2019) like the Okpella granites. The metaluminous to peraluminous nature of the granites as well as the presence of muscovite in them suggests that they are I- to S-type granitoids derived from the partial melting of crustal igneous and sedimentary sources (Chappell and White 2001; Frost et al. 2001). This is also inferred from their plots mainly within the field of re-melting of crust on the mg# versus SiO$_2$ diagram (Fig. 9b). The crustal rocks present in the Okpella area aside the granites include granite gneiss, metasedimentary rocks and charnockites. It appears that the granites were probably not derived from partial melting of the charnockites as evidenced by the similarity of their geochemical features such as identical K/Rb and K$_2$O/Na$_2$O ratios, erratic variations between SiO$_2$ and most of the major oxides, enrichment in LILEs and depletion in HFSEs.

The discrimination plot of Patiño Douce (1999) (Fig. 9a) showed that the granites of the Okpella area plotted within and around the greywackes field. On the K$_2$O versus SiO$_2$ diagram (Fig. 8b), the granites plotted close to tonalitic and trondhjemitic melts. These discrimination plots, therefore, suggest that Okpella granites were mainly derived from partial melting of lower- to mid-crustal tonalites-trondhjemites-granodiorites (TTGs) and/or metagreywackes. Patiño Douce (2005) confirmed that high-K granitic melts can be generated by dehydration-melting of tonalites in deep thickened

Table 3 Major (wt%) and trace (ppm) elements of the studied metasedimentary rocks, and metasedimentary rocks from other sectors of the Igarra Schist Belt[(a)] and other Precambrian sediments from international references[(b)]

Rock	Garnet-biotite schist				Calc-silicate gneiss					Quartzite	Metasedimentary rocks[(a)]					Precambrian sediments[(b)]		
Sample	GBS1	GBS3	GBS4	GBS2	CGN1	CGN2	CGN3	CGN5	CGN4	Qtz	A(2)	B(2)	C(8)	D(8)	E(8)	F	G	H
(wt%) SiO$_2$	65.23	67.4	68.4	71.58	47.2	55.1	55.4	65.58	70.94	87.5	68.89	75.41	73	69.7	49.69	62.8	66.1	66.6
TiO$_2$	1.47	1.3	1.42	0.86	1.58	1.3	1.3	0.9	1	1.22	0.23	0.4			0.78	1	0.77	0.64
Al$_2$O$_3$	14.64	15	14.52	14.02	16.1	18.04	18.1	13.97	13.58	4.06	13.1	9.77	15	14.84	14.38	18.9	15	15.4
Fe$_2$O$_3$*	6.77	6.23	6.68	3.69	12.2	9.1	9.42	6.82	4.27	1.46	7.65	4.99	3.23	7.51	5.49	6.5	5.8	5.04
MnO	0.22	0.09	0.07	0.11	0.17	0.34	0.26	0.17	0.16	0.07	0.03	0.12	0.09	0.09	0.08	0.11		0.1
MgO	4.42	0.65	0.61	2.51	3	2	1.7	4.9	2.54	0.58	0.67	1.3	1.33	0.69	2.84	2.2	2.1	2.48
CaO	1.78	2.34	2.12	1.77	11.3	6.1	5.61	3.04	2.96	1.1	1.01	1.54	1	1	19.8	1.3	2.6	3.59
Na$_2$O	2.35	2.37	2.4	1.74	1.6	1.4	1.8	2.83	2.07	2	1.19	1.99	1.67	1.18	1.23	1.2	2.8	3.27
K$_2$O	3.13	3.71	2.94	2.77	1.2	2	1.9	1.56	1.56	1.3	2.26	3.51	3.9	3.8	3.05	3.7	2.5	2.8
P$_2$O$_5$	0.03	0.01	0.01	0.02	0.12	0.03	0.03	0.01	0.02	0.02					0.1	0.16	0.14	0.15
LOI	0.56	0.9	0.78	0.42	5.56	3.87	3.34	0.73	0.43	0.94					2.19			
Total	100.6	100	99.95	99.49	100.03	99.28	98.86	100.51	99.53	100.25								
(ppm)																		
Ba	840	740	370	370	290	740	680	980	270	860						650	600	628
Co	7	9	4	6	6	4.8	4	5	11	11								
Cr	6.3	1	0.51	3	3	2	1	7.6	3.4	2						110	80	92
Cu	48	34	32	70	61	42	40	83	60	7								28
Nb	18	5	4	5		2	4	12	9	3						19	10	12
Ni	7	12	16	4	8	9	12	11	3	14						55	45	47
Rb	160	158	120	140	160	138	149	60	60	210						160	80	82
Sc	16	14	3	4	3	2	3	2.2	2	7						16	17	14
Sr	150	40	38	290	260	162	114	356	320	47						200	240	320
Ta	3	1	15	5	2	2	2	7	9	1						1.28	0.8	0.9
Th	29	22	26	8	20	16	10	20	7	28						14.6	9	10.5
V	5.9	3	1	2	14	15.2	14	6	20	2						150	140	97
Y	48	16	20	40	18	38	18	60	30	12						27	27	21
Zn	71	10	8	44	30	42	40	19	46	12								28
Zr	230	220	64	190	116	118	120	330	280	82						210	148	193
SiO$_2$/Al$_2$O$_3$	4.46	4.49	4.71	5.12	2.59	3.05	3.06	4.69	5.22	21.55	5.26	7.72	4.87	4.7	3.46	3.32	4.41	4.32
K$_2$O/Na$_2$O	1.33	1.56	1.23	1.59	0.75	1.43	1.06	0.55	0.75	0.65	1.9	1.76	2.33	3.22	2.48	3.08	0.89	0.86
K/Rb	162.34	194.86	203.32	164.19	62.24	120.27	105.82	215.77	215.77	51.37						191.91	259.43	283.37
Th/Sc	1.81	1.57	8.67	2	6.66	8	3.33	9.09	3.5	4						0.91	0.53	0.75
Zr/Sc	14.37	15.71	21.33	47.5	38.67	59	40	150	140	11.71						13.1	8.71	13.8

A Quartz-mica schist from Idoani, western Igarra Schist Belt (Adegbuyi et al. 2017), *B* Quartzite from Idoani, western Igarra Schist Belt (Adegbuyi et al. 2017), *C* Quartzite from Igarra, central Igarra Schist Belt (Okeke and Meju 1985), *D* Mica schist from Igarra, central Igarra Schist Belt (Okeke and Meju 1985), *E* Calc-silicate gneiss from Igarra, central Igarra Schist Belt (Ikoro et al. 2012), *F* Post-Archean Australian Shale (McLennan 1989), *G* Proterozoic Greywackes (Condie 1993), *H* Upper Continental Crust (Rudnick and Gao 2003)

*Total Fe as Fe$_2$O$_3$

[(a)] Data from published literature

[(b)] Data from published literature

[(*n*)] Number of analysis

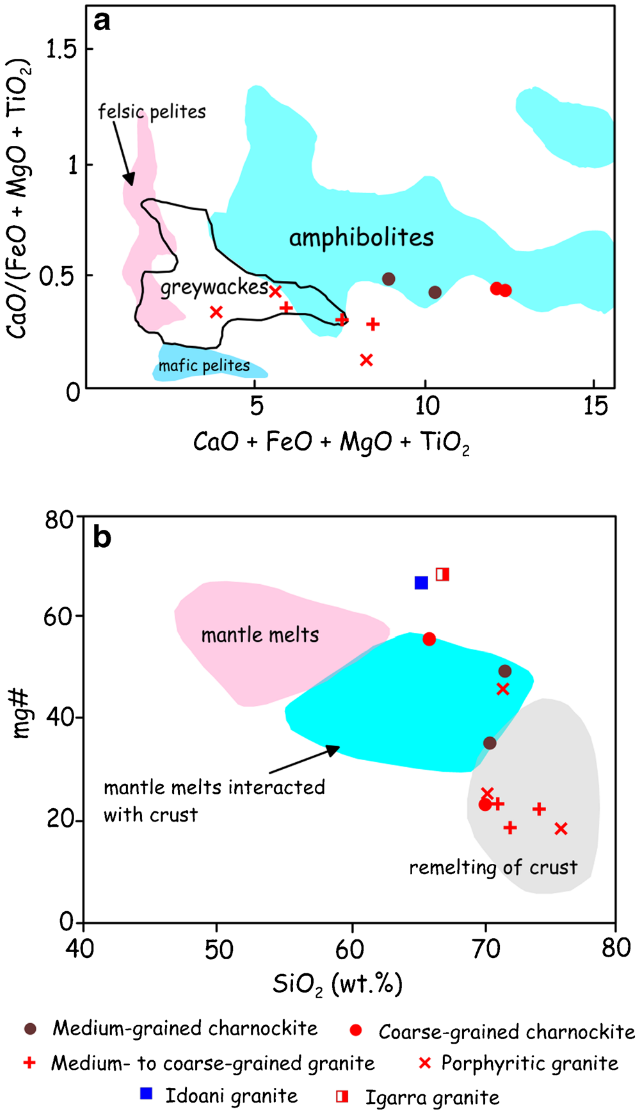


Fig. 9 **a** CaO/(FeOt + MgO + TiO$_2$) versus CaO + FeOt + MgO + TiO$_2$ discrimination plot of Patiño Douce (1999) for determining the source rock compositions of Okpella granitoids. The fields show the compositions of melts produced by experimental dehydration-melting of various lithologies. All values are in wt%. **b** mg# versus SiO$_2$ plot for Okpella granitoids and the Idoani and Igarra granites (after Peng et al. 2019)

continental crust at pressures of 1.5–3.2 GPa and temperatures above 900 °C. However, Castro (2004) and Watkins et al. (2007), from experimental melting of tonalites, argued that most TTGs are too sodic to produce the large volumes of potassic granites and hence, the former study suggested that the generation of voluminous high-K granitic magmas from lower crustal tonalites (Archean) requires the addition of H_2O- and K-rich fluids from a mantle-derived magma. The plot of a sample of the Okpella granites as well as the Idoani and Igarra granites within and around the field of mantle melts interacted with crust on the mg# versus SiO$_2$ diagram (Fig. 9b) probably suggests that the granitic magma generated from the TTGs and/or metagreywackes could possibly have mixed with some amounts of K-rich mafic (mantle-derived) magma, most likely the underplated parental basaltic magma of the charnockites and/or the generated charnockitic melt. H_2O-bearing and K-rich fluids could have been supplied to the granitic and possibly to the charnockitic magmatic systems by the melting of subducted metagreywackes as these rocks are important reservoirs of such fluids (Laurent et al. 2014). The metagreywacke protoliths of the granites were potentially the metasedimentary rocks in the area. On emplacement at the upper crust, the charnockites and granites probably interacted to form hybrid rock as observed in the field, suggesting that both rocks are coeval. These, therefore, establish important petrogenetic links between the charnockites and granites of Okpella, suggesting that they are co-genetic.

Comparing the chemical composition of Okpella granites with those from other sectors of the Igarra Schist Belt, the Idoani and Igarra granites have higher average mg# of 69.42 and 72.87, respectively (Table 2) (Adegbuyi et al. 2017; Okeke et al. 1988). These values are higher than the values for continental crustal rocks (≤60.1, Rudnick and Gao 2003) but less than that of the mantle (89.6 ± 1, Lyubetskaya and Korenaga 2007). As suggested by the plot of the Idoani and Igarra granites around the field of mantle melts interacted with crust on the diagram of Peng et al. (2019) (Fig. 9b), it is most likely that there was significant mantle contribution to the magma from which the granites of the Igarra Schist Belt were formed. With respect to SiO$_2$ contents and mg#, the Okpella granites probably represent more evolved end-members of the granites of the Igarra Schist Belt.

The undeformed nature of the granites and charnockites of Okpella suggests that they were most probably emplaced at the waning stage of the last orogeny that affected the Nigerian basement—the ca. 650–580 Ma Pan-African Orogeny. Roberts and Clemens (1993) have suggested that, in post-collisional settings, decompression and extension following crustal thickening initiates melting of source rocks, mantle upwelling and underplating of the lower continental crust by mafic magmas. Following the tectono-magmatic models of Dada (1998), Ferré et al. (2002), Bute et al. (2019) and Girei et al. (2019) for the late- to post-collisional stage of the Pan-African Orogeny, we hypothesize that during the post-collisional period, planar delamination of the continental lithospheric mantle allowed upwelling of basaltic magmas that underplated and crystallized in the lower continental crust and was subsequently partially melted to generate the charnockitic melt. The generated high-temperature charnockitic melt and/or the underplated basaltic magma probably supplied heat to the lower to mid-crustal TTGs and/or subducted metagraywackes which melted and mixed with a K-rich mafic (mantle-derived) magma to produce the high-K calc-alkaline I- to S-type granites. The K-rich mafic (mantle-derived) magma source of the granite was most likely the underplated parental basaltic magma from which the charnockites were generated and/or the charnockitic melt itself. Therefore, the generation of the charnockitic and granitic melts is associated with significant growth and reworking of the crust during post-collisional stages of the ca. 650–580 Ma Pan-African Orogeny, similar to the findings of Bute et al. (2019).

Provenance, weathering history and tectonic settings of the metasedimentary rocks

Field relationships and mineralogical compositions strongly suggest sedimentary origin for the garnet-biotite schist, calc-silicate gneiss, marble, quartzite and banded iron formation (BIF) lithologies around Okpella. They represent supracrustal rocks that were deposited and infolded on the granitic gneiss. The geochemical classification diagram of Herron (1988) (Fig. 10a) discriminated the protoliths of the garnet-biotite schist as mainly greywackes (and shales); the calc-silicate gneiss as Fe-shales and the quartzite as subarkose. This suggests that the garnet-biotite schist is a metagreywacke, the calc-silicate gneiss is a metamorphosed Fe-shale or marl and the quartzite is a metamorphosed subarkose. The K versus Rb diagram (Fig. 10b) suggests that the protoliths of the garnet-biotite schist, calc-silicate gneiss and quartzite were sourced essentially from intermediate to acid rocks, probably granodioritic to granitic rocks. The low concentrations of V, Cr and Ni in the samples (Table 3) also suggest a relatively felsic provenance and provide no support for significant amounts of mafic-ultramafic rocks in the source area (Garcia et al. 2014).

The Index of Compositional Variability (ICV), which measures the abundance of alumina relative to other major cations

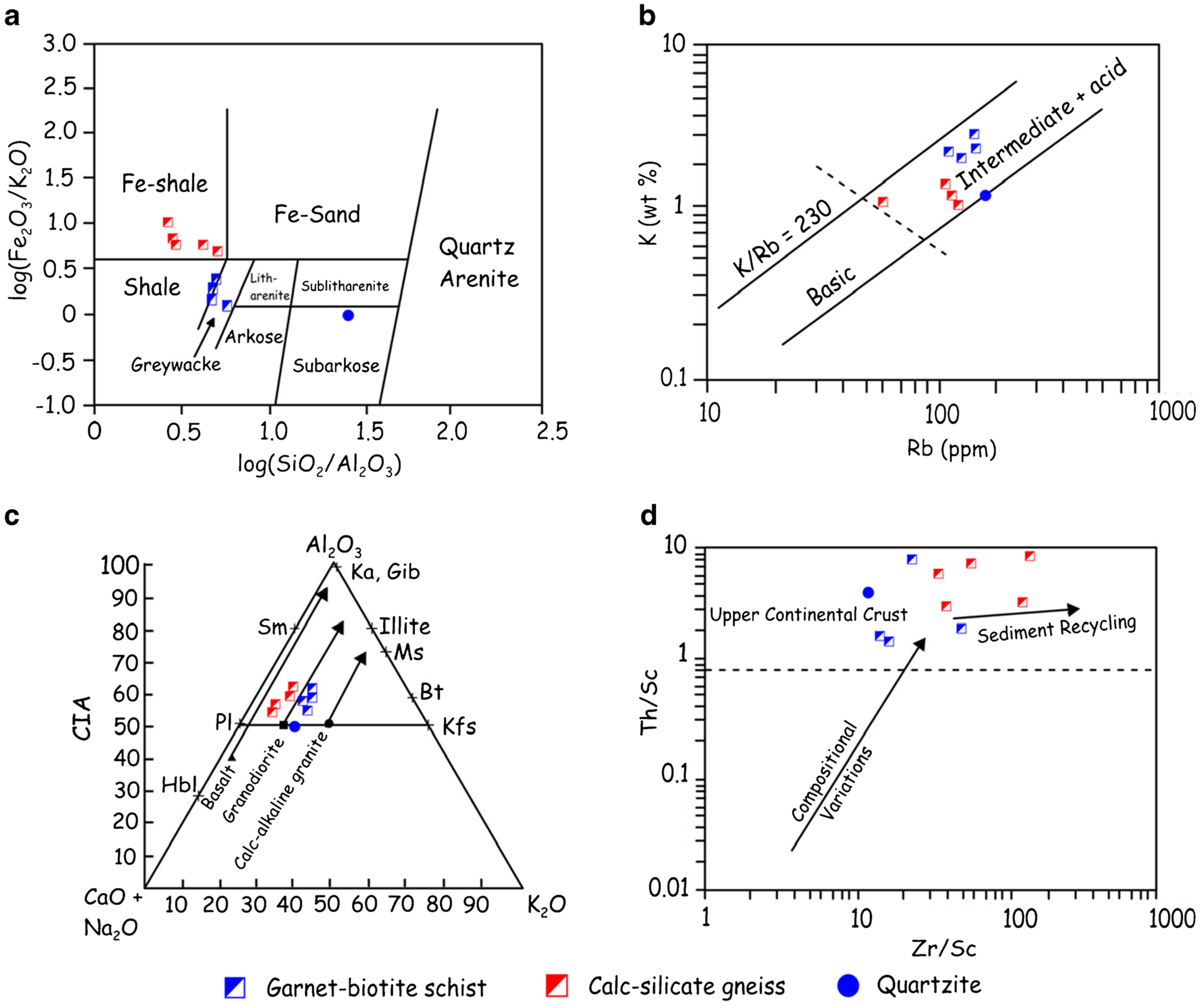


Fig. 10 Geochemical plots for determining the provenance and weathering history of Okpella metasedimentary rocks: **a** log(SiO_2/Al_2O_3) versus log(Fe_2O_3/K_2O) diagram (after Herron 1988); **b** K versus Rb plot (after Shaw 1968); **c** Ternary diagram of molar Al_2O_3 – (CaO + Na_2O) – K_2O versus chemical index of alteration (CIA) (after Fedo et al. 1995; Nesbitt 2003); and **d** Th/Sc versus Zr/Sc diagram (after McLennan et al. 2003)

(except silica), was also used to determine the provenance and compositional maturity of the metasediments (Cox et al. 1995). The ICV is expressed by ($Fe_2O_3 + K_2O + Na_2O + CaO + MgO + TiO_2$)/$Al_2O_3$. Pelites (compositionally mature mudrocks/shales), dominated by clays, would show low ICV values (<1) suggesting tectonically quiescent or cratonic environments, while compositionally immature shales with high percentage of non-clay silicate minerals and greywackes would exhibit high ICV values (<1) representing first-cycle deposits, often found in tectonically active settings. Similarly, mature and immature sandstones would have ICV<1 and ICV>1, respectively. The garnet-biotite schist of the Okpella area has an average ICV value of 1.13 (range from 0.95 to 1.36), calc-silicate gneiss with average ICV value of 1.37 (range from 1.06 to 1.92) and the quartzite has an average ICV of 1.89. This indicates that all the metasediments were immature to slightly mature and were first-cycle deposits derived by moderate to low weathering processes in tectonically active settings. The average SiO_2/Al_2O_3 ratios of the garnet-biotite schist (4.7) and calc-silicate gneiss (3.72) also indicate that these rocks were immature to slightly mature sediments prior to metamorphism. The quartzite, however, have a high average SiO_2/Al_2O_3 ratio (21.55), suggesting a high degree of maturity in contrast to interpretations derived from the ICV. The low K_2O/Na_2O values (0.65–1.59) of all the metasedimentary rocks relative to PAAS (3.08) reflect the low contents of clay minerals in their protoliths.

The Chemical Index of Alteration (CIA) was used to assess the degree of chemical weathering that the intermediate to acid sources of the metasediments underwent. According to Nesbitt and Young (1982), CIA is expressed as [(Al_2O_3/$Al_2O_3 + CaO + Na_2O + K_2O$) × 100] where oxides are expressed as molar proportions and CaO represents Ca in silicate minerals as opposed to phosphates and carbonates. In general, CIA values for slightly altered igneous and metamorphic rocks are of the order of 55 or less, whereas very altered rocks, which produce residual clay minerals, such as kaolinite and/or gibbsite, correspond to CIA values close to 100 (Nesbitt and Young 1982; Nesbitt 2003). Values of 70–75 and ~56 are typical for shales and greywackes, respectively (Condie 1993; McLennan et al. 2003; Garcia et al. 2014). The average CIA values of the garnet-biotite schist, calc-silicate gneiss and quartzite are 57.90 (range from 55.29 to 60.85), 53.81 (range from 52.00 to 56.60) and 50.34, respectively, suggesting that their intermediate to acid source rocks underwent low to moderate chemical weathering at the sediment source area. The average CIA values of the garnet-biotite schist and calc-silicate gneiss are very close to that of greywacke (56; Condie 1993). The CIA values of samples of the metasedimentary rocks were plotted against the $Al_2O_3 - (CaO + Na_2O) - K_2O$ ternary system (Fig. 10c) in order to assess the nature of the source rock(s) that were weathered to produce the metasediments (Fedo et al. 1995; Nesbitt 2003). The metasedimentary rocks seem to follow the alteration trend of granodiorite (intermediate rock), suggesting that rock types with such compositions may have constituted part of the source area. This confirmed earlier interpretation in Fig. 10b.

The Th/Sc and Zr/Sc ratios are measures of chemical differentiation and the degree of sediment recycling, respectively (Santos et al. 2017). The Th/Sc versus Zr/Sc plot of McLennan et al. (2003) can, therefore, reflect the extent of sedimentary sorting and recycling. First-cycle sediments commonly show a simple positive correlation between Th/Sc and Zr/Sc, whereas additionally recycled sediments usually show a more rapid increase in Zr/Sc than in Th/Sc. All the samples of the metasedimentary rocks of the Okpella area tend toward higher Zr/Sc ratios (>10), indicative of some degree of sediment reworking and sorting (Fig. 10d). This is confirmed by the slight enrichment of Zr in the metasediments relative to UCC (Table 3), indicating there was preferential accumulation of detrital zircon in their protoliths. The ternary diagram of Bhatia and Crook (1986) suggested active continental margin as the most plausible tectonic setting for the depositional basin of the metasedimentary rocks (Fig. 11), but secondary contributions from continental island-arc and passive margin-derived sediments are probable. The sediments sourced and transported from the continental arc and passive margins probably represents recycled sediments added to the first-cycle deposits in the active continental environment.

Notes on the Neoproterozoic evolution of the Igarra Schist Belt

Adetunji et al. (2018) have suggested that at least three west-dipping subduction zones that were different from the main

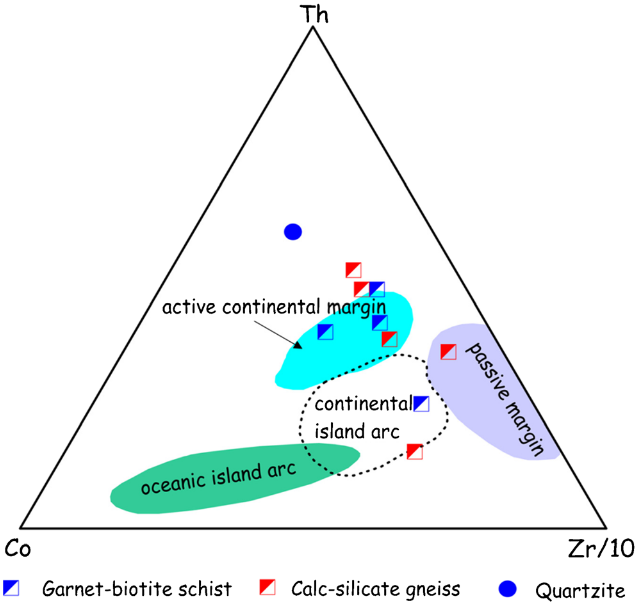


Fig. 11 Th – Co – Zr/10 tectonic setting discrimination ternary diagram (Bhatia and Crook 1986) for Okpella metasedimentary rocks

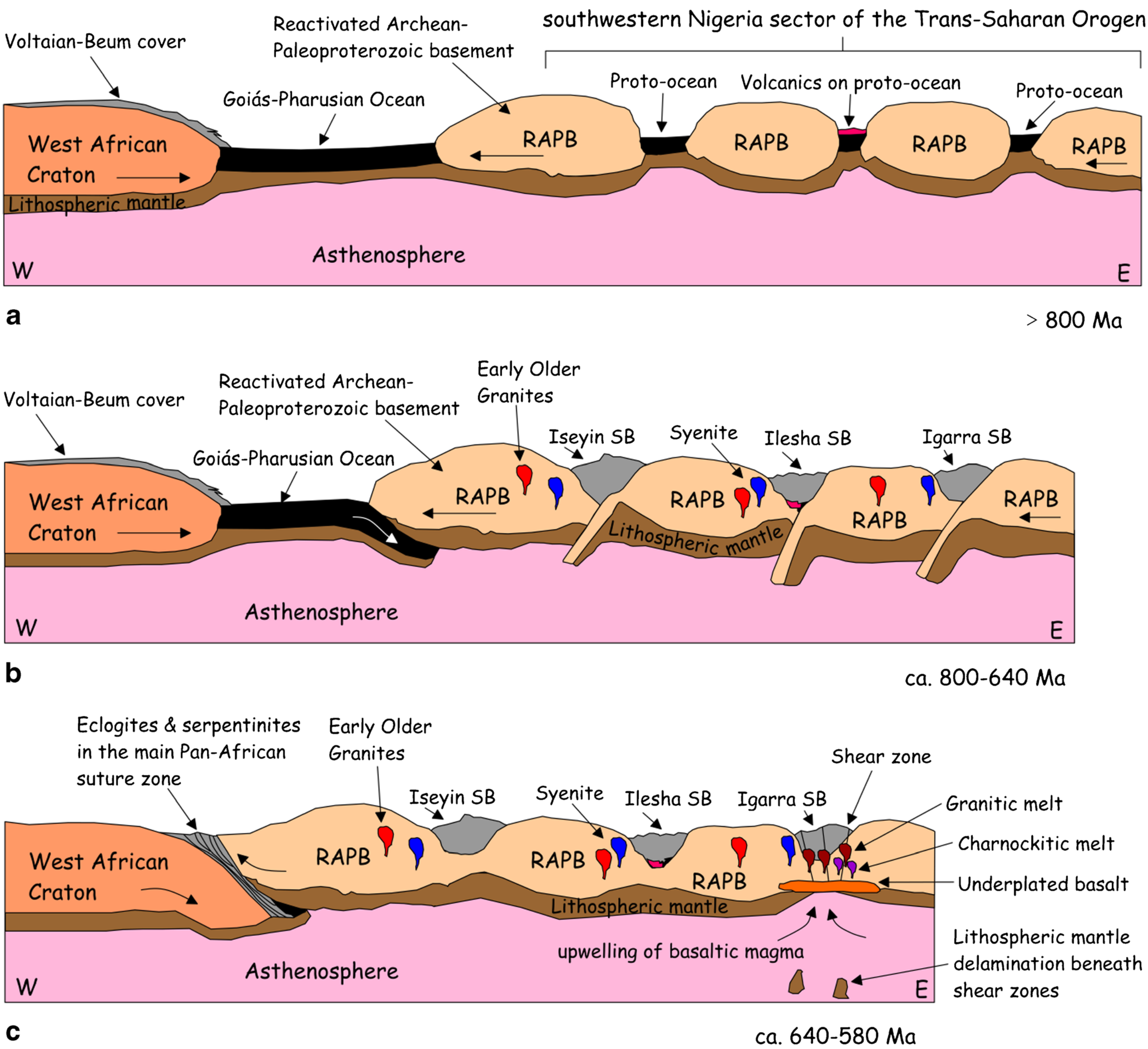


Fig. 12 Schematic evolutionary model of the Igarra Schist Belt, southwestern Nigeria, during the Neoproterozoic (with respect to the southwestern Nigerian Basement Complex and the West African Craton) (modified after Ajibade and Fitches 1988; Rahaman 1988; Dada 1998; Ferré et al. 2002; Adetunji et al. 2018; Girei et al. 2019; Bute et al. 2019): **a** westward movement of the four micro-blocks in the southwestern Nigeria sector of the Trans-Saharan Orogen toward the east moving West African Craton; **b** closure of the three proto-oceans between the four micro-blocks of southwestern Nigeria; followed by collision, westward subduction and amalgamation of the micro-blocks; deposition and infolding of sediments at the active margins of the micro-blocks; and the generation of early Older Granites and syenites; **c** closure of the Goiás-Pharusian Ocean and final collision of the West African Craton with the Saharan-Congo Cratons; causing crustal thickening, slab break-off, planar delamination of the continental lithospheric mantle below shear zones, upwelling of basaltic magma from the asthenosphere, underplating and crystallization of the basaltic magma in the lower continental crust and subsequent partial melting and fractionation to generate charnockitic melt. Granitic melt was generated at the lower to middle continental crust by mixing of the melt derived from TTGs and/or subducted metagraywackes with a mafic magma (probably the charnockitic melt and/or its progenitor). NB: Figure not to scale

east-dipping Pan-African subduction zone (Ghana-Togo-Benin suture zone) exist in the southwestern Nigerian sector of the Trans-Saharan mobile belt in the Upper Neoproterozoic. These west-dipping subduction zones correspond to the closure of three proto-oceans and subsequent collision or amalgamation of four different terranes or micro-blocks. The three major schist belts of southwestern Nigeria including the Igarra Schist Belt were probably deposited in the proto-oceans and/or at the margins of the west-dipping subduction zones during and after collision of two micro-blocks. The collision of two micro-blocks probably led to the generation of syenitic melts. The absence of typical ophiolite suite and high-pressure minerals characteristic of suture zones has been the main weakness of this model; however, the ocean floor affinity of the metamafites and meta-ultramafites in the Ife-Ilesha schist belt (Elueze 1988; Rahaman et al. 1988) as well as the large-scale nappe system and strike-slip shear zone in the belt (Caby and Boessé 2001) represent structures produced as a result of the post-collisional convergence. Although the Igarra Schist Belt (~220 km east of the Ife-Ilesha Schist Belt) does not contain metamafites and meta-ultramafites and a large-scale nappe system is yet to be identified, however, large-scale strike slip shear zones divide the belt and a large syenite pluton has been reported (Rahaman 1976). The Igarra metasedimentary rocks are, therefore, considered to be synchronous with those of the Ife-Ilesha Schist Belt and fits well with the Adetunji et al. (2018) model. Cordani et al. (2013) and Ugwuonah et al. (2017) have also suggested a similar model for the Pan-African Trans-Saharan mobile belt and further explained that the multiple collisions of the micro-blocks was followed by the closure of the Goiás-Pharusian Ocean and the final collision of the West African Craton, the Congo Craton and the Tuareg Shield.

The evolutionary models of Adetunji et al. (2018), Ugwuonah et al. (2017) and Cordani et al. (2013) combined with other available data in literature (Ajibade and Fitches 1988; Rahaman 1988; Dada 1998; Ferré et al. 2002; Bute et al. 2019; and Girei et al. 2019) and the detailed discussions on the charnockite–granite association and metasedimentary rocks of Okpella and neighbouring areas were, therefore, used to develop a schematic evolutionary model of the Igarra Schist Belt during the Neoproterozoic as shown in Fig. 12. Isotopic data is, however, needed to confirm this model.

Conclusion

Based on detailed field, petrographic and whole-rock geochemical data for the charnockite–granite association and metasedimentary rocks around Okpella, eastern Igarra Schist Belt, southwestern Nigeria, the following were inferred as possible conclusions:

i. The charnockites and granites of Okpella are co-genetic and coeval, and form close association in the field. The charnockites were derived by a two-stage process involving an initial partial melting of mafic lower continental crustal rocks followed by assimilation and fractional crystallization.

ii. The lower charnockitic melt and/or underplated basaltic magmas probably supplied heat to the lower to mid-crustal TTGs and/or subducted metagraywackes which melted and was mixed with a K-rich mafic (mantle-derived) magma to produce the high-K calc-alkaline granites. The K-rich mafic magma source of the granites was most likely the underplated parental basaltic magma of the charnockites and/or the generated charnockitic melt. The charnockites and granites are presumed to be emplaced at the waning stage of the Pan-African Orogeny.

iii. The garnet-biotite schist, calc-silicate gneiss and quartzite, which form a supracrustal cover on the granitic gneiss, may have been derived from immature to slightly mature sediments, probably greywacke, marl and subarkose, respectively. The metasedimentary rocks are first cycle in origin, with little recycled components.

iv. The sedimentary protoliths of the metasedimentary rocks were probably sourced from igneous rocks of intermediate to acid composition(s) which underwent slight to moderate chemical weathering and were deposited in an active margin setting.

v. The Igarra Schist Belt is thought to have evolved in the Neoproterozoic during which sediments were sourced, deposited and infolded in active continental margins formed by the collision of two micro-blocks, followed by upwelling of basaltic magmas from the mantle which underplated and crystallized in the lower continental crust and was partially melted to generate the charnockitic and granitic melts through mantle-crust interaction during the late Pan-African.

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