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Garnet chemical zoning: a clue for the tectono-metamorphic history of the Proterozoic Mayombe chain (West Congo Belt), Congo-Brazzaville

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Abstract

The Mayombe chain of Congo is part of the West Congo Belt, which belonged to the western Gondwana supercontinent. It consists of Paleoproterozoic gneisses and schists that are tectonically stacked and overthrust Neoproterozoic low-grade metamorphic rocks. Although Neoproterozoic context of the chain is relatively well established, the tectono-metamorphic evolution of its Paleoproterozoic basement still under discussion.

Petrography, garnet chemistry and phase equilibria modelling were used to constrain tectono-metamorphic evolution of meta-plutonic and meta-sedimentary rocks from the Western Domain of the Mayombe chain. Microprobe analysis reveals three garnet types: (i) 2-stage garnets with distinct cores (Grt₁) and rims (Grt₂), (ii) unzoned garnet showing narrow diffusion zones along cracks and rims and (iii) syn-kinematic garnet with normal growth zoning. These complex and simple features of garnet growth are, respectively, related to a polycyclic evolution linked in this area to: (i) the superposition of Eburnean (c. 2000 Ma) and Pan-African (c. 600 Ma) orogenies and (ii) a monocyclic evolution related to a single Pan-African event taking into account ages of the protoliths. The oldest metamorphic assemblage (Eburnean) is preserved in amphibolite facies conditions marked by the first generation of garnet, whereas the younger (Pan-African) event varies from amphibolite facies in the southwest (4–6 kbar, 550°C–600°C) to greenschist facies in the northeast (4–6 kbar at 450°C–550°C) confirming the westward increase in metamorphic grade during the Pan-African event. Mineral equilibria modelling shows also a relatively *HP* episode culminated at 11.5–12.5 kbar and 525°C–550°C which tectonic environment stills less understood.

1. Introduction

The Mayombe chain, located in the southwest of the Republic of Congo forms the central part of the West Congo Belt (Dévigne, 1959; Dadet, 1969; Schermerhorn, 1981; Boudzoumou & Trompette, 1988; Maurin *et al.* 1991; Vicat & Pouclet, 2000; Fullgraf *et al.* 2015b). It is traditionally recognized as one of the orogenic belts of the Pan-African system (Kröner & Stern, 2005) resulting from the collision of São Francisco and Congo cratons (Fig. 1a–b) during the assembly of the western Gondwana in the late Neoproterozoic-early Cambrian times (Rapela *et al.* 2007; Gray *et al.* 2008; Heilbron *et al.* 2008; Gaucher *et al.* 2009; Chemale *et al.* 2012; Schmitt *et al.* 2018). This part of the West Congo Belt encloses precious geological information, which constitutes the witnesses of Proterozoic evolution of the Earth. Rocks in this area recorded at a time geodynamic and paleoclimatic processes. It is argued that the West Congo Belt (Fig. 1c), including its Brazilian counterpart, the Araçuaí Belt, has played a crucial role in the development of the São Francisco-Congo paleocontinent from Proterozoic to early Paleozoic (Kuchenbecker & Barbuena, 2023). Understanding its geological record is a crucial task to those seeking to reconstruct the tectonic history of West Gondwana.

Geologically, the Mayombe chain is divisible into three distinct tectono-stratigraphic domains according to the recent mapping (Callec *et al.* 2015a; Callec *et al.* 2015b; Fullgraf *et al.* 2015a; Fullgraf *et al.* 2015b; Le Bayon *et al.* 2015a; Le Bayon *et al.* 2015b), known as, from west to east, the Western, Central and Eastern domains (Fig. 1d), which have different rock associations and very different intensity of deformation and metamorphic grade. The Central and Eastern domains are made up of the relatively well-known Neoproterozoic low-grade metamorphic rocks of the West Congolian Supergroup, deformed during the Pan-African orogeny (Hossie, 1980; Boudzoumou, 1986; Maurin *et al.* 1991; Fullgraf *et al.* 2015a; Fullgraf *et al.* 2015b).

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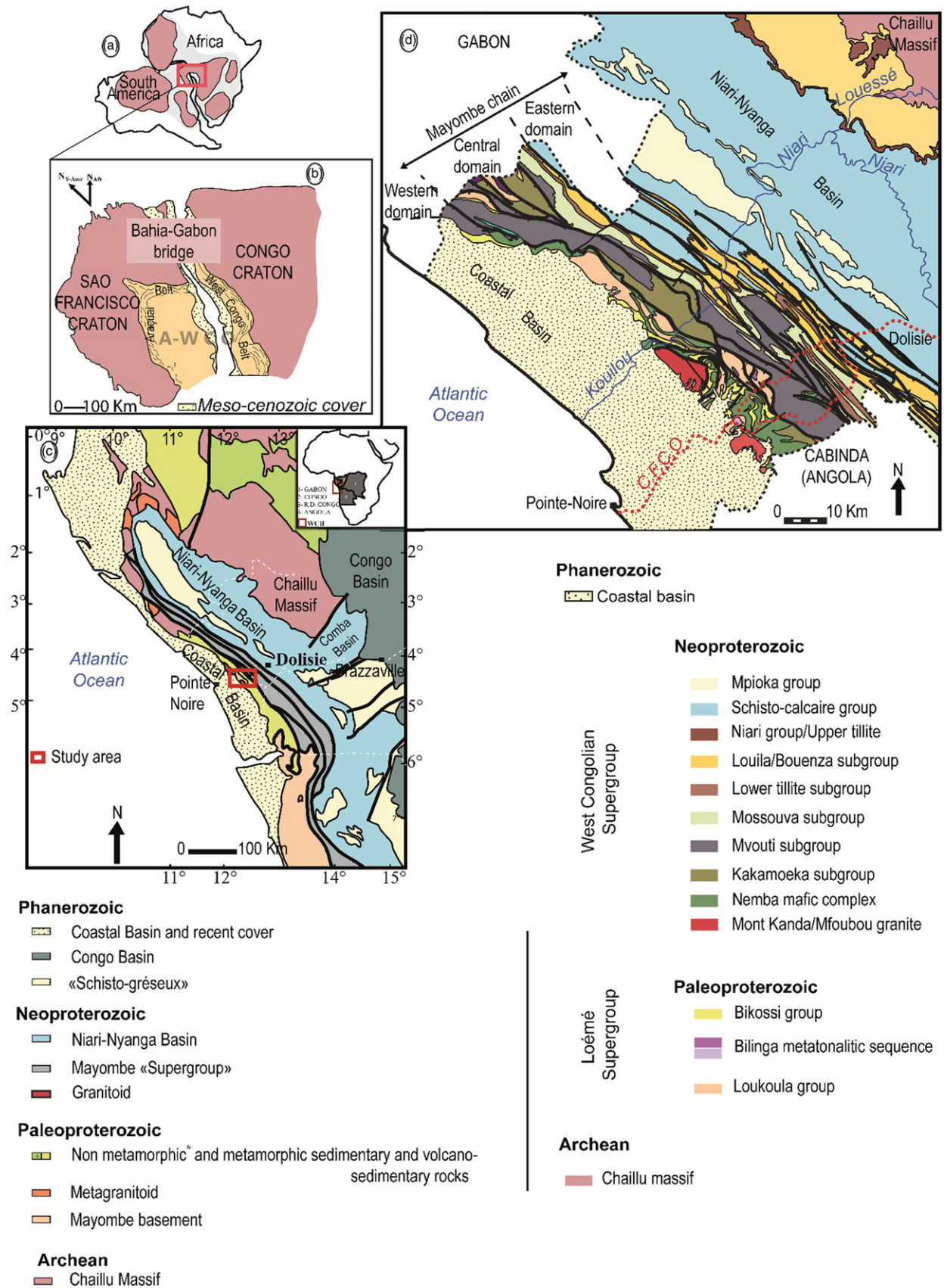


Figure 1. (Colour online) The Araçuaí-West Congo orogenic system. (a) and (b) Location of the Araçuaí-West Congo orogen in relation to the Sao Francisco and Congo cratons (Pedrosa-Soares *et al.* 2008). (c) Geological map of the West Congo belt (modified after Maurin, 1993 and Thiéblemont *et al.* 2016) and his location in Africa. (d) Geologic map of the southwestern part of Republic of Congo showing the main structural units of the Mayombe chain (Callec *et al.* 2015a).

In contrast, the Western Domain mainly consists of Paleoproterozoic tectono-stratigraphic terranes assigned to the Loémé Supergroup, commonly thought to represent an Eburnean-aged basement inlier in the Mayombe chain, that are conventionally correlated with the Paleoproterozoic Kimezian basement rocks in Democratic Republic of Congo (Hossié, 1980; Djama, 1988; Tack *et al.* 2001) and with the Transamazonian-aged basement inliers of the Araçuá Belt in eastern Brazil (Ledru *et al.* 1994; Toteu *et al.* 1994; Trompette, 1997; Feybesse *et al.* 1998; Barbosa & Sabaté, 2004; Lerouge *et al.* 2006). It is widely acknowledged that these Paleoproterozoic basement inliers are the product of a complex geological evolution. In fact, different geological studies done on the Mayombe chain indicated that the Paleoproterozoic metamorphic basement rocks of the Loémé Supergroup are affected by a poly-phase deformation and metamorphosed to a high grade (Hossié, 1980; Djama, 1988; Fullgraf *et al.* 2015b). Consequently, they can provide precious information on the P - T conditions that characterized the petrological assemblages related to the Eburnean and Pan-African orogenies. Moreover, there is evidence to show that the Paleoproterozoic metamorphic basement rocks of the Loémé Supergroup were experienced at least two significant metamorphic events through the Proterozoic Era, linked to the Eburnean and/or Pan-African orogenies, which are relatively little documented and poorly constrained by metamorphic petrology or geochronology. Yet, there are still unanswered questions regarding (i) the preservation and P - T conditions of the Eburnean record and (ii) evaluation of the Pan-African overprint.

The goal of the present study is to address these questions by focusing on the metamorphic petrology of garnet, which is a common mineral in the metamorphic rocks that composed the Loémé Supergroup. The composition and texture of this mineral will give clues to the metamorphic P - T conditions and the deformation to which the rocks were exposed (Tracy *et al.* 1976; Du Bray, 1988; Skrzypek *et al.* 2011; Enami *et al.* 2017). Chemical zoning can be used to reconstruct the P - T path of the rocks during prograde metamorphism (Atherton & Edmunds, 1966; Hollister, 1966; Brown, 1969; Anderson & Buckley, 1973; Kerr, 1981; Cygan & Lasaga, 1982; Dempster, 1985; Tropper & Recheis, 2003) and compositional zoning in garnet is a common feature in numerous metamorphic environments (Cygan & Lasaga, 1982; Tracy, 1982; Kohn, 2005; Baxter *et al.* 2017). Our results and interpretations are utilized to better reconstruct the poorly known tectono-metamorphic context of the Western Domain of the Mayombe chain.

2. Geological setting

2.a. Structural context

The tectono-metamorphic architecture of the West Congo Belt in the Mayombe chain has been established by geological mapping and structural analysis supported by remote sensing of Landsat 7_T imagery, petrography and geochronology (Hossie, 1980; Maurin *et al.* 1991; Fullgraf *et al.* 2015a, Fullgraf *et al.* 2015b). It allows subdivision into three western, central and eastern domains bound by crustal-scale thrusts and characterized by distinct structural elements (Fig 1d).

The **Western Domain** corresponds to the internal domain of Hossié (1980). It is covered to the south by Mesozoic to Quaternary beds of the Congolese passive margin and limited to the north by Mandzi-Loukéné shear zone. This domain mainly comprises the Paleoproterozoic rocks of the Loémé Supergroup, which were strongly deformed and locally intruded by early Neoproterozoic

plutons (Djama, 1988; Maurin *et al.* 1990; Mpemba Boni, 1990; Djama *et al.* 1992; Fullgraf *et al.* 2015a; Fullgraf *et al.* 2015b; Affaton *et al.* 2016). The interpretation of the structures of this Western Domain is complex due to the polyphase deformation and the variability of lithologies. Accordingly, the structural patterns and spatial distribution, internal stratigraphy and geochronology of rock units across the Western Domain are still largely unknown (Djama *et al.* 1992; Fullgraf *et al.* 2015b). Some authors have recognized two main phases of folding marked by NNW-SSE and NW-SE trending attributed to the Pan-African orogeny (Hossié, 1980; Boudzoumou, 1986; Djama, 1988; Maurin *et al.* 1991). Vellutini *et al.* (1983) suggesting a Kibarian and Pan-African evolution of these structures. Maurin *et al.* (1990; 1991) have recognized traces of the Eburnean orogeny overprinted by the Pan-African orogeny.

Recently, based on an integration of outcrop observation, structural and geochronological data, Fullgraf *et al.* (2015b) have recognized at least three major structural events affecting the Paleoproterozoic basement terranes in the Western Domain, which were attributed to the enigmatic pre-Eburnean deformation, the Eburnean orogeny marked by NNW-SSE shortening and to the Pan-African orogeny marked by weakly penetrative ductile deformations.

The **Central Domain** (the 'intermediate domain' of Hossié, 1980) is located to the north-east of the Western Domain and extends from the Mandzi-Loukéné shear zone to the Moukondo back-thrust. From south to north, this heterogeneous domain mainly comprises early Neoproterozoic metavolcanic and metasedimentary assemblages of the West Congolian Supergroup (Fullgraf *et al.* 2015b). Structurally, the unit is characterized by open to closed, upright to NE-verging folds attributed to the Pan-African orogeny (Hossié, 1980; Maurin, 1993; Fullgraf *et al.* 2015b).

The **Eastern Domain** (the 'external domain' of Hossié, 1980) is limited by the eastern Moukondo thrust/backthrust system and the western Mt Belo shear zone, which is considered as the terminal thrust system of the West Congo Belt (Fullgraf *et al.* 2015b). It is made entirely of Neoproterozoic metasediments, including two key marker horizons; namely, the Lower and Upper Tillite (Fullgraf *et al.* 2015b; Affaton *et al.* 2016). The structural style is characterized by open, upright folds whose NW-SE trending axes can be followed along the strike for more than 100 km and together with several discrete NE-verging thrusts define the frontal fold-and-thrust belt of the West Congo Belt (Hossié, 1980; Boudzoumou & Trompette, 1988). In the more internal parts of the Eastern Domain, a penetrative schistosity (axial-planar to the large-scale folds) is observed in less competent layers. More competent layers, such as the quartzites, are characterized by flexural slip folding and are devoid of penetrative schistosity. The metamorphic grade is always very low (lower than the chlorite zone), grading to anchizonal in the adjacent Niari-Nyanga basin (Fullgraf *et al.* 2015b; Mfere *et al.* 2020).

2.b. Paleoproterozoic lithostratigraphic setting

The study area is in the Western Domain of the Mayombe mountain which contains Paleoproterozoic polycyclic high-grade metamorphic rocks of the Loémé Supergroup overlain by a series of weakly metamorphosed igneous and volcano-sedimentary rocks linked to the West Congolian Supergroup (Fig. 2).

2.b.1. The Loémé Supergroup

At regional scale, the Loémé Supergroup has been correlated with the Kimezian Supergroup in the Democratic Republic of Congo

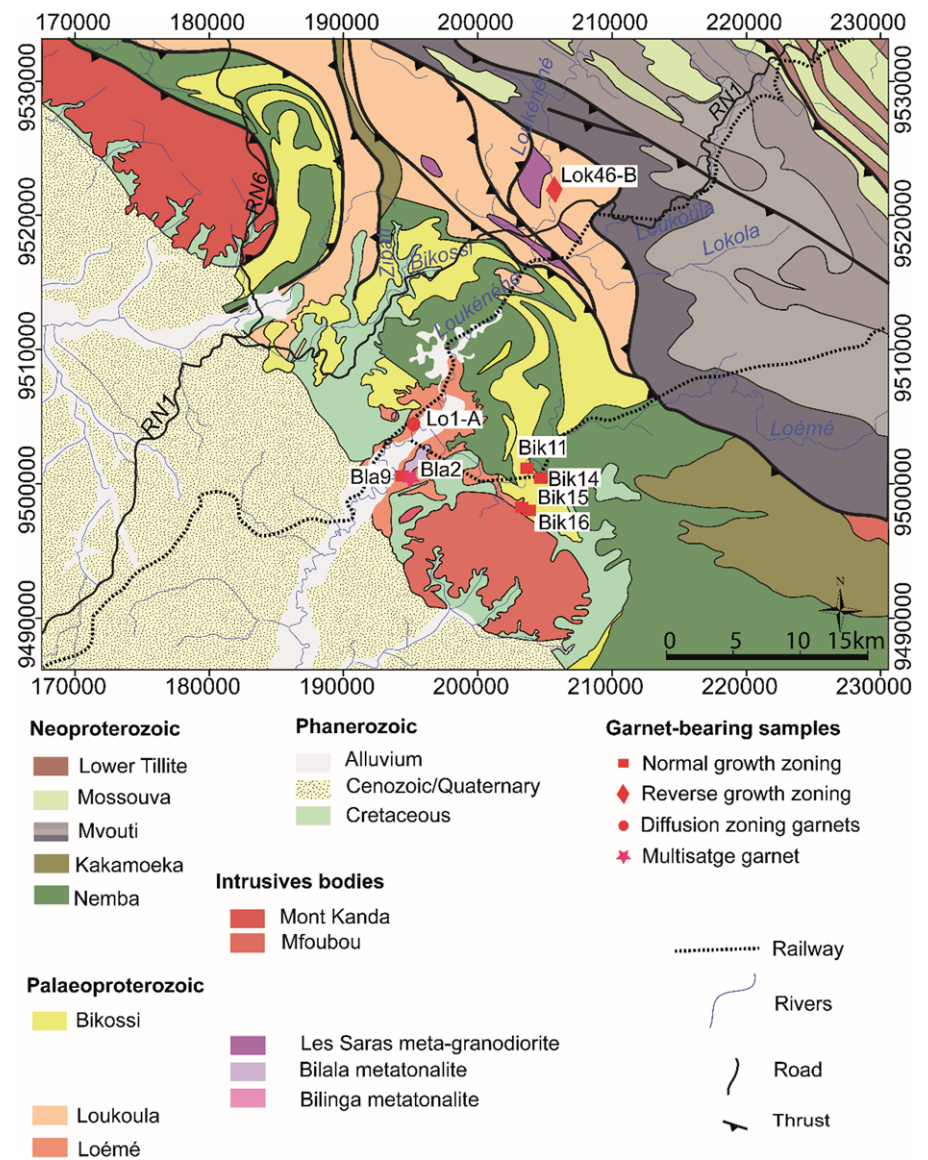


Figure 2. (Colour online) Geological map of the studied area in the Mayombe chain (Republic of Congo), modified after Fullgraf *et al.* (2015a), showing sample location.

(Tack *et al.* 2001), the Ogooué Complex in Gabon (Thiéblemont *et al.* 2009; Weber *et al.* 2016) and, across the south Atlantic, with the Mantiqueira and Juiz de Fora Complexes in the Brazilian Ribeira and Araçuaí Orogens (Noce *et al.* 2007). This Supergroup consists of supracrustal rocks assigned to the Loukoula and Bikossi Groups. To better constrain metamorphic evolution in Loémé Supergroup, this study splits into two Groups the Loukoula Group of Fullgraf *et al.* (2015b). We distinguish Loémé Group in south area from Loukoula Group in north.

(i) Loémé and Loukoula Groups

Loémé and Loukoula Groups are made of paragneiss, schists, amphibolite and quartzite that were intruded by the calc-alkaline granitoids of the Bilala, Bilinga and Les Saras plutons dated between 2060 and 2040 Ma (Djama, 1988; Djama *et al.* 1992; Fullgraf *et al.* 2015b; Affaton *et al.* 2016; Bouenitela, 2019) and by early Neoproterozoic alkaline to peralkaline granitic bodies, locally known as the Mfoubou and Mont Kanda granite, dated between 1050 and 925 Ma (Djama, 1988; Djama *et al.* 1992; Fullgraf *et al.* 2015b; Bouenitela, 2019).

(ii) Bikossi Group

The Bikossi Group is a metasedimentary sequence, characterized by thick quartzitic layers sometimes associated with meta-conglomerates, and fine-grained graphite-bearing schists deriving from anoxic pelitic sediments. Detrital zircon geochronology in the quartzite yields age of sources between 3.08 and 2.04 Ga (Fullgraf *et al.* 2015b) and 2.20 and 2.00 Ga (Affaton *et al.* 2016), indicating maximum age deposition at about 2.00 Ga. The Bikossi Group has been correlated with the Paleoproterozoic Francevillan Group in Gabon (Le Bayon *et al.* 2015b).

2.b.2. West Congolian Supergroup

In the Western Domain of the Mayombe chain, the West Congolian Supergroup is represented by the early Neoproterozoic volcanic rocks of Nemba Complex which is essentially made of fine-grained amphibolites deriving from basalts, dolerites and a few gabbro. Geochemical analyses indicate that the amphibolites have a tholeiitic composition (Vellutini, Rocci & Vicat, 1983; Vicat & Vellutini, 1987; Vicat & Vellutini, 1988; Djama *et al.* 2018;

Bazika *et al.* 2022; Matiaba-Bazika *et al.* 2024). A metagabbro attributed to the Nemba Complex has provided a Neoproterozoic age (U–Pb data on zircon at 915 ± 8 Ma: Fullgraf *et al.* 2015b). The interpretation of the origin of Nemba rocks is a matter of debate. According to a first hypothesis, the Nemba Complex is an ophiolitic complex (Vellutini, Rocci & Vicat, 1983; Vicat & Vellutini, 1987; Vicat & Vellutini, 1988), implying that the Mayombe chain results from the collision of two continental domains after oceanic subduction. However, in other hand, the metavolcanic rocks from the Nemba Complex are considered as the equivalent, in composition and age, of the Gangila meta-basalts from the Zadinian Group in the DRC, and were linked to the early Neoproterozoic rifting phase (Tack *et al.* 2001; Fullgraf *et al.* 2015b; Bazika *et al.* 2022; Matiaba-Bazika *et al.* 2024).

2.c. Tectono-metamorphic history

The metamorphic history of the Mayombe chain has not been properly characterized, particularly within the polycyclic Paleoproterozoic basement rocks of the Loémé Supergroup.

The Neoproterozoic rocks of the West Congolian Supergroup in the Mayombe chain and their equivalents in other parts of the West Congo Belt and in Brazil were subjected to at least one tectono-metamorphic event marked by prograde and retrograde *P–T* paths linked to the Pan-African/Brasiliano orogenic events between 580 and 500 Ma (Hossié, 1980; Cahen, 1982; Boudzoumou & Trompette, 1988; Porada, 1989; Maurin, 1993; Alkmin *et al.* 2006; De Waele *et al.* 2008; Pedrosa-Soares *et al.* 2008; Thiéblemont *et al.* 2009; Monie *et al.* 2012; Fullgraf *et al.* 2015b; Fossen *et al.* 2020; Schannor *et al.* 2021).

Metamorphic and geochronological studies of the Mayombe chain (Hossié, 1980; Boudzoumou & Trompette, 1988; Djama, 1988; Djama *et al.* 1992; Maurin, 1993; Fullgraf *et al.* 2015b) show that Pan-African metamorphism decreased from amphibolite facies in the Western Domain to greenschist facies in the Eastern Domain.

Disagreement exists in the interpretation of the metamorphism of the polycyclic Paleoproterozoic basement rocks assigned to the Loémé Supergroup. Some authors hypothesized that the multi-phase deformation and high-grade metamorphism in the remaining Paleoproterozoic basement rocks across the West Congo Belt may be attributed to Pan-African orogenic episodes, except in the former Loémé Supergroup for which they postulated a metamorphism of Eburnean age (Hossié, 1980; Boudzoumou & Trompette, 1988; Maurin, 1993). In contrast to this traditional interpretation, the recent work (Fullgraf *et al.* 2015b) has revealed that the Paleoproterozoic basement of the Mayombe chain has been subjected to high-grade pre-Eburnean metamorphism (M1) and Eburnean metamorphism (M2, ca. 2056–2050 Ma) as shown in Oogoué complex in Gabon (Thiéblemont *et al.* 2009). However, the reworking of Paleoproterozoic basement by Pan-African orogeny remains less clear.

3. Materials and methods

3.a. Sampling

Rock description, structural measurements and sampling were done in the western Mayombe (Fig. 2) area during two field campaigns. Samples were collected in active or disused quarries, along the railway talus from the CFCO (Chemin de Fer Congo-Océan), and along river beds. The previous studies reported only few garnet and chloritoid-bearing rocks, in most cases without

precise location (e.g. Dadet, 1969). Staurolite has never been reported, and aluminosilicates are lacking. Therefore, particular attention has been paid to collect garnet-bearing samples for the purpose of the study. This included four gneiss samples from the Loémé (Bla2, Bla9 and Lo1-A) and Loukoula (Lok46-B) Groups, and four micaschists from the Bikossi Group (Bik11, Bik14, Bik15 and Bik16) (Fig. 3, Table 1).

3.b. Mineral chemistry

Mineral chemical composition was determined on polished thin sections through Electron Probe Micro Analyzer (EPMA) Cameca SX 100 (Microsonde Ouest, Plouzané) using a wavelength dispersive mode. Operating conditions for spot analyses were set to 15 keV for accelerating voltage, 20 nA for beam current and 10 s counting time (spot size = 1 μ m). The standards used are natural albite (Si and Na), orthoclase (K), corundum (Al), wollastonite (Ca), forsterite (Mg), MnTiO₃ (Ti and Mn) and andradite (Fe). Mineral mapping and element profiles of selected garnets were performed for Fe, Mn, Mg and Ca. BSE and X-ray element maps were produced by applying SX100 software.

3.c. Whole-rock chemistry

Samples were crushed and powdered using agate mortar. Analysis of whole-rock chemistry was done at the Geochemical and Petrographical Research Center of Nancy (CRPG, CNRS-SARM Laboratory). Major and trace elements analyses were measured using Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) and Inductively Coupled Plasma Mass Spectrometer (ICP-MS). Detailed analytical procedures are described in Carignan *et al.* (2001).

3.d. *P–T* estimations

In a first step, *P–T* conditions were estimated using conventional methods for geothermobarometry. The **garnet–biotite Fe–Mg exchange** is used as a geothermometer for the metapelitic rocks after the calibration of Williams & Grambling (1990). We used their preferred model 3 (Table 2), which involves non-ideal Fe–Mg mixing in garnet, and for which uncertainties range from 25°C in low-Mn samples to 45°C for high-Mn samples. The **garnet–chlorite Fe–Mg exchange** was used to estimate temperature in metapelitic rocks. Three calibrations have been used, namely those of Dickenson & Hewitt (1986), as modified in Laird (1988), Grambling (1990) and Perchuk (1991). The **chloritoid–chlorite Fe–Mg exchange** use the *P*-insensitive empirical calibration of Vidal *et al.* (1999). In all these approaches, all Fe was considered to be ferrous. The **Ti-in-biotite** geothermometer is empirically established for a pressure range of 4–6 kbar (Henry, Guidotti & Thomson, 2005). Ti saturation is reached when biotite coexists with an aluminous phase (chlorite, staurolite or sillimanite) and a Ti-bearing phase (ilmenite or rutile), and in the presence of graphite (to reduce the amount of Fe³⁺). Precision of the Ti-in-biotite geothermometer is estimated to be $\pm 24^\circ\text{C}$ in the low temperature range (<600°C) and decreases to $\pm 12^\circ\text{C}$ at high temperature (>700°C).

Further refinement of the *P–T* conditions was achieved through pseudosection approach (Hensen, 1971; Powell & Holland, 1990; Tinkham *et al.* 2001) using the Theriak/Domino software version 10.0 (De Capitani & Petrakakis, 2010) with the bulk composition of sample Bik11 as determined by XRF (Table 3). The thermodynamic data set of Holland and Powell (ds5.5, 1988) converted to

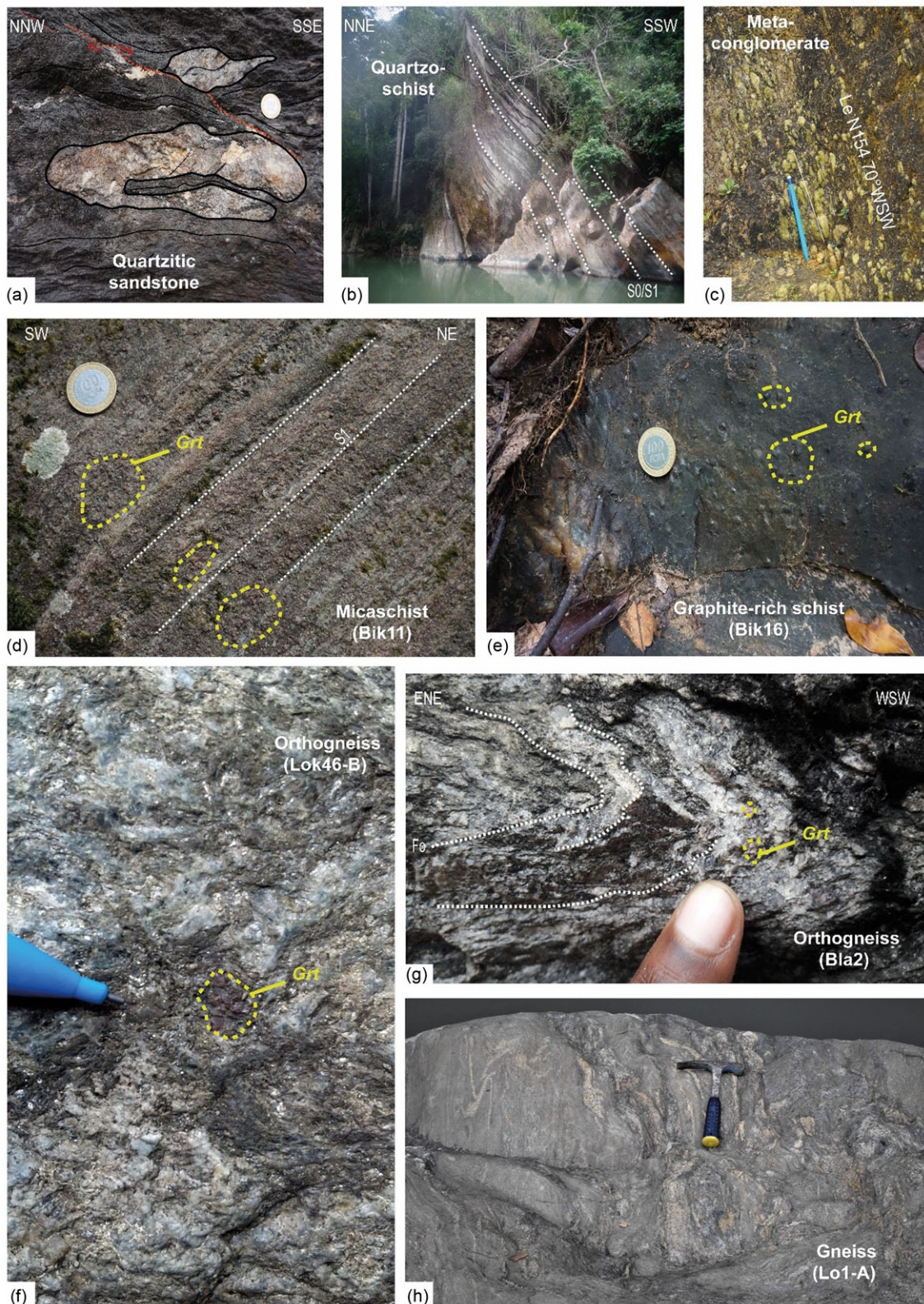


Figure 3. (Colour online) Field photographs of rocks from the western domain of the Mayombe chain. From Bikossi Group (a) quartzitic sandstone with isoclinal folded quartz-calcite vein, (b) quartzo-schist with a straighten schistosity, (c) metaconglomerate with stretched pebbles, (d) garnet bearing micaschist with straighten schistosity, (e) graphite-rich schist with garnets porphyroblasts. From Loukoula Group (f) Pegmatitic gneiss. From Loémé Group (g) folded orthogneiss, (h) fine-grained gneiss.

Table 1. Location, petrography, mineralogy, paragenesis and texture of the eight studied samples

Sample	Easting Northing	Outcrop	Lithology	Paragenesis	Garnet texture/zonation
Monocyclic units – Bikossi Group					
Bik11	E203578 N9499968	Loeme river	Micaschist	Qtz-Ms-Grt-Cld-Chl-Ilm	Synkinematic growth Grt in equilibrium with Cld and Chl Normal growth zoning
Bik14	E204184 N9500162	Railway cutting (at point 88.800 km)	Fine-grained black graphite-rich schist, Two deformation episodes (S_1 pervasive schistosity, S_2 crenulation cleavage)	Qtz-Ms-Grt-Chl-Ilm-Gp Note very few inclusions of Cld in Grt cores	Synkinematic porphyroblast Grt in equilibrium with Chl Normal growth zoning
Bik15	E204229 N9498302	Moutsoungou river	Black graphite-rich schist Two deformation episodes	Qtz-Ms-Grt-Bt-Ilm-Gp Late Chl porphyroblasts overgrowing S_1	Synkinematic porphyroblast Grt in equilibrium with Bt Normal growth zoning
Bik16	E204119 N9497912	Moutsoungou river (about 30 m from sample Bik15)	Black graphite-rich schist Two deformation episodes	Qtz-Ms-Grt-Bt-Ilm-Gp Note very abundant Bt Late Chl porphyroblasts overgrowing S_1	Pre- to syn-kinematic porphyroblast Grt in equilibrium with Bt Normal growth zoning
Polycyclic units (1) Loukoula Group					
Lok46-B	E205712 N9521943	Loukenene river (right bank)	Fine-grained gneiss crossed by coarse-grained, folded leucocratic veins	(1) Qtz-Pl (An_{25})-minor Kfs/Bt-Grt-Ap (2) coarse-grained Ms overgrowing Bt (3) fine-grained Ms-Chl-Ep-Ttn	Reverse growth zoning
Polycyclic units (2) Loémé Group					
Bla2	E194343 N9500668	Bilala (=Guéna) quarry	Tonalitic orthogneiss	(1) Qtz-Grt1-Ilm-Rt (2) Qtz-Pl (An_{26-28})-Ms-Grt2-Bt (3) Qtz-Bt-Chl-Ttn	Grt dissolved and replaced by Bt Multistage garnet: Grt 1 – Reverse growth zoning Grt 2 – Normal growth zoning
Bla9	E194310 N9500673	Bilala (= Guéna) quarry	Tonalitic orthogneiss	(1) Qtz-Pl-Kfs (2) Qtz-Pl ₁ (An_{18-36})-Kfs-Ms-Grt-Ep (3) Qtz-Pl ₂ -Bt-Chl-Ep-Cal	Grt dissolved and replaced by Bt Growth zoning
Lo1-A	E195310 N9504346	Loeme river (right bank)	Paragneiss	(1) Qtz-Grt (2) Qtz-Pl (An_{19-28})-Ms-Bt-Chl	Grt dissolved and replaced by Bt Flat profile with narrow diffusion zoning along rims and cracks

Table 2. P–T estimations using conventional methods for geothermobarometry

	Grt-Bt Williams and Grambling (1990)	Grt-Chl Grambling (1990)	Cld-Chl Vidal <i>et al.</i> (1999)
Bik11		553°C - 586°C at 12 kbar	566°C - 610°C
Bik15	465°C-546°C at 6 kbar		
Bik16	569°C-592°C at 6 kbar		
Bla2	545°C-679°C at 6 kbar		
Bla9	630°C-680°C at 6 kbar	461°C - 473°C at 5 kbar	
Lok46-B		563°C at 5 kbar	
Lo1-A	539°C-652°C at 6 kbar	517°C at 5 kbar	

Theriak–Domino format by Tinkham (tcds55_p07, march 2012) was applied for calculations on MnO-Na₂O-CaO-K₂O-FeO-MgO-Al₂O₃-SiO₂-H₂O-TiO₂ (MnNCKFMASHT) chemical system.

4. Results

4.a. Petrography and mineral chemistry

4.a.1. Bikossi Group

The Bikossi Group is chiefly made of mica-, graphite- and quartz-schists, as well as quartzites with locally intercalations of metaconglomerate (Fig. 3a–e). Four samples from garnet–chlorite schist (Bik11 and Bik14), and garnet–biotite schist (Bik 15 and Bik 16) were selected for the metamorphic study (Fig. 4a–d).

Sample Bik11 displays compositional layering of cm-scale, with darker domains consisting of quartz–garnet–chloritoid–chlorite

Table 3. Bulk-rock chemical analysis of the sample Bik11 used for phase diagram calculations; sample Bik11 was selected for numerical modelling but due to its heterogeneous composition, it was split in Bik11-1 and Bik11-2. The model has been calculated for Bik11-1, a muscovite-bearing part of the sample. Total Fe is measured as Fe₂O₃

Group	Bikossi	Bikossi
Rock	Micaschist	Micaschist
Sample	Bik11-1	Bik11-2
SiO ₂	56,55	55,91
TiO ₂	1,42	0,91
Al ₂ O ₃	22,61	17,11
Fe ₂ O ₃	11,22	18,00
MnO	0,23	0,16
MgO	0,84	2,06
CaO	0,11	0,35
Na ₂ O	0,33	0,06
K ₂ O	4,24	0,80
P ₂ O ₅	<D.L.	0,25
LOI	2,25	3,20
Total	99,80	98,80

and lighter domains having additional abundant muscovite ($3.1 \leq \text{Si} \leq 3.2$ pfu). The microstructure is characterized by a faint S₁ cleavage and a penetrative crenulation cleavage (S₂). Garnet is generally idioblastic and contains quartz, ilmenite and chloritoid inclusions (Fig. 4a). Transect of garnet reveals regular zoning with Fe and Ca contents decreasing from core ($X_{\text{Sps}} = 0.12$ and $X_{\text{Grs}} = 0.05$) to rim ($X_{\text{Sps}} = 0.04$ and $X_{\text{Grs}} = 0.01$), whereas Fe and Mg show sharp increases from core ($X_{\text{Alm}} = 0.8$ and $X_{\text{Prp}} = 0.04$) to rim ($X_{\text{Alm}} = 0.9$ and $X_{\text{Prp}} = 0.05$) (Fig. 4a, Fig. 5a–d).

Sample Bik14, a micaschist in close contact with mafic rocks (Nemba Group), displays a well-developed crenulation cleavage (S₂) refolding the S₁ schistosity. Subhedral garnets contain quartz inclusion trails defining a sigmoidal internal schistosity indicating syn-D₁ growth (Fig. 4b). In addition, rare inclusions of chloritoid ($X_{\text{Mg}} = 0.09$ –0.10) were identified. The matrix contains quartz, muscovite ($3.08 \leq \text{Si} \leq 3.18$), graphite and chlorite defining the schistosity (S₁) and crenulation cleavage (S₂). Ilmenite is found in the matrix and as inclusions in some garnet crystals. The latter display a regular zoning profile, characterized by a bell-shaped curve for spessartine (X_{Mn} varies from 0.16 in the core to 0.01 at the rim), and a correlative increase in almandine content from core to rim (67 to 85%). The pyrope content increases very slightly from core (3 mole %) to rim (5 mole %), and the grossular content is almost stable (10–14 mole %) (Fig. 4b, Fig. 5e–h). Overall, the X_{Mg} ratio slightly increases from 0.04 in the core to 0.05 in the rim.

Sample Bik15, a graphite-rich schist (Fig. 4c), exhibits an early pervasive schistosity (S₁) and a crenulation cleavage (S₂). Graphite, muscovite, biotite, and ilmenite are major components with minor secondary chlorite replacing biotite. Garnet crystals (c. 2 mm in diameter) display sigmoidal inclusion trails, indicating syn-kinematic growth. Garnet zoning is characterized by a decrease in Sps content (from 0.14 to 0.01 from core to rim, respectively), an increase in Alm (from 59 to 75%) and Prp (from 1 to 8%) content. The Grs content is stable at around 24 moles % in the core, then

decreases to 16% in the rim (Fig. 4c, Fig. 5i–l). The X_{Mg} ratio varies from 0.04 to 0.10.

Sample Bik16 is a graphite-rich schist with a larger amount of biotite compared to sample Bik15. Garnet crystals are around 4 mm in diameter and display euhedral shapes. The largest garnet grains display two growth stages (Fig. 4d). In the inner part, inclusions display a star-like arrangement, as already reported in several examples of garnet grains from graphite schists (e.g. Andersen, 1984; Burton, 1986; Rice & Mitchell, 1991; Castellanos *et al.* 2004; Kleinschmidt *et al.* 2008; Castellanos *et al.* 2016). The outer part of garnet porphyroblasts comprises numerous minute graphite inclusions, defining an internal schistosity (S₁) that continues into the schistosity of the matrix. Some cracks crosscut grains perpendicular to the cleavage crenulation S₂. Garnet X-ray maps and profiles display a smooth zoning, with decreasing Sps (14–3 mole %) and Grs (15–20 mole %) and increasing Alm (64–72 mole %) and Prp (4–8 mole %) from core to rim. Its X_{Mg} ratio varies from 0.06 to 0.10. There is no chemical discontinuity along the interface between the inner and outer parts of the porphyroblasts (Fig. 4d, Fig. 5m–p).

In summary, the samples from the Bikossi Group contain garnets that have been variously formed in paragenesis with i) chloritoid and chlorite (Bik11), ii) chlorite (Bik14) or iii) biotite (sample Bik15 and Bik16). The crystals in these samples have euhedral or subhedral shapes and contain sigmoidal inclusions trails that indicate syn-kinematic growth.

4.a.2. Loukoula Group

The Loukoula Group is composed of paragneiss, and amphibolite intruded by orthogneiss; the rocks display generally planar folded foliation and/or straighten foliation. *Sample Lok46-B* is a coarse-grained leucocratic gneiss most probably derived from a pegmatite vein (Fig. 3f) in fine-grained paragneiss and strongly deformed. It contains coarse-grained minerals, represented by quartz, abundant plagioclase and rare K-feldspar. Muscovite occurs either as large grains (100 to 200 µm) ($3.12 \leq \text{Si} \leq 3.20$ pfu) or as minute flakes disseminated in the matrix ($3.01 \leq \text{Si} \leq 3.08$ pfu). Biotite is partially replaced by chlorite. Garnet is locally present in biotite-rich domains (Fig. 6a) showing cracks filled by chlorite. Garnet from sample Lok46-B (Fig. 6a and Fig. 7a–d) displays a very gentle zoning marked by increasing spessartine from 8% in core to 19% in rim and decreasing almandine and pyrope (from 78% to 70% and 12% to 6%, respectively). The amount of grossular is nearly constant and very low (2–4%). The garnet zoning is characterized by reverse zoning with a slight enrichment in Mn from core to rim, with distinct peaks in Mn inside the grains along fractures.

4.a.3. Loémé Group

The Loémé Group consists of isoclinally folded paragneisses and orthogneiss (Fig. 3g–h), both cut by mafic dykes. *Sample Bla2* is a strongly foliated biotite-garnet gneiss (Fig. 3g). The matrix is made of quartz, plagioclase, muscovite and biotite. Partial retrograde metamorphism is recorded by the crystallization of chlorite, epidote and ilmenite. Disseminated anhedral garnet shows evidence of rim dissolution against biotite (Fig. 6b). The central part of the zoned crystals is rich in quartz inclusions (Fig. 6b) and shows a nearly constant composition with $\text{Alm}_{79-81} \text{Sps}_{04-08} \text{Prp}_{09-12} \text{Grs}_{03-06}$. It is in sharp contact with the outer zone that is marked by significantly lower almandine, spessartine and pyrope and a higher grossular contents (Fig. 7e–h).

Sample Bla9 (Fig. 6c) comprises in decreasing proportion, quartz, plagioclase, biotite, epidote, titanite, and calcite.

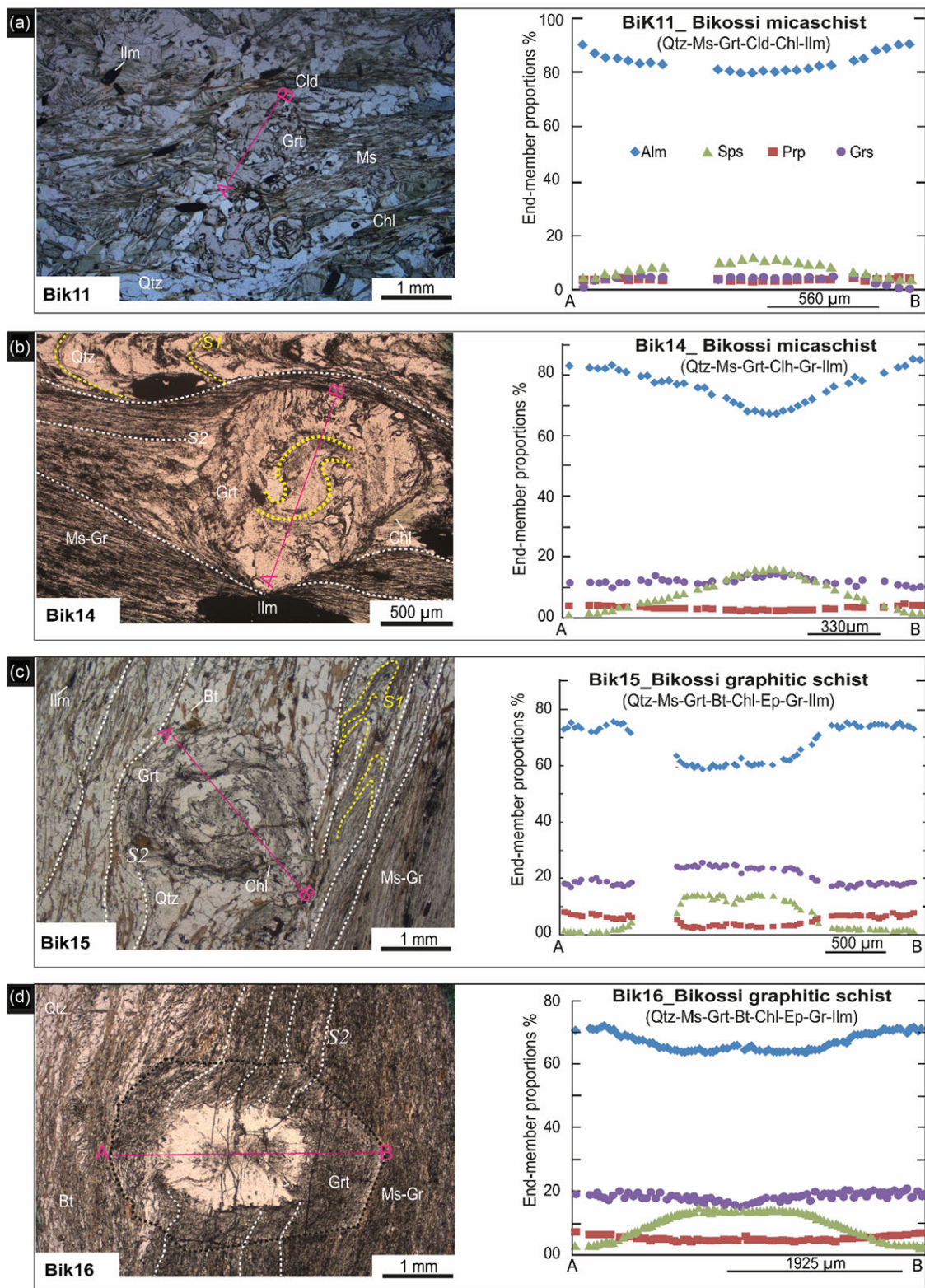


Figure 4. (Colour online) Microphotographs of the garnet-bearing rocks and traverses across garnet from the western domain of the Mayombe chain, showing variations in almandine (Alm, in blue), spessartine (Sps, in green), pyrope (Prp, in red) and grossular (Grs, in violet). a–d: micaschists of the Bikossi Group (Bik11, Bik14, Bik15, Bik16).

The latter is also present as inclusion in garnet where it is associated with apatite, clinozoisite and quartz. Garnet from sample Bla9 (Fig. 6c and Fig. 7i–l) is zoned, with a slight

decrease of Mn (from 14% to 9% mole) and Ca from core to rim corresponding to slight increase in Fe and Mg. The X_{Mg} ratio varies from 0.09 to 0.11.

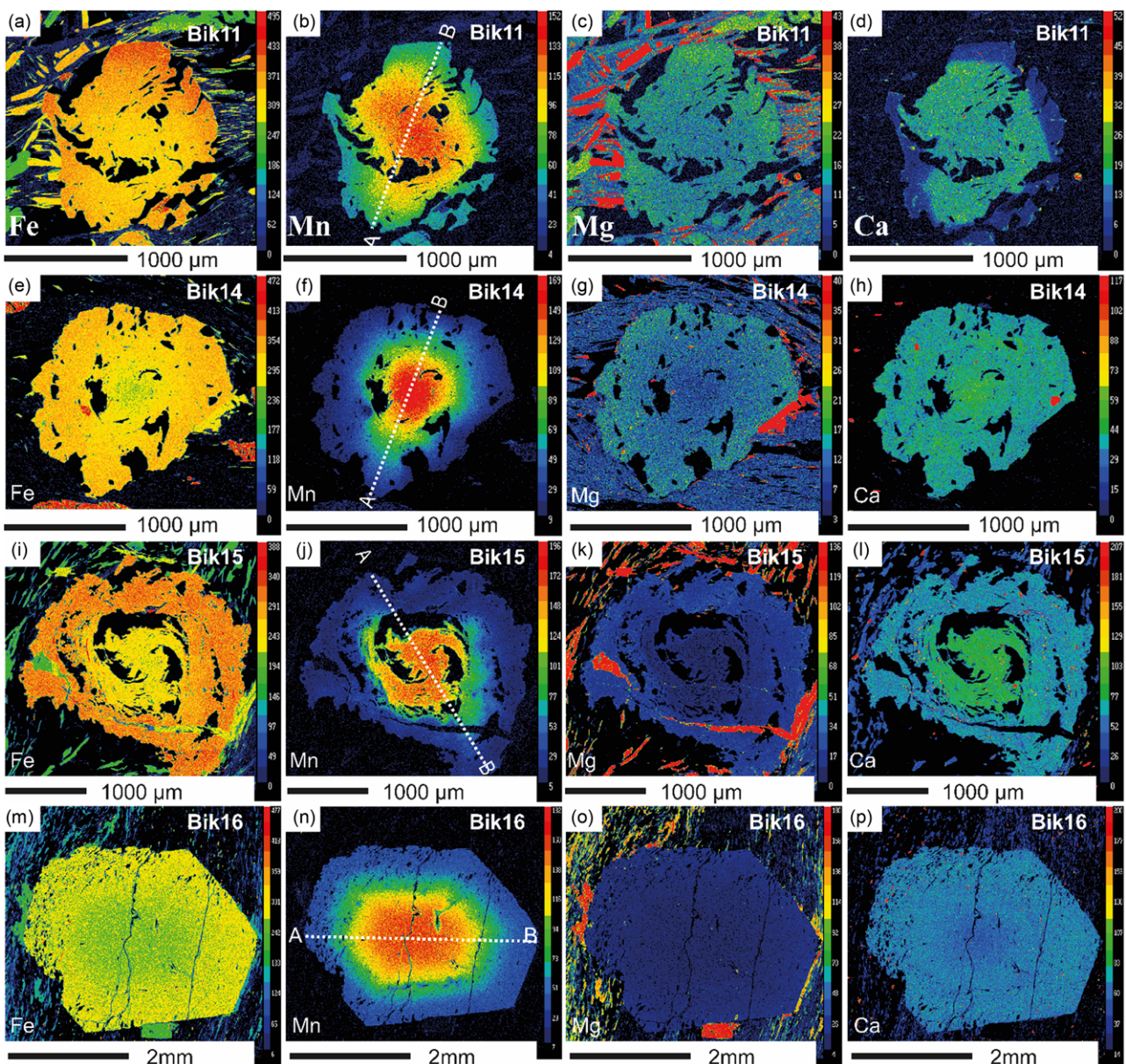


Figure 5. (Colour online) X-ray maps showing Fe, Mn, Mg and Ca distribution in garnets from the micaschists of the Bikossi Group (from top to bottom: Bik11, Bik14, Bik15, Bik16).

Sample Lo1-A, a fine-grained gneiss (Fig. 3h) is composed of quartz, plagioclase, muscovite, biotite, chlorite and garnet which are xenoblastic with less than 1 mm in diameter (Fig. 6d), with a homogeneous composition $\text{Alm}_{80} \text{Sps}_{05} \text{Prp}_{15} \text{Grs}_{05}$. Along the cracks that affect the grains or at the contact with the matrix, garnets are characterized by a decrease in Alm and Prp (respectively, down to 0.78 and 0.09) and an increase in Sps (up to 0.10) (Fig. 6d and Fig. 7m–p). Accordingly, the X_{Mg} ratio varies from 0.16 in garnet core to 0.10 along garnet rims.

In these samples, garnets co-exist with brown biotite defining the main foliation and/or the crenulation schistosity (S2).

4.b. *P–T estimations by conventional methods for geothermobarometry*

The garnet–biotite Fe–Mg exchange geothermometer has been applied on samples Bik15, Bik16, Bla2, Bla9, and Lo1-A following

the calibration of Williams & Grambling (1990, corrected in 1992). A nominal pressure of 6 kbar is used for most samples, based on the mineralogical assemblage and structure of the concerned samples. We assumed that these samples did not experience high pressure due to the lack of *HP*-index minerals. For sample Bik 11 we used 12 kbar taking into account the range of pressure provides by the pseudo-section calculations. The results from this geothermometer (Table 2) yields temperature ranges of 465–546°C for sample Bik15, 569–592°C for sample Bik16, 545–679°C for sample Bla2, 630–680°C for sample Bla9, and 539–652°C for sample Lo1-A.

According to petrographic observations, chlorite is assumed to be part of the peak assemblage in sample Bik11 whereas in the other samples of the Loukoula group (Lok46-B, Lo1-A) and the orthogneisses (Bla9) it is a late (retrograde) phase. Therefore, the **garnet–chlorite Fe–Mg exchange** has been used to estimate temperature only in sample *Bik11*. Three calibrations have been

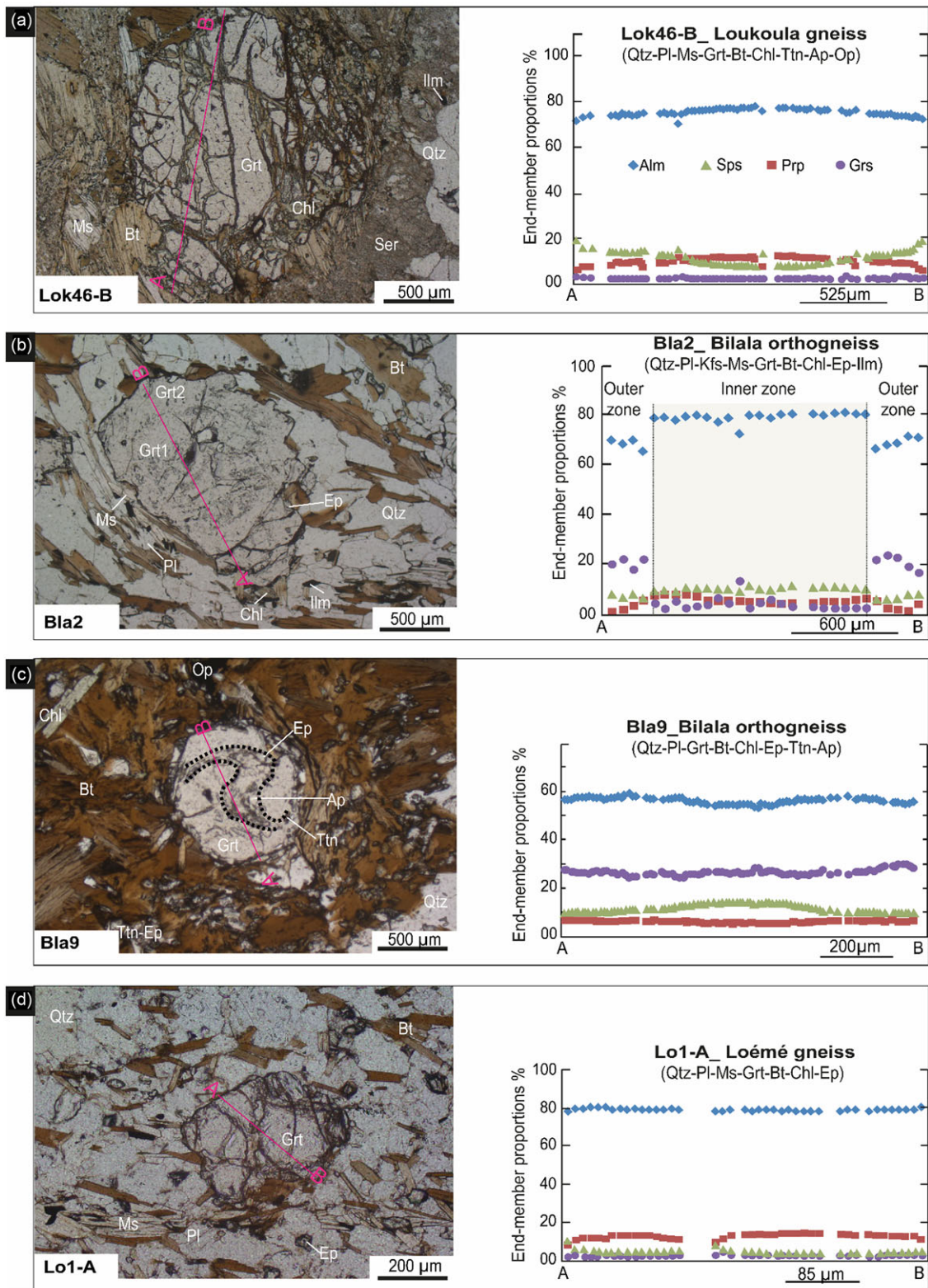


Figure 6. (Colour online) Microphotographs of the garnet-bearing rocks and traverses across garnet from the western domain of the Mayombe chain, showing variations in almandine (Alm, in blue), spessartine (Sps, in green), pyrope (Prp, in red) and grossular (Grs, in violet). a–d: gneiss of the Loémé (Bla2, Bla9, Lo1-A) and Loukoula (Lok46-B) Groups.

used to estimate temperature in this sample (Table 2). The pressure has been estimated between 10 and 14.5 kbar using pseudo-section method. This constrains temperatures (i) from 564°C–617°C at 10 kbar, 570°C–600°C at 12 kbar and 577°C–631°C at 14.5 kbar in

Laird’s (1988) model, (ii) from 548°C–581°C at 10 kbar, 553°C–586°C at 12 kbar and 560°C–593°C at 14.5 kbar using Grambling (1990) and (iii) from 566°C to 591°C at 10 to 14.5 kbar using the calibration of Perchuk (1991).

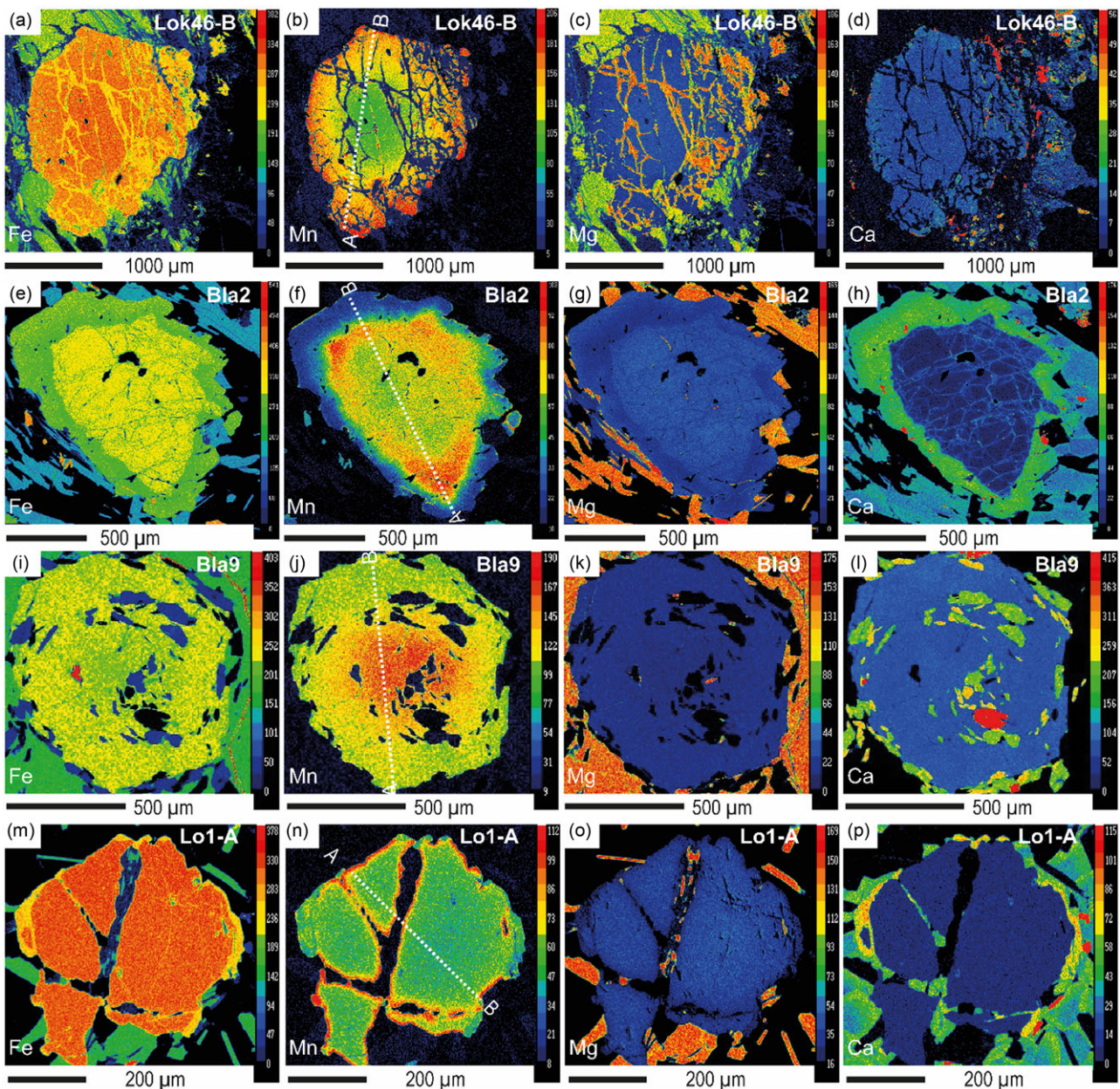


Figure 7. (Colour online) X-ray maps showing Fe, Mn, Mg and Ca distribution in garnets from the gneisses of the Loukoula Group (Lok46-B) and Loémé Groups (Bla2, Bla9 and Lo1-A); see text for details.

The **chloritoid–chlorite Fe–Mg exchange** may be used in sample Bik11, where estimated temperature (T) ranges from 566°C to 610°C, using the P-insensitive empirical calibration of Vidal *et al.* (1999).

The **Ti-in biotite** geothermometer (Henry *et al.* 2005) has been used on samples Bik15 and Bik16 (Fig. 8), where a biotite X_{Mg} value varies, respectively, from 0.45 to 0.47 and 0.46 to 0.48. The concentration of Ti is measured at 0.17–0.23 apfu in sample Bik15 and 0.14–0.20 apfu in sample Bik16. In sample Bik15, temperature is estimated from 546°C to 590°C for the biotite in the matrix and from 582°C to 608°C for the biotite in contact with garnet. In sample Bik16, temperature is in the range from 498°C to 585°C regardless whether biotite is in the matrix or in contact with garnet.

4.c. *P–T estimations using calculated isochemical phase diagrams*

In a first step, the calculations have been made considering all Fe as Fe^{2+} (Fig. 9a). The phase diagram displays the classical sequence of assemblages for aluminous pelitic bulk-rock chemistries (e.g. Harte & Hudson, 1979; Powell & Holland, 1990; Tinkham *et al.* 2001), with garnet–chloritoid, garnet–staurolite and garnet–aluminosilicate (kyanite/sillimanite) assemblages at low, medium and high temperatures, respectively. The assemblage in sample Bik11 consists of garnet–chloritoid–chlorite–ilmenite with quartz and muscovite constraining metamorphic conditions between 510°C–568°C and 5.5–12.5 kbar. A critical point is the lack of rutile and biotite during the entire history of the sample.

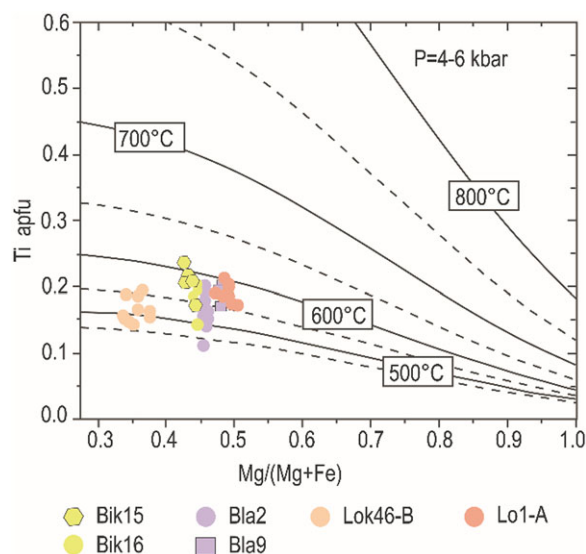


Figure 8. (Colour online) Biotite chemistry as a function of Mg/(Mg+Fe) and Ti content in the studied samples from the Bikossi (Bik15 and Bik16), Loémé (Bla2, Bla9 and Lo1-A), and Loukoula Groups (Lok46-B). The isotherms for the Ti-in-biotite geothermometer are shown after Henry *et al.* (2005).

In a second step, the effect of Fe_2O_3 was taken into account by transforming 3% of the total FeO content into Fe_2O_3 (Table 3). This stabilizes epidote rather than clinozoisite, and enlarges the stability field of ilmenite relative to rutile (Fig. 9b). As a result, the observed assemblage garnet–chloritoid–chlorite–ilmenite is stable at pressures between 6.5 and 14.5 kbar, in a temperature range from 500°C–575°C that is not significantly different from the model in the Fe^{3+} -absent system.

To model the P – T path of the sample, the isopleths for garnet (X_{Mg} , X_{Mn} and X_{Ca}) and muscovite (X_{Si} in cations pfu) are calculated in the Fe^{3+} -bearing system (Fig. 9c). The isopleths for Mn are nearly vertical (isothermal), indicating that garnet growth took place at increasing T , a feature which is consistent with the slight increase in pyrope content. During the early stage of its growth, the grossular content in garnet is buffered by the presence of clinozoisite. Once this phase is consumed, garnet is the only Ca-bearing phase, and the grossular decreases to almost zero close to the rim. These observations are consistent with the prograde sequence Cld–Chl–Ilm–Czo (with excess Qtz, Ms and H_2O), to Grt–Cld–Chl–Czo and finally Grt–Cld–Chl. Estimation of the peak pressure relies largely on the muscovite composition. The measured values of Si (3.13–3.15 pfu) indicate a relatively high P of 11.5 kbar–12.5 kbar (Fig. 9c).

5. Discussion

5.a. Distinguishing poly- and monocyclic rocks in the Mayombe chain

The present study has shown that the Paleoproterozoic metamorphic rocks outcropping in the Western Domain of the Mayombe chain present compositional zoning in garnet. The rationale behind the interpretation of garnet zonation may be summarized as follows:

Consider first the simple case where the studied rocks have been submitted to a single tectonothermal cycle. During growth at increasing T , garnet partitions Fe, Mn, Mg and Ca with the coexisting phases, and records the changing P – T conditions

through its growth zoning, a process for which different numerical models have been performed (e.g. Hollister, 1966). In calculated pseudosections displaying the isopleths for almandine, spessartine, pyrope and grossular, growth zoning may be used to depict graphically the changing P – T conditions during garnet growth. However, with increasing T , intracrystalline (volume) diffusion becomes more efficient, and will progressively relax, and finally erase, the growth zoning (Caddick *et al.* 2010; Ague & Carlson, 2013). As a consequence, garnet grains tend to be homogeneous at high T (i.e. from and above the sillimanite–muscovite zone), as shown by several studies across metamorphic field gradients (Woodsworth, 1977; Yardley, 1977; Azor & Ballèvre, 1997).

A complex case is found when the studied rocks contain multistage garnet, i.e. grains whose texture and composition show abrupt changes due to at least two episodes of growth. In this case, the first garnet generation may have different origin. They may have crystallized during cooling of a magma or more frequently, during a previous metamorphic cycle (e.g. Tropper & Recheis, 2003; Gaidies *et al.* 2006; Le Bayon *et al.* 2006). In exceptional cases, it has been proposed that the first garnet ‘generation’ results from the presence of detrital garnet grains in the sedimentary protolith of the studied rock (Yardley *et al.* 1996; Manzotti & Ballèvre, 2013). Careful examination of the garnet chemistry provides valuable information on the P – T conditions associated to the growth of both garnet generations.

In the basement units, where the Paleoproterozoic rocks have been geochronologically characterized, garnet grains show two types of responses. In the more external area (the Loukoula Group), an early garnet generation is identified, which is partly replaced by chlorite along fractures and rims during a second metamorphic episode, taking place in the chlorite stability field. In the more internal Loémé Group, a second generation of garnet was able to grow during the Pan-African orogeny, which took place in the biotite stability field.

Unlike garnets from the basement units, garnets in the metamorphic rocks of the Bikossi Group only exhibit normal growth zoning. The interpretation of these garnets can be challenging because this type of garnet zoning can be found in metamorphic, plutonic and volcanic rocks (Ruiz, 1976). However, the syn-kinematic features of garnets from the Bikossi Group confirm their formation in metamorphic setting. The absence of change in zoning suggests that these minerals nevertheless undergo some significant change in the P – T conditions since their crystallization as evoked by Ruiz (1976). According to this evidence of a single tectonometamorphic cycle, we believe that the metasedimentary rocks of Bikossi Group underwent one of the most recent tectonothermal cycles known in Mayombe chain, which is associated with its tectono-thermal evolution during the Pan-African event (Fullgraf *et al.* 2015b, Bouénitela, 2019). This interpretation is supported by $^{40}\text{Ar}/^{39}\text{Ar}$ dating of biotite and muscovite from Bilala othogneiss and Bikossi Group rocks that have yielded exclusively Neoproterozoic to Cambrian ages 615–496 Ma (Bouénitela, 2019). However, some complementary geochronological analyses (e.g. in situ U–Pb or Lu–Hf garnet dating) are required to better constrain the timing of garnet growth during this metamorphic event.

Based on our textural and chemical observations, garnet-bearing rocks of the Mayombe chain allow to distinguish two tectono-metamorphic events. The first one, observed in both the Loémé and Lokoula Groups, is related to a high T event, able to homogenize through volume diffusion garnets grains up to a few mm in diameter. This high T event may be associated to the

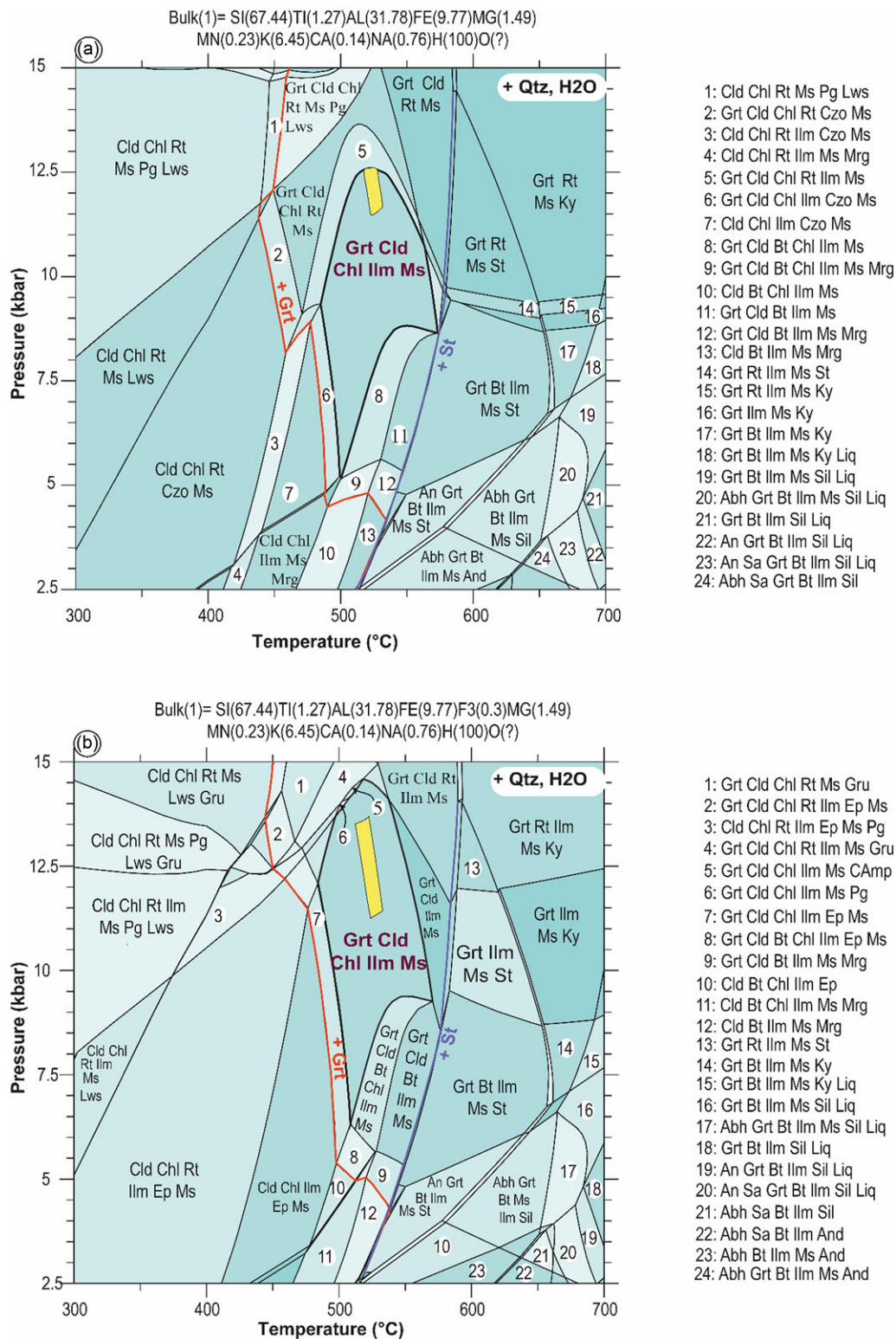


Figure 9. (Colour online) a, b. Calculated isochemical phase diagrams (pseudosections) for sample Bik11 using the Theriak/Domino software, considering all Fe as ferrous (A) or converting 3% of the total Fe into ferric iron. Mineral abbreviations are from Kretz (1983). The box in yellow shows the restricted stability domain for the observed mineral assemblage.

Eburnean orogeny. The imprint of the second tectono-metamorphic event, of probable Pan-African age, depends on the T gradient that was established at the scale of the belt. In the Loémé and Loukoula Groups (i.e. in the Paleoproterozoic basement), the

second episode occurred at slightly higher T in the Loémé Groups (allowing the garnet overgrowth in the Bilala orthogneiss than in the Loukoula Group, characterized by chlorite growth at the expense of garnet, with some Mn back-diffusion. In the Bikossi

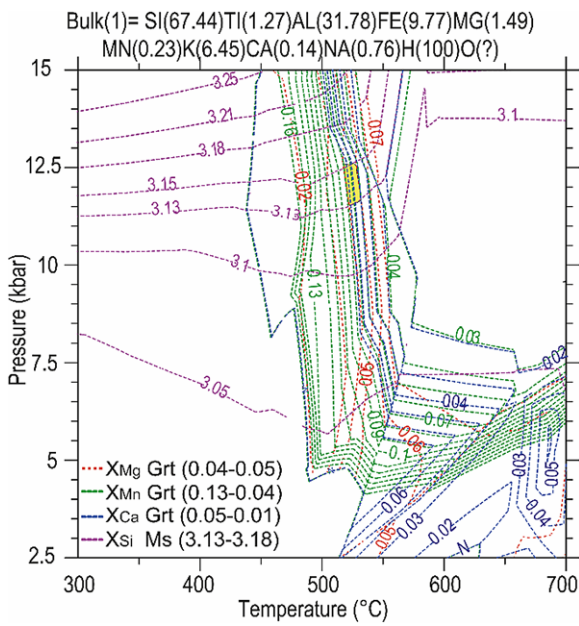


Figure 9c. (Colour online) Isopleths of spessartine, pyrope, and grossular (in mole per cent) in garnet and Si (in cations pfu, on the basis of 11 oxygens) in muscovite.

Group, garnet grains display evidence for a single tectonometamorphic cycle related to the Pan-African metamorphic event.

5.b. P-T history of metamorphic rocks of the Western Domain of the Mayombe chain

A compilation of our results indicates that the Loémé Group presents metamorphic conditions reached at 6 kbar and 539°C–680°C suggesting an evolution in amphibolite facies (Fig. 10). The prograde metamorphic path is reflected in the multistage zoning of the garnet, indicating at least two stages of metamorphism. In contrast, the Loukoula Group shows retrograde stage characterized by lower grade overprinting in greenschist facies marked by the fracturing and reverse zoning of garnet.

The Bikossi Group presents mainly garnet with normal growth zoning showing a single tectono-thermal cycle. However, significant differences in P-T estimates have been noted. Conventional geothermobarometry has shown that the peak metamorphic conditions reached by the rocks of the of the Bikossi Group vary from 6 kbar for 465°C–592°C and 10–14.5 kb for 548°C–631°C. HP values were used in the conventional model in relation to the pseudo-section estimation model. Then, the sample Bik 11 shows an assemblage equilibrium with relative HP

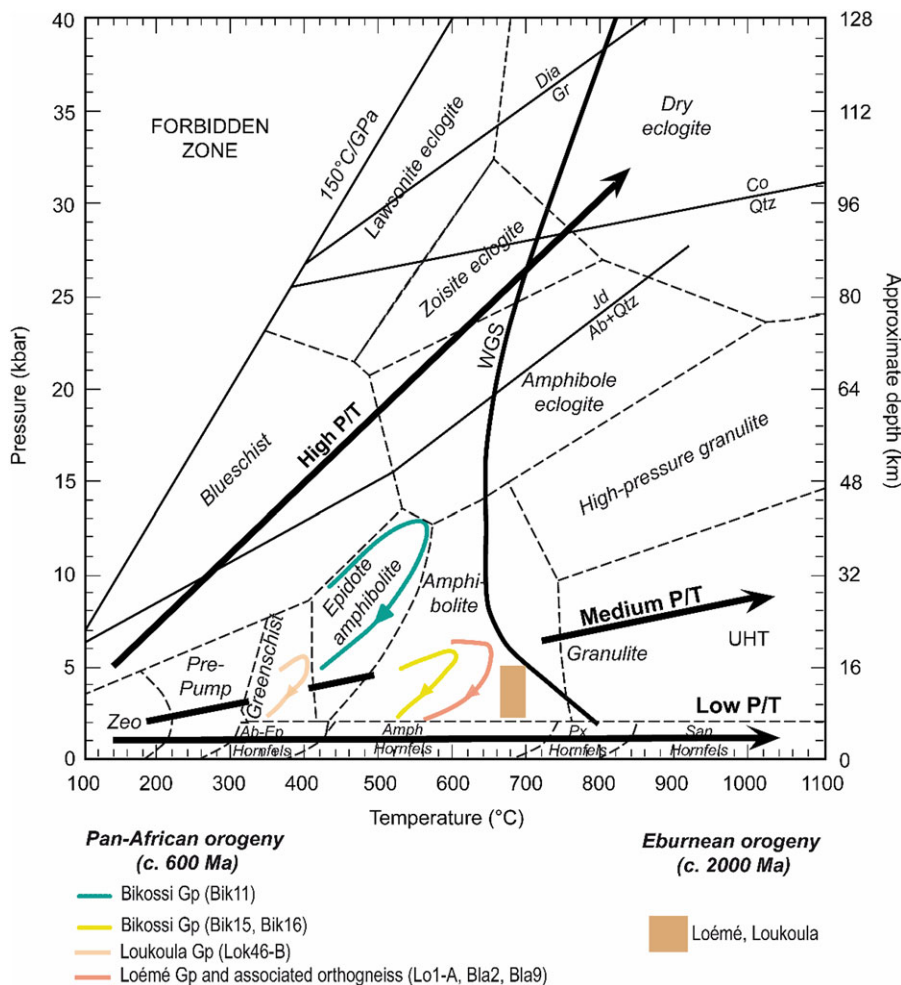


Figure 10. (Colour online) P-T history of the studied samples showing the difference of metamorphic grade across the Mayombe chain (Loémé, Loukoula, Bikossi Groups) during the Eburnean and Pan-African tectono-metamorphic events.

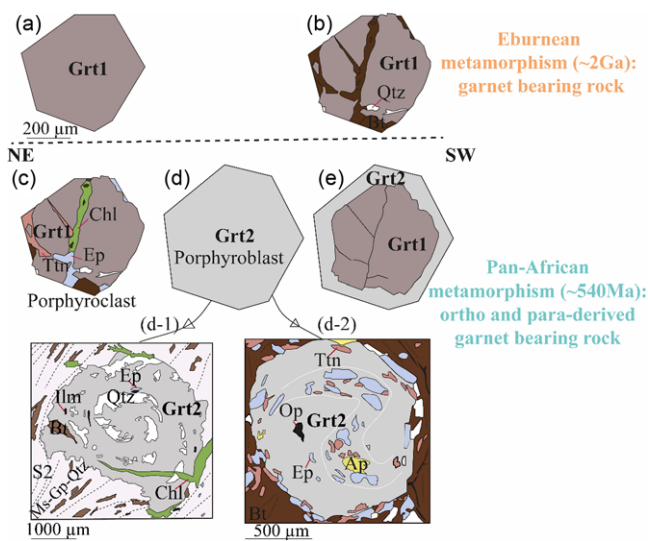


Figure 11. (Colour online) Schematic evolution of garnet crystals during Eburnean and Pan-African orogeny. *Eburnean context:* (a) and (b) represent the first setting of garnet Grt1 with (a) which correspond to the nucleation of garnet and (b) the relic texture of garnet marked by fracturation and partial dissolution during Eburnean event affecting rocks from Mayombe chain basement, including Loémé and Loukoula groups. *Pan-African context:* Eburnean porphyroclastic garnet obtain on stage (b) are partly replaced by chlorite in the Loukoula Group located to the north-east (c) and have been overprinted by newly formed garnet Grt2 in the Loémé Group located to the south-west (e). Neoblasts of garnet Grt2 (d) are generated during the Pan-African event in the Bikossi Schist (d-1) and in the Bilala Gneiss (d-2).

(11.5–12.5 kbar). This range of pressure is also found on the Brazilian side of the orogenic system (Faleiros *et al.* 2011), where it can be associated with high temperatures that give rise to high-pressure granulites that are interpreted as rocks formed as a result of short-lived tectonic events that led to crustal thickening or subduction of the crust into the mantle (O'Brien & Rötzler, 2003). The very well-preserved prograde zoning patterns in garnet may also be a feature of the short-lived tectonics (O'Brien & Rötzler, 2003). Monié *et al.* (2012) have provided evidence for partial melting in northwestern Angola and Nsungani (2012) obtained P - T conditions ranging between 7–12 kbar and 620°C–780°C from garnet–kyanite–biotite–plagioclase–quartz–rutile bearing gneiss. The presence of kyanite even if rutile, indicates a relatively high-pressure environment. In all these cases there is the connexion with subduction.

In our area, P estimation is more difficult, as usual, and relies on the presence of ilmenite and lack of rutile in the sample, and on the composition of muscovite, suggesting relatively high values (c. 12 kbar). Following peak P - T conditions, the decompression occurred without significant T increase, allowing the preservation of the syn-kinematic assemblages developed at the end of garnet growth. For example, exhumation of sample Bik11 has taken place in the Grt-Cld-Chl stability field, defining clockwise P - T loop. The absence of some minerals index of high P/T environment, such as carpholite and paragonite leads to the consideration of the epidote amphibolite facies that gives the medium P/T environment which is likely compatible with the collisional setting in the West Congo Belt during the Pan-African orogeny. However, we point out that the tectonic setting for reaching these P - T conditions is still not well understood. We also acknowledge that these data raise the question of how the metamorphic grade evolved in the West Congo Belt from the south to the north.

5.c. Large-scale zonation of the metamorphism in the West Congo Belt

The Pan-African West Congo Belt displays consistent metamorphic zonation perpendicular to the axis of the orogen, if Eburnean parageneses are identified correctly and subtracted from the Pan-African event.

In the Congo-Brazzaville (this study), the above distinction of polycyclic and monocyclic units and their attribution to Eburnean and Pan-African events is consistent with the available U–Pb dating of zircon (Djama, 1988; Djama *et al.* 1992; Maurin *et al.* 1991; Fullgraf *et al.* 2015b; Affaton *et al.* 2016; Bouenitela, 2019) and $^{40}\text{Ar}/^{39}\text{Ar}$ dating of micas and amphibole, revealing the existence of Paleoproterozoic (2000 Ma) and late Neoproterozoic (540 Ma) tectono-metamorphic events. According to the structural analyses in the Mayombe chain, most authors concluded that the Eburnean basement was reworked during the Pan-African episode (Hossié, 1980; Boudzoumou & Trompette, 1988; Djama, 1988; Maurin *et al.* 1991; Djama *et al.* 1992; Affaton *et al.* 2016). However, Fullgraf *et al.* (2015b) highlighted pre-Eburnean and syn-Eburnean metamorphic episodes in the Loémé Supergroup.

In Gabon Thiéblemont *et al.* (2009) show a polyphase evolution of the Ogooué complex marked by two Paleoproterozoic metamorphic events related to the pre- and syn-Eburnean orogeny setting and displays respectively, meso- to catazonal grade and epito- anchizonal grade. Thus, the polycyclic garnet observed in the Loémé Group can be limited just to the Eburnean context. However, the geochemical characteristics of the metatonalites of the Bilinga suite (Fullgraf *et al.* 2015b) establish their emplacement in a syn to post-orogenic setting, which therefore constrain them to a single pre-Pan-African metamorphic event. The absence of xenocrysts features on these garnets supports this assertion.

In NW and SW Angola, syn and post-Eburnean metamorphic crust has been later reworked during the Pan-African orogeny (Pereira *et al.* 2011; Monié *et al.* 2012). The NW domain as southern part of West Congo Belt displays upper amphibolites facies with evidence of migmatization dated by U–Pb on zircon method at 544 ± 14 Ma (Monié *et al.* 2012). These data suggest that Pan-African orogeny occurs with high-intensity induced overgrowth of zircon in NW Angola and garnet in Mayombe chain.

In Brazil, the counterpart of the West Congo belt is the Araçuaí fold belt which contains the Espinhaço Supergroup consisting of Palaeo- and Mesoproterozoic formations (Alkmim *et al.* 2006). In Brazil, all units older than 1.8 Ga are considered basement of the Araçuaí orogen (de Almeida *et al.* 1981). These units are similar of those of Loukoula, Loémé and Bikossi in Mayombe chain. Alkmim & Marshak (1998) mentioned severe overprint of Brasiliano tectonism on Transamazonian terranes of southeast São Francisco craton. Based on the U–Pb SHRIMP dating, da Silva *et al.* (2000) suggest a Neoproterozoic overprint in Paleoproterozoic orthogneiss in southern Brazil related to the Brasiliano orogeny.

Our petrological data indicates that the Loémé Group displays evidence of multistage garnet, clear evidence in favour of a Pan-African reworking of the Eburnean basement (Fig. 11–12).

5.d. Implications for tectono-stratigraphic reconstruction

Examination of garnet texture and chemical zoning has led to generate new knowledge on the metamorphic evolution of the Paleoproterozoic basement rocks in the Mayombe chain. This can be used as a tool to improve existing geological model of the Mayombe chain (Fig.13) and permits a re-evaluation of the tectono-stratigraphic relationship between these Paleoproterozoic

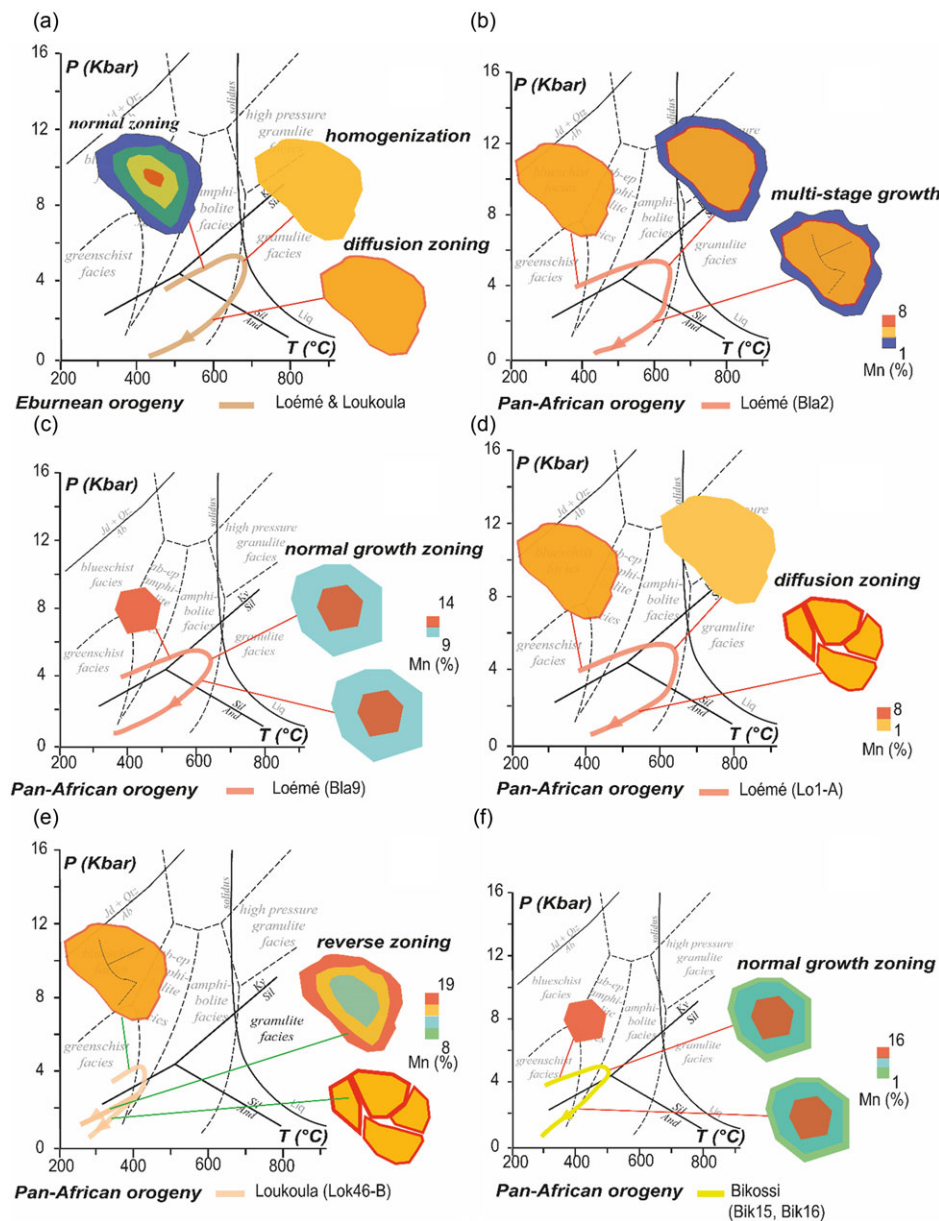


Figure 12. (Colour online) Schematic evolution of garnet crystals during Eburnean and Pan-African orogenies with P-T path in Loémé, Loukoula and Bikossi Groups. Evidence of growth zoning, diffusion zoning (homogenization, reverse zoning) and multi-stage growth.

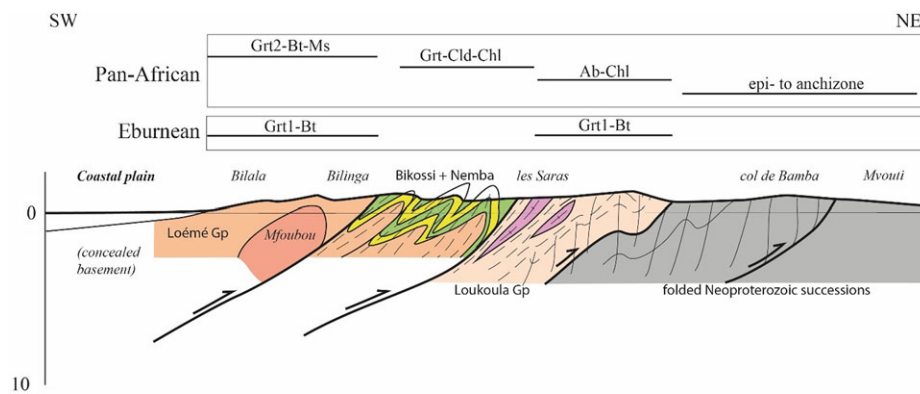


Figure 13. (Colour online) Simplified cross-section of the studied area. The insets on top of the cross-section show the mineral assemblages observed both in the polycyclic (Loémé and Loukoula) and monocyclic units (Bikossi, Nemba); see text for further details on garnet texture and chemistry.

basement rocks and the overlying early Neoproterozoic units cross the Western Domain that remains a matter of interpretation. It is argued that Paleoproterozoic high-grade gneisses of Loémé and

Loukoula groups represent the remnant of Eburnean terranes and experienced at least two distinct metamorphic events which are response of the Eburnean and Pan-African collisional orogenies as

previously recognized (Fullgraf *et al.* 2015b). However, the present study shows that the metamorphic rocks of the Bikossi Group underwent a quite distinct metamorphic evolution of the rest of the Paleoproterozoic basement units. In contrast to the Loémé and Loukoula groups, the metasedimentary rocks from Bikossi Group record a single amphibolite to transitional metamorphic event of Pan-African age implying that it does not record Eburnean metamorphism. In the light of these new petrological data, the authors' previous interpretations regarding tectono-metamorphic history of the Bikossi Group (Fullgraf *et al.* 2015b) can be reviewed. Thus, the Bikossi Group is more correctly interpreted as a cover sequence to older gneisses of the Loémé Supergroup metamorphosed to amphibolite facies during the Pan-African orogeny. These contradictory interpretations have significant implications for defining the structural and stratigraphic relationships between the metasedimentary rocks of the Bikossi Group with the overlying metabasites of the Nemba Complex (Fig. 13) which stills poorly documented and a matter of debate due to limited detailed field investigations and petrochronologic studies. Until recently both of metasedimentary rocks of Bikossi and metabasites of the Nemba Complex have been identified as one single lithological unit of upper-Precambrian age (Dadet, 1969; Vellutini *et al.* 1983) that unconformably overlies the Paleoproterozoic polycyclic basement rocks (i.e. the Loukoula and Loémé Groups). On the other hand, a recent proposal would be to dissociate the Bikossi Group from the Nemba Complex (Fullgraf *et al.* 2015b), considering the former as Paleoproterozoic in age, and the latter as the lower part of the Neoproterozoic Sounda Group. In this hypothesis, the metavolcanic rocks from the Nemba Complex may be the equivalent, in composition and age, of the Gangila meta-basalts from the Zadinian Group in the DRC (Tack *et al.* 2001; Fullgraf *et al.* 2015b). Arising from this study, evidence of one episode of metamorphism in Bikossi Group and Nemba Complex cannot agree with their dissociation as previously thought. In spite of the substantive progress made in reconstructing the metamorphic evolution of lithological units within the Western Domain of the Mayombe chain, the geological setting of the Bikossi Group, as well as its tectonic and stratigraphic interpretations, remains uncertain (Fullgraf *et al.* 2015b). Therefore, more detailed mapping, structural analysis, and petrochronologic studies are needed to unravel the stratigraphic complexity in Western Domain of the Mayombe chain.

6. Conclusions

Within the Western Domain of the Mayombe chain, geochronological data have unambiguously confirmed the occurrence of the Paleoproterozoic polycyclic basement. This study has used garnet texture and chemistry as a proxy to characterize ancient Eburnean assemblages and to evaluate their Pan-African overprint.

The main conclusions are as follows:

1. Normal growth zoning of garnets in rocks of the Bikossi Group indicates only one metamorphic event with peak P - T conditions reaching epidote-amphibolite facies (garnet-chloritoid-chlorite or garnet-biotite assemblages).
2. Some of Paleoproterozoic rocks from the Loukoula Group display an early garnet-bearing paragenesis, which is largely overprinted during a greenschist-facies episode. Given the homogeneous composition of the first garnet generation, indicative of a high- T event, these are interpreted as Eburnean relics overprinted at relatively low- T during the Pan-African event
3. In contrast, the Paleoproterozoic basement of the Loémé Group displays evidence for a multistage history, with a first (Eburnean) garnet generation overgrown during a second (Pan-African) metamorphic episode, at a higher T than in the Loukoula Group (i.e. in the garnet-biotite stability field).

These observations are consistent with an overall SW-ward increase in metamorphic grade during the Pan-African orogeny, whether it reworked the Paleoproterozoic basement (which is therefore polycyclic) or rocks that have never seen before any metamorphism (like the monocyclic Bikossi Group). This pattern of metamorphism is similar to what has been described in other segments of the West Congo-Araçuaí Belt.

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References

- Affaton P, Kalsbeek F, Boudzoumou F, Trompette R, Thrane K and Frei R (2016) The Pan-African West Congo belt in the Republic of Congo (Congo Brazzaville): stratigraphy of the Mayombe and West Congo Supergroups studied by detrital zircon geochronology. *Precambrian Research* **272**, 185–202.
- Ague JJ and Carlson WD (2013) Metamorphism as garnet sees it: the kinetics of nucleation and growth, equilibration, and diffusional relaxation. *Elements* **9**, 439–445.
- Alkmim FF and Marshak S (1998) Transamazonian Orogeny in the Southern São Francisco Craton Region, Minas Gerais, Brazil: evidence for Paleoproterozoic collision and collapse in the Quadrilátero Ferrífero. *Precambrian Research* **90**, 29–58.
- Alkmim FF, Marshak S, Pedrosa-Soares AC, Peres GG, Cruz SCP and Whittington A (2006) Kinematic evolution of the Araçuaí-West Congo orogen in Brazil and Africa: Nutcracker tectonics during the Neoproterozoic assembly of Gondwana. *Precambrian Research* **149**, 43–64.
- Andersen TB (1984) Inclusion patterns in zoned garnets from Magerøy, north Norway. *Mineralogical Magazine* **48**, 21–26.
- Anderson DE and Buckley GR (1973) Zoning in garnets? Diffusion models. *Contributions to Mineralogy and Petrology* **40**, 87–104.
- Atherton MP and Edmunds WM (1966) An electron microprobe study of some zoned garnets from metamorphic rocks. *Earth and Planetary Science Letters* **1**, 185–193.
- Azor A and Ballèvre M (1997) Low-Pressure Metamorphism in the Sierra Albarrana Area (Variscan Belt, Iberian Massif). *Journal of Petrology* **38**, 35–64.
- Barbosa JSF and Sabaté P (2004) Archean and Paleoproterozoic crust of the São Francisco Craton, Bahia, Brazil: geodynamic features. *Precambrian Research* **133**, 1–27.
- Baxter EF, Caddick MJ and Dragovic B (2017) Garnet: a rock-forming mineral petrochronometer. *Reviews in Mineralogy and Geochemistry* **83**, 469–533.
- Bazika UVM, Bouénitéla VTT, Lekeba NM and Boudzoumou F (2022) Petrology and Geochemistry of Loukounga Metabasites Rocks: Constraining the Geodynamic Context of Neoproterozoic Nemba Complex in the Mayombe Belt. *Open Journal of Geology* **12**, 919–946.

- Boudzoumou F** (1986) *La chaîne ouest-congolienne et son avant-pays au Congo : relations avec le mayombien : sédimentologie des séquences d'âge protérozoïque supérieur*. 3e cycle. France: Université d'Aix-Marseille, 220p. Published thesis.
- Boudzoumou F and Trompette R** (1988) La chaîne panafricaine ouest-congolienne au Congo (Afrique équatoriale); un socle polycyclique charrie sur un domaine subautochtone forme par l'aulacogène du Mayombe et le bassin de l'Ouest-Congo. *Bulletin de la Société Géologique de France* **IV**, 889–896.
- Bouenitela VTT** (2019) *Le domaine paléoprotérozoïque (éburnéen) de la chaîne du Mayombe (Congo-Brazzaville) : origine et évolution tectono-métamorphique*. Thèse de doctorat, France: Université de Rennes 1, 448p. Published thesis.
- Brown EH** (1969) Some zoned garnets from the greenschist facies. *American Mineralogist* **54**, 1662–1667.
- Burton KW** (1986) Garnet-quartz intergrowths in graphitic pelites: the role of the fluid phase. *Mineralogical Magazine* **50**, 611–620.
- Caddick MJ, Konopásek J and Thompson AB** (2010) Preservation of garnet growth zoning and the duration of prograde metamorphism. *Journal of Petrology* **51**, 2327–2347.
- Cahen L** (1982) Geochronological correlation of the late Precambrian sequences on and around the stable zones of equatorial Africa. *Precambrian Research* **18**, 73–86.
- Callec Y, Lasseur E, Gouin J, Paquet F, Le Bayon B, Thiéblemont D, Fullgraf T, Le Metour J, Delhaye-Prat V, Giresse P, Malounguila D and Boudzoumou F** (2015a) Carte géologique de la République du Congo à 1/200 000, feuille Pointe-noire. Editions BRGM.
- Callec Y, Lasseur E, Le Bayon B, Thiéblemont D, Fullgraf T, Gouin J, Paquet F, Le Metour J, Delhaye-Prat V, Giresse P, Malounguila D and Boudzoumou F** (2015b) Notice explicative de la carte géologique de la République du Congo à 1/200 000, Feuille Pointe-Noire. Editions BRGM, 216 p.
- Carignan J, Hild P, Mevelle G, Morel J and Yeghicheyan D** (2001) Routine analyses of trace elements in geological samples using flow injection and low pressure on-line liquid chromatography coupled to ICP-MS: a study of geochemical reference materials BR, DR-N, UB-N, AN-G and GH. *Geostandards Newsletter* **25**, 187–198.
- Castellanos O, Rios C and Takasu A** (2004) Chemically sector-zoned garnets in the metapelitic rocks of the Silgará Formation in the central Santander Massif, colombian andes: occurrence and growth history. *Boletín de Geología* **26**, 9–18.
- Castellanos Alarcón OM, Ríos Reyes CA and Chacón Avila CA** (2016) Occurrence and growth history of texturally sector- and sigmoidal-zoned garnet in the San Lorenzo schists in the Sierra Nevada de Santa Maria massif (Colombia). *Boletín de Geología* **38**(3), 71–88.
- Chemale F, Mallmann G, Bitencourt MDF and Kawashita, K** (2012) Time constraints on magmatism along the Major Gercino Shear Zone, southern Brazil: implications for West Gondwana reconstruction. *Gondwana Research* **22**, 184–199.
- Cygan RT and Lasaga AC** (1982) Crystal growth and the formation of chemical zoning in garnets. *Contributions to Mineralogy and Petrology* **79**, 187–200.
- da Silva LC, Hartmann LA, McNaughton NJ and Fletcher I** (2000) Zircon U-Pb SHRIMP dating of a Neoproterozoic overprint in Paleoproterozoic granitic-gneissic terranes, southern Brazil. *American Mineralogist* **85**, 649–667.
- Dadet P** (1969) Notice explicative de la carte géologique de la République du Congo Brazzaville au 1/500 000e (zone comprise entre les parallèles 2° et 5° sud). *Mémoires du BRGM* **70**, 107.
- de Almeida FFM, Hasui Y, de Brito Neves BB and Fuck RA** (1981) Brazilian structural provinces: An introduction. *Earth-Science Reviews* **17**, 1–29.
- De Capitani C and Petrakakis K** (2010) The computation of equilibrium assemblage diagrams with Theriak/Domino software. *American Mineralogist* **95**, 1006–1016.
- De Waele B, Johnson SP and Pisarevsky SA** (2008) Palaeoproterozoic to Neoproterozoic growth and evolution of the eastern Congo Craton: Its role in the Rodinia puzzle. *Precambrian Research* **160**, 127–141.
- Dempster TJ** (1985) Garnet zoning and metamorphism of the Barrovian type area, Scotland. *Contributions to Mineralogy and Petrology* **89**, 30–38.
- Dévigne J-P** (1959) *Le précambrien du Gabon occidental en Afrique équatoriale française et régions limitrophes*. Thèse de doctorat. Université de Clermont-Ferrand, 315p. Published thesis.
- Dickenson MP and Hewitt DA** (1986) A garnet-chlorite geothermometer. *Geological Society of America, Abstracts with programs* **18**, 584.
- Djama L-M** (1988) *Le massif granitique de Mfoubou et le socle métamorphique de Guena (chaîne du Mayombe, Congo)*. *Pétrologie - Géochimie - géochronologie*. Thèse de doctorat. Nancy 1, 175p. Published thesis.
- Djama LM, Leterrier J and Michard A** (1992) Pb, Sr and Nd isotope study of the basement of the Mayumbian belt (Guena gneisses and Mfoubou granite, Congo): implications for crustal evolution in Central Africa. *Journal of African Earth Sciences (and the Middle East)* **14**, 227–237.
- Djama LMJ, Matiaba Bazika UV, Boudzoumou F and Mouzeo K** (2018) Petrology and geodynamic context of metabasic rocks of Nemba complex in the West Congo Fold Belt (Republic of Congo). *International Journal of Geosciences* **09**, 1–18.
- Du Bray EA** (1988) Garnet compositions — and their use as indicators of peraluminous granitoid petrogenesis — southeastern Arabian Shield. *Contributions to Mineralogy and Petrology* **100**, 205–212.
- Enami M, Nagaya T and Win MM** (2017) An integrated EPMA-EBSD study of metamorphic histories recorded in garnet. *American Mineralogist* **102**, 192–204.
- Faleiros FM, Campanha GA, Martins L, Vlach SRF and Vasconcelos PM** (2011) Ediacaran high-pressure collision metamorphism and tectonics of the southern Ribeira Belt (SE Brazil): Evidence for terrane accretion and dispersion during Gondwana assembly. *Precambrian Research* **189**, 263–291.
- Feybesse JL, Johan V, Triboulet C, Guerrot C, Mayaga-Mikolo F, Bouchot V and Eko N'dong J** (1998) The West Central African belt: a model of 2.5–2.0 Ga accretion and two-phase orogenic evolution. *Precambrian Research* **87**, 161–216.
- Fossen H, Cavalcante C, Konopásek J, Meira VT, De Almeida RP, Hollanda MHB and Trompette R** (2020) A critical discussion of the subduction-collision model for the Neoproterozoic Araçuaí-West Congo orogen. *Precambrian Research* **343**, 105715.
- Fullgraf T, Callec Y, Gloaguen E, Thiéblemont D, Le Metour J, Boudzoumou F, Delhaye-Prat V, Kebi-Tsoumou S and Ndiele B** (2015a) Carte géologique de la République du Congo à 1/200 000, Feuille Dolisie. Editions BRGM.
- Fullgraf T, Callec Y, Thiéblemont D, Gloaguen E, Charles N, Le Metour J, Prian J-P, Boudzoumou F, Delhaye-Prat V, Moreau F, Kebi-Tsoumou S and Ndiele B** (2015b) Notice explicative de la carte géologique à 1/200 000 feuille Dolisie. Editions BRGM, 331 p.
- Gaidies F, Abart R, De Capitani C, Schuster R, Connolly JAD and Reusser E** (2006) Characterization of polymetamorphism in the Austroalpine basement east of the Tauern Window using garnet isopleth thermobarometry. *Journal of Metamorphic Geology* **24**, 451–475.
- Gaucher C, Frimmel HE and Germs GJB** (2009) Chapter 8 Tectonic Events and Palaeogeographic Evolution of Southwestern Gondwana in the Neoproterozoic and Cambrian. In *Developments in Precambrian Geology* (eds C. Gaucher, A. N. Sial, H. E. Frimmel and G. P. Halverson), pp. 295–316. Neoproterozoic-Cambrian Tectonics, Global Change And Evolution: A Focus On South Western Gondwana, Elsevier.
- Grambling JA** (1990) Internally-consistent geothermometry and H₂O barometry in metamorphic rocks: the example garnet-chlorite-quartz. *Contributions to Mineralogy and Petrology* **105**, 617–628.
- Gray DR, Foster DA, Meert JG, Goscombe BD, Armstrong R, Trouw RAJ and Passchier CW** (2008) A Damara orogen perspective on the assembly of southwestern Gondwana. *Geological Society, London, Special Publications* **294**, 257–278.
- Harte B and Hudson NFC** (1979) Pelite facies series and the temperatures and pressures of Dalradian metamorphism in E Scotland. *Geological Society, London, Special Publications* **8**, 323–337.
- Heilbron M, Valeriano CM, Tassinari CCG, Almeida J, Tupinambá M, Siga O and Trouw R** (2008) Correlation of Neoproterozoic terranes between the Ribeira Belt, SE Brazil and its African counterpart: comparative tectonic evolution and open questions. *Geological Society, London, Special Publications* **294**, 211–237.

- Henry DJ, Guidotti CV and Thomson JA (2005) The Ti-saturation surface for low-to-medium pressure metapelitic biotites: Implications for geothermometry and Ti-substitution mechanisms. *American Mineralogist* **90**, 316–328.
- Hensen B (1971) Theoretical phase relations involving garnet and cordierite in the system MgO–FeO–Al₂O₃–SiO₂. *Contributions to Mineralogy and Petrology* **33**, 191–214.
- Hollister LS (1966) Garnet Zoning: An Interpretation Based on the Rayleigh Fractionation Model. *Science, New Series* **154**, 1647–1651.
- Hossié G (1980) *Contribution à l'étude structurale de la Chaîne Ouest-Congolienne (Pan-Africaine) dans le Mayombe congolais*. Thèse 3e cycle. France: Université des Sciences et Techniques du Languedoc, Montpellier, 124p. Published thesis.
- Kerr A (1981) Zoning in garnets from the mainland Lewisian. *Mineralogical Magazine* **44**, 191–194.
- Kleinschmidt G, Heberer B and Läufer AL (2008) Pre-Alpine sector-zoned garnets in the southeastern Alps. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften* **159**, 565–573.
- Kohn MJ (2005) Geochemical zoning in metamorphic minerals. In *The Crust*, pp. 229–261. Rudnick R.L.
- Kretz R (1983) Symbols for rock-forming minerals. *American Mineralogist* **68**, 277–279.
- Kröner A and Stern RJ (2005) AFRICA | Pan-African Orogeny. In *Encyclopedia of Geology* (eds R. C. Selley, L. R. M. Cocks and I. R. Plimer), pp. 1–12., Oxford: Elsevier.
- Kuchenbecker M and Barbuena D (2023) Basement inliers of the Araçuaí-West Congo orogen: key pieces for understanding the evolution of the São Francisco-Congo paleocontinent. *Journal of South American Earth Sciences* **125**, 104299.
- Laird J (1988) Chlorites; metamorphic petrology. *Reviews in Mineralogy and Geochemistry* **19**, 405–453.
- Le Bayon B, Callec Y, Fullgraf T, Lasseur E, Thiéblemont D, Charles N, Gloaguen E, Paquet F, Gouin J, Giresse P, Makolobongo B, Obambi U, Mouloundou Niangui E and Miassouka Mpika R (2015b) Notice explicative de la carte géologique de la République du Congo à 1/200 000, feuille Conkouati. *Editions BRGM*, 242 p.
- Le Bayon B, Callec Y, Lasseur E, Thiéblemont D, Paquet F, Gouin J, Giresse P, Makolobongo B, Obambi U, Mouloundou Niangui E and Miassouka Mpika R (2015a) Carte géologique de la République du Congo à 1/200 000, feuille Conkouati. Editions BRGM.
- Le Bayon B, Pitra P, Balleuvre M and Bohn M (2006) Reconstructing P–T paths during continental collision using multi-stage garnet (Gran Paradiso nappe, Western Alps). *Journal of Metamorphic Geology* **24**, 477–496.
- Ledru P, Johan V, Milési JP and Tegye M (1994) Markers of the last stages of the Palaeoproterozoic collision: evidence for a 2 Ga continent involving circum-South Atlantic provinces. *Precambrian Research* **69**, 169–191.
- Lerouge C, Cocherie A, Toteu SF, Penaye J, Milési J-P, Tchameni R, Nsifa EN, Mark Fanning C and Deloule E (2006) Shrimp U–Pb zircon age evidence for Paleoproterozoic sedimentation and 2.05 Ga syntectonic plutonism in the Nyong Group, South-Western Cameroon: consequences for the Eburnean–Transamazonian belt of NE Brazil and Central Africa. *Journal of African Earth Sciences* **44**, 413–427.
- Manzotti P and Balleuvre M (2013) Multistage garnet in high-pressure metasediments: Alpine overgrowths on Variscan detrital grains. *Geology* **41**, 1151–1154.
- Matiaba-Bazika UV, Makamba NL, Bouénitéla VTT, Tchiguina NCB, Miyouna T and Boudzoumou F (2024) Geochemical and petrological insights into the neoproterozoic moubamba metabasites: implications for crustal processes in the West Congo Belt (Republic of Congo). *Journal of Geoscience and Environment Protection* **12**, 1–29.
- Maurin C, Boudzoumou F, Djama L-M, Gioan P, Michard A, Mpemba Boni J, Peucat JJ, Pin C and Vicat J-P (1991) La chaîne protérozoïque ouest-congolienne et son avantpays au Congo: Nouvelles données géochronologiques et structurales, implications en Afrique centrale. *Comptes Rendus de l'Académie des Sciences* **312**, 1327–1334.
- Maurin JC (1993) La chaîne panafricaine ouest-congolienne : corrélation avec le domaine est-brésilien et hypothèse géodynamique. *Bulletin de la Société Géologique de France* **164**, 51–60.
- Maurin JC, Mpemba Boni J, Pin C and Vicat J-P (1990) La granodiorite de Les Saras, un témoin de magmatisme éburnéen (2 Ga.) au sein de la chaîne ouest-congolienne : conséquences géodynamiques. *Comptes Rendus - Académie des Sciences, Serie II* **310**, 571–575.
- Mfere APA, Delpomdor F, Proust J-N, Boudzoumou F, Callec Y and Prétat A (2020) Facies and architecture of the SCIC formation (Schisto-Calcaire Group), Republic of the Congo, in the Niari-Nyanga and Comba subbasins of the neoproterozoic west Congo basin after the marinoan glaciation event. *Journal of African Earth Sciences* **166**, 103776.
- Monié P, Bosch D, Bruguier O, Vauchez A, Rolland Y, Nsungani P and Buta Neto A (2012) The Late Neoproterozoic/Early Palaeozoic evolution of the West Congo Belt of NW Angola: geochronological (U–Pb and Ar–Ar) and petrostructural constraints. *Terra Nova* **24**, 238–247.
- Mpemba Boni J (1990) Contribution à l'étude du magmatisme anté-pan africain de la chaîne du Mayombe. L'exemple du Massif de Les Saras (SW du Congo, Afrique Centrale). *Pétrologie structurale - Géochimie - Géochronologie*. France: Université de Nancy, 351p. Published thesis.
- Noce CM, Pedrosa-Soares AC, Da Silva LC, Armstrong R and Piuzana D (2007) Evolution of polycyclic basement complexes in the Araçuaí Orogen, based on U–Pb SHRIMP data: Implications for Brazil–Africa links in Paleoproterozoic time. *Precambrian Research* **159**, 60–78.
- Nsungani PC (2012) *La chaîne panafricaine du Nord-Ouest de l'Angola : Etude pétrostructurale, géochimique et géochronologique. Implications géodynamiques*. France: Université de Montpellier II, 328p. Published thesis.
- O'Brien PJ and Rötzler J (2003) High-pressure granulites: formation, recovery of peak conditions and implications for tectonics. *Journal of Metamorphic Geology* **21**, 3–20.
- Pedrosa-Soares AC, Alkmim FF, Tack L, Noce CM, Babinski M, Silva LC and Martins-Neto MA (2008) Similarities and differences between the Brazilian and African counterparts of the Neoproterozoic Araçuaí-West Congo orogen. *Geological Society, London, Special Publications* **294**, 153–172.
- Perchuk LL (1991) Derivation of a thermodynamically consistent set of geothermometers and geobarometers for metamorphic and magmatic rocks. In *Progress in Metamorphic and Magmatic Petrology: A Memorial Volume in Honour of D. S. Korzhinskiy* (ed L. L. Perchuk), pp. 93–112. Cambridge: Cambridge University Press.
- Pereira E, Tassinari CCG, Rodrigues JF and Van-Dúnem MV (2011) New data on the deposition age of the volcano-sedimentary Chela Group and its Eburnean basement: implications to post- Eburnean crustal evolution of the SW of Angola. *Comunicações Geológicas* **98**, 29–40.
- Porada H (1989) Pan-African rifting and orogenesis in southern to equatorial Africa and eastern Brazil. *Precambrian Research* **44**, 103–136.
- Powell R and Holland T (1990) Calculated mineral equilibria in the pelite system, KFMASH (K₂O–FeO–MgO–Al₂O₃–SiO₂–H₂O). *American Mineralogist* **75**, 367–380.
- Rapela CW, Pankhurst RJ, Casquet C, Fanning CM, Baldo EG, González-Casado JM, Galindo C and Dahlquist J (2007) The Río de la Plata craton and the assembly of SW Gondwana. *Earth-Science Reviews* **83**, 49–82.
- Rice AHN and Mitchell JI (1991) Porphyroblast textural sector-zoning and matrix displacement. *Mineralogical Magazine* **55**, 379–396.
- Ruiz JL (1976) The zoning of garnets as an indicator of the P.T. history of their host-rocks. *Annales de la Société géologique de Belgique* **99**, 337–346.
- Schannor M, Lana C, Nicoli G, Cutts K, Buick I, Gerdes A and Hecht L (2021) Reconstructing the metamorphic evolution of the Araçuaí orogen (SE Brazil) using in situ U–Pb garnet dating and P–T modelling - Schannor - 2021 - Journal of Metamorphic Geology - Wiley Online Library. *Journal of Metamorphic Geology* **39**, 1145–1171.
- Schermerhorn LJJ (1981) The West Congo Orogen: a key to Pan-African thermotectonism. *Geologische Rundschau* **70**, 850–867.
- Schmitt RDS, Fragozo RDA and Collins AS (2018) Sutured Gondwana in the Cambrian: The Orogenic Events of the Final Amalgamation. In *Geology of Southwest Gondwana* (eds S. Siegesmund, M. A. S. Basei, P. Oyahantçabal and S. Oriolo), pp. 411–432. Cham: Springer International Publishing.
- Skrzypiek E, Schulmann K, Štípská P, Chopin F, Lehmann J, Lexa O and Haloda J (2011) Tectono-metamorphic history recorded in garnet porphyroblasts: insights from thermodynamic modelling and electron

- backscatter diffraction analysis of inclusion trails. *Journal of Metamorphic Geology* **29**, 473–496.
- Tack L, Wingate MTD, Liégeois J-P, Fernandez-Alonso M and Deblond A** (2001) Early Neoproterozoic magmatism (1000–910 Ma) of the Zadinian and Mayumbian Groups (Bas-Congo): onset of Rodinia rifting at the western edge of the Congo craton. *Precambrian Research* **110**, 277–306.
- Thiéblemont D.** (edit) *et al.* (2016) Geological Map of Africa at 1:10M scale, CGMW-BRGM.
- Thiéblemont D, Astaïng C, Billa M, Bouton P and Pr  at A** (2009) Notice explicative de la carte g  ologique et des ressources min  rales de la R  publique Gabonaise    1/1 000 000. *Editions DGMG - Minist  re des Mines, du P  trole, des Hydrocarbures*, Libreville, 384 p.
- Tinkham DK, Zuluaga CA and Stowell HH** (2001) Metapelite phase equilibria. *Geological Materials Research* **3**, 1–42.
- Toteu SF, Van Schmus WR, Penaye J and Nyob   JB** (1994) U-Pb and Sm-Nd evidence for Eburnian and Pan-African high-grade metamorphism in cratonic rocks of southern Cameroon. *Precambrian Research* **67**, 321–347.
- Tracy RJ** (1982) Compositional zoning and inclusions in metamorphic minerals. In *Characterization of Metamorphism through Mineral Equilibria* (ed. J. M. Ferry), pp. 354–398. Reviews in mineralogy, De Gruyter.
- Tracy RJ, Robinson P and Thompson AB** (1976) Garnet composition and zoning in the determination of temperature and pressure of metamorphism, central Massachusetts. *American Mineralogist* **61**, 762–775.
- Trompette R** (1997) Neoproterozoic (~600 Ma) aggregation of Western Gondwana: a tentative scenario. *Precambrian Research* **82**, 101–112.
- Tropper P and Recheis A** (2003) Garnet zoning as a window into the metamorphic evolution of crystalline complex: the northern and central Austroalpine   tztal-Complex as a polymorphic example. *Mitteilungen der   sterreichischen Geologischen Gesellschaft* **94**, 27–53.
- Vellutini P, Rocci G and Vicat JP** (1983) Mise en   vidence de complexes ophiolitiques dans la cha  ne du Mayombe (Gabon-Angola) et nouvelle interpr  tation g  otectonique. *Precambrian Research* **22**, 1–21.
- Vicat J-P and Pouclet A** (2000) Pal  o- and Neoproterozoic granitoids and rhyolites from the West Congolian Belt (Gabon, Congo, Cabinda, north Angola): chemical composition and geotectonic implications. *Journal of African Earth Sciences* **31**, 597–617.
- Vicat J-P and Vellutini P** (1987) Sur l'origine oceanique des metabasites de la cha  ne du mayombe (Gabon, Congo, Za  re, Angola). *Precambrian Research* **36**, 163–175.
- Vicat JP and Vellutini PJ** (1988) G  ologie et g  ochimie de la s  rie pr  cambrienne de la Bikossi, le long du r  alignement du chemin de fer congo-oc  an, dans la cha  ne du Mayombe (R  publique populaire du Congo). *Journal of African Earth Sciences (and the Middle East)* **7**, 811–820.
- Vidal O, Goff   B, Bousquet R and Parra T** (1999) Calibration and testing of an empirical chloritoid-chlorite Mg-Fe exchange thermometer and thermodynamic data for daphnite. *Journal of Metamorphic Geology* **17**, 25–39.
- Weber F, Gauthier-Lafaye F, Whitechurch H, Ulrich M and El Albani A** (2016) The 2-Ga Eburnean Orogeny in Gabon and the opening of the Francevillian intracratonic basins: a review. *Comptes Rendus. G  oscience* **348**, 572–586.
- Williams ML and Grambling JA** (1990) Manganese, ferric iron, and the equilibrium between garnet and biotite. *American Mineralogist* **75**, 886–908.
- Woodsworth GJ** (1977) Homogenization of zoned garnets from pelitic schists. *Canadian Mineralogist* **15**, 230–242.
- Yardley BWD** (1977) An empirical study of diffusion in garnet. *American Mineralogist* **62**, 793–800.
- Yardley BWD, Condliffe E, Lloyd GE and Harris DHM** (1996) Polyphase garnets from western Ireland: two-phase intergrowths in the grossular-almandine series. *European Journal of Mineralogy* **8**, 383–392.