Structural Characterization of Outcrop-Scale in Edea and Eseka Area: Evidence for a Complex Polyphase Deformation in the Paleoproterozoic Nyong Serie (Congo craton-South Cameroon)

Ndema Mbongué Jean Lavenir¹, ²*, Sigué Cyrille¹, ², Nzenti Jean Paul¹, and Cheo Emmanuel Suh²

¹(Department of Earth Sciences, Faculty of Sciences / University of Yaoundé I, Cameroon) ²(Department of Geology, Faculty of Sciences / University of Buea, Cameroon)

Abstract: The Edea and Eseka area belongs to the Nyong Series which is the north-western extension of the Congo Craton in Cameroon. Structural analyses were carried out in this region in order to delineate the tectonic evolution. The structures of this area are the result of a complex structural evolution and the area experienced a polyphase deformation resulting to a succession of several phases of deformation. Detailed information on the structures and the relative timing of deformation are as follows: (1) an early stage (pre- D₁) phase corresponds to the relics of an early schistosity preserved as inclusion trails in garnet and pyroxene crystals, immediately followed by (2) two main stages (D₂ and D₃). D₂ evolved in tangential movements, it is typically ductile and characterized by a regional-scale S₂ mylonitic foliation associated with F₂ folds and a sub-horizontal stretching lineation L₂. D₃ is the main deformation phase due to the diversity of its structures. The deformation style of the D₂ phase is heterogeneous affecting the previous D₁ fabric by transposition, and evolved in a trans-current tectonic regime. The late- D₃ deformation phase is underlined by brittle features. At the regional scale, the chronology of the deformaional phases in the Nyong serie is still controversy. The structural evolution of the Nyong serie in Edea and Eseka area has similarities with the Ogooué metamorphics in Gabon and the Trans-Amazonian belt in Northeast Brazil. Therefore the Nyong serie is correlated with the collision belts (Ogooué metamorphics) of about the same age on the eastern margin of the Congo craton and with the Trans-Amazonian Orogenic Belt.

Key words: Edea and Eseka area; Nyong serie; Congo craton; tangential movements; transcurent tectonic regime; Ogooué metamorphic; Trans-Amazonian belt.

I. Introduction and General geology

In central Africa the structural evolution of the continental crust is dominated by several tectonic events: the Archaean orogeny (3.0-2.5 Ga), the Eburnean or Paleoproterozoic orogeny (2.2-1.8 Ga) and the Pan-African orogeny (600-500 Ma). In Cameroon the Paleoproterozoic terrains have been reported mainly in the Ntem complex, and also occur as relics within the Neoproterozoic formations¹. Paleoproterozoic terrains of the Ntem complex in Cameroon are known as Nyong serie ²,³,⁴. The Edea and Eseka area (Fig. 1) is located in this serie within the Congo craton. The North-Western corner of this craton in South Cameroon refers to the Ntem Complex ⁵,⁶, which is bordered in the north by the Yaoundé Group ⁷,⁸,⁹,¹⁰ of the Pan-African orogenic belt in central Africa. The Ntem complex is divided into two main structural units: the Nyong serie, to the northwest end, and the Ntem unit, in the south-central area. The Ntem unit is dominated by massive and banded plutonic rocks of the charnockite suite and by intrusive tonalities, trondhjemites and granodiorites (TTG), dated at 2.9 Ga ²,¹¹,¹².

The Nyong serie in the NW corner of the Congo craton is a well-preserved granulitic unit of the West Central African Belt resting as an Eburnean nappe on the Congo craton ².¹³. The Nyong unit consists of metasedimentary and metavolcanic rocks, syn-to late-tectonic granitoids and syenites ¹⁴,¹⁵. It displays three groups of ages ²,³,¹²,¹⁶: (1) Archaean ages (2500–2900 Ma); (2) Paleoproterozoic (2050 Ma) and (3) Neoproterozoic ages (626 ± 26 Ma). The high-grade metamorphism associated with arrested charnockite formation is dated at 2050 Ma. The recent works of ² indicate in this unit the Paleoproterozoic ages for the granulitic metamorphism ranged between 1734 ± 22 Ma and 1893 ± 43 Ma (Th-U-Pb EMP-dating on monazites), they are interpreted as the ages of the granulitic metamorphism, contemporaneous with the charnockitisation and the emplacement of igneous protoliths. New Pan-African ages for the amphibolitic metamorphic facies have also determined and ranged between 577 ± 2 Ma-677 ± 36 Ma (Th-U-Pb, EMP-dating on monazites). These ages correspond to the melt and the emplacement of the sedimentary protoliths. The Ages
of 1969 ± 170 Ma of charnockites represent the Eburnean cooling \(^{17}\). The Nyong unit includes some Archaean parts of the Ntem complex that were reworked during a Palaeoproterozoic event, and new Palaeoproterozoic material that was accreted to the Archaean craton.

The main structural characteristic of the Nyong series refers to the Kribi-Campo Shear Zone (KCSZ\(^{5,12,13,18}\). The KCSZ is a Precambrian mega dextral shear zone \(^{19,20}\), well studied from Kribi towards the south (Campo). The Edea and Eseka region located in the Nyong serie (western border of Ntem complex in Congo craton) shows very conspicuous and spectacular examples of deformation at the outcrop scale. Therefore this paper presents the structural characteristics of the deformation.

![Figure 1: Geologic map of South-West Cameroon \(^{14,21}\) as modified from\(^{5}\) showing the lithologic units of Ntem Complex or Congo craton in Cameroon and the studied area (Edea and Eseka).](image)

**II. Methods**

The exploration method used in this work is a field survey based on the search and localization of outcrops with the help of the topographic map, and the Global Positioning System (GPS). In order to make this field campaign a successful, we used the following steps: (i) we moved round the study area searching for rock outcrops from which information and structural measurements have been collected, these measurements have been carried out with a compass clinometers and took into consideration the orientations of the structural elements, their extension and the characterization of these elements; (ii) photographs of the outcrops were taken from different angles; (vi) the samples were characterized in situ. In the laboratory the readings of structural measurements have been plotted in the lower hemisphere of Schmidt net using the Stereonet software in order to determine the major directions of structures.
III. Results

III. 1. Brief lithology

Lithologically and according to Ndema Mbongue et al (2014) and Ndema Mbongue (2016), the study area comprises (i) a unit of metaigneous rocks (pyroxene-gneiss, charnockitic gneiss, garnet-charnockitic gneiss, biotite-gneiss, amphibole-biotite gneiss, garnet-amphibole gneiss, pyrōpite, pyrigarnite and garnet-amphibolite), (ii) a metasedimentary rock unit (garnet micaschist mainly and schist) and (ii) the rocks resulting from the melt (they include migmitite and TTG).

Figure 2: Photomacrosgraphs for the structures of $D_1$ phase. (a) Compositional banding. (b) Boudinaged aggregate of quartz showing fault and δ-shaped structures as shear sense indicators. (c) Sigmoid-shaped feldspar with shear sense indicators. (d) Lens-shaped feldspar + quartz crystal showing a symmetric shaped and a quartz-rich tail. (e) $L_1$ stretching lineation. (f) $F_1$ intrafolial fold display axial plane schistosity.

III. 2. Structural analysis

Many structures have been mapped in the basement metamorphic rocks in Edea and Eseka area and chronologically, they have been grouped into an early deformation phase pre-$D_1$ and two (02) main ductile deformation phases termed as $D_1$ and $D_2$. The $D_2$ deformational phase ends with the emplacement of late structures that characterize the late-$D_2$ phase.

III. 2.1. $D_1$ deformation phase

The $D_1$ deformation phase is recorded in pyroxene-gneiss, garnet-charnockitic gneiss, amphibole-biotite gneiss, garnet-amphibole gneiss, pyrōpite and migmitite. It is characterized by: a $S_1$ foliation associated with $L_1$ lineation and the development of $F_1$ folds. The $S_1$ foliation is outlined by (i) a compositional...
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banding (Fig. 2a), the thicknesses of the bands vary from millimeters to centimeters. The light bands contain minerals such as quartz and feldspars while the dark bands are rich in ferromagnesian minerals such as pyroxene, amphibole and biotite; (ii) a mylonitic schistosity S1 is underlined by the preferred orientation of biotite, stretched quartz, boudinaged aggregate of quartz with sigmoid-shaped displaying fault (Fig. 2b), (iii) Large crystals of feldspars displaying sigmoid-shaped (Fig. 2c), and lens-shaped quartz + feldspar crystal showing a symmetric shaped and a quartz-rich tail (Fig. 2d). In the pyrigarnite, pyroxene-gneiss, garnet-charnockitic gneiss, garnet-amphibole and garnet-amphibole gneiss, S1 minerals surround coronitic garnet and pyroxene crystals implying that these garnet and pyroxene are related to pre-D1 phase. The attitude of the foliation is nearly constant in the study area. The foliation surfaces S1 strike NE-SW and have gentle dips (0 to 15°) to the NW and to the SE direction. The poles to S1 show a girdle distribution (Fig. 3) that implies subsequent folding around a gently NNE plunging axis.

The related lineation L1 is conspicuous and corresponds to a stretching lineation (Fig. 2e). It trends NNE-SSW with a gentle plunge (0-10°) towards the NNE/SSW (Fig. 3). F1 folds (Fig. 2f) are mainly upright folds, recumbent folds and intrafolial isoclinal folds, and they display S1 as axial plane schistosity. The average fold axis trend is N25°E plunging between 2-20° in the SW and in the NE (Fig. 3).

**III. 2.2. D2 deformation phase**

This tectonic phase is well-recorded in both the meta-igneous and metasedimentary rock units. It is characterized by a heterogeneous deformation affecting the previous D1 fabric by transposition of S1 foliation. D2 deformation is associated with the development of S2 schistosity, C2 shear planes (Fig.4a), F2 folds (Fig.4b) and β2 Boudins (Fig.4c). The S2 schistosity is an axial plane schistosity for the F2 folds, It is linked to the shear and to the folds. The S2 plane is defined by preferred orientation of quartz ribbons, ferromagnesian lamellae, biotite and muscovite flakes. The attitudes of S2 fabrics were measured and the stereographic projection reveals N100°E to N120°E (Fig.4d) dipping 50-75° toward the NE.

C2 shear planes (Fig.4a) are more abundant, they appear as steep ductile zones that disrupt the S1 foliation and they characterize sinistral and dextral movements. Their dip is no less than 10° and the average orientation is N125°E, 13°NE/SW (Fig.4d). F2 folds admit S2 as axial plane schistosity (Fig.4b); they include flanking folds linked to shear planes and displaying inverted limbs, and upright folds. Folds with inverted limbs are dissymmetric, they consist of western verging folds.

β2 boudins (Fig.4c) include (i) complete boudins made up of quartz and feldspar enveloped by S2 schistosity and displaying pinch and swell structures and (ii) incomplete boudinage made up of mafic minerals. The extensional value of the boudin axes varies between 10 and 48 cm for the long axis (L) and 3 to 4 cm for the short axis (S). L/S ratios ranging between 3/16 and 5/6 suggest flattened boudins of fold axis. The direction of the boudin axes range between N130°E to N-S, plunges are smaller than 20° (Fig.4d). As mentioned above, the D2 deformation ends with the emplacement of late structures that characterize the late- D2 deformational phase.
III. 2.3. The late- $D_2$ deformatonal phase

The late- $D_2$ phase is highlighted by brittle features such as late shear planes $C'_2$, joints $J'_2$ and fractures $F'_2$. Late shear planes $C'_2$ (Fig. 5a) are mapped in pyroxene-gneiss and garnet-charnockitic gneiss. They are outlined by the conjugated late quartzo-feldspathic bands that cross-cut the structures of $D_2$ phase with a gentle angle (sub-parallel or secant to $S_2$). Some measured $C'_2$ planes strike approximately N-S and E-W and dipping 5 to 40°N.

$J'_2$ joints (Fig. 5b) are veins that are filled up with late recrystallization fluids. They are most often grouped into two sets generally oblique displaying rectilinear and parallel edges. The joints developed during the late- $D_2$ phase exhibit an average direction of N18°E and N25°E.

$F'_2$ fractures (Fig. 5c) occur as a result of tensile stress with rupture in the rock without displacement of compartments. They are developed in various directions and reveal two major sets that are obliquely secant. The two sets are sub-vertical to vertical and strike approximately N115°E and N120°E.
IV. Discussion

The Edea and Eseka area in the Nyong serie that is located NW margin in the Congo craton displays a complex and a polyphase structural evolution. This area is overprinted by an earlier pre-D$_1$ phase and two main phases of deformations namely D$_1$ and D$_2$. S$_1$ minerals surround coronitic garnet and pyroxene crystals implying they related to pre-D$_1$. Also S$_1$ surround large lenticular and sigmoid microlithons of quartz and feldspar; lenticular and sigmoid microlithons structures are mostly found in shear zone 22,24,25,26.

D$_1$ deformation phase evolved in a tangential phase regime characterized by a flat or sub-horizontal S$_1$ mylonitic foliation, associated with a stretching sub-horizontal lineation and F$_1$ folding (upright, recumbent and intrafolial isoclinal folds). These characteristics also testify according to 27 to a thickening stage of D$_1$. S$_1$ foliation is dipping oppositely to the NW and to the SE and the attitude is nearly constant in the study area. The mylonitic foliation corresponds to the regional-scale foliation S$_1$ in the study area and in the entire Nyong serie. D$_1$ phase is responsible of the nappe stacking that was emplaced horizontally to form a classical fold-and-thrust belt 28. The nappe vergence in Edea and Eseka area, deduce from transport direction toward the East, is different to that observed in Pan-African belt 29,30. D$_1$ fabric has been progressively overprinted by D$_2$ deformation.

The D$_2$ tectonic phase is the main tectonic phase in the study area. It is characterized by a diversity of structural elements: (1) axial plane schistosity S$_2$ associated (3) with F$_2$ folds with different morphology; (4) abundant C$_2$ shear planes and (5) boudinage $\beta_2$. These structures result from a heterogeneous deformation affecting the previous D$_1$ fabric by transposition of S$_1$ foliation; therefore D$_2$ phase consists of a coaxial and rotational deformation evolved in a trans-current tectonic regime. The coexistence of folding and shearing in the Edea and Eseka area can be understood as the effect of deformation partitioning at mid-crustal depth 31,32. Shear sense indicators are consistently dextral and sinistral and the D$_1$ and D$_2$ structures testify of a progressive deformation during the activity of a major ductile shear zone 33.

Late- D$_2$ is a phase of brittle tectonic with sub-vertical fractures, regional-scale joints and conjugated shear planes. In the Nyong Serie the Late- D$_2$ is also reported by 1,34,35,36. However this Late- D$_2$ phase has been labeled as D$_3$ phase by 26,37,38. Therefore at the regional scale, the chronology of the deformational phases in the Nyong serie is still controversy.

The Nyong serie in Edea and Eseka area whose structural evolution is polyphase and complex has structurally similarities with the Ogooué metamorphics 39 in Gabon and the Trans-Amazonian belt 40,41 in Northeast Brazil. In the study area, a pre-D$_1$ phase and two main phases of deformation (D$_1$ and D$_2$) have been recorded, and three phases (D$_1$, D$_2$ and D$_3$) in the Ogooué metamorphics and two phases (D$_1$, D$_2$) in the Trans-
Amazonian belt. The pre-D1 phase corresponds to the relics of an early schistosity preserved as inclusion trails in garnet and pyroxene crystals and does not have an equivalent in the Ogooué metamorphics and in the Trans-Amazonian belt. As far as the D1 is concerned, the S1 foliation describes in the Ogooué Series 42,43 and in the Trans-Amazonian belt 44,45 has similarity with the regional-scale mylonitic foliation S1, striking NE-SW reported in Edea and Eseka area. The D2 tectonic phase is the main tectonic phase in all the three Series (Nyong, Ogooué and Trans-Amazonian). It is trans-current and ends with the late structures in Edea and Eseka area; whilst in the Ogooué serie D2 is contemporaneous with the emplacement of the granitic Abamé Dome 42,43. This tangential deformation indicates major crustal shortening in the collisional suture zone (Ledru et al., 1989). In the Trans-Amazonian belt, the second episode (D2) evolved in a transpressional tectonic regime and its deformation geometric pattern is partitioned between a network of NNW-trending folded and steep-dipping oblique to strike-slip sinistral shear zone domains 44,45. The kinematic indicators (S–C structures, asymmetric foliation trajectories and oblique to subhorizontal L2 stretching lineations) outline tectonic transport from ESE toward WNW. In general, the geologic structures describe in the three series correspond to a part of a collisional N–S chain recognized in the Pan-African belt and in the Trans-Amazonian belt 36,47,48,49,50,51. Therefore the Nyong serie is correlated with the collision belts (Ogooué metamorphics) of about the same age on the eastern margin of the Congo craton and with the Trans-Amazonian Orogenic Belt.

V. Conclusion

Field campaigns in Edea and Eseka area show different aspects that took in consideration structural elements at different outcrop scales and the results reveal that the structural evolution is complex and the area experienced a polyphase deformation.

The pre-D1 phase corresponds to the relics of an early schistosity preserved as inclusion trails in garnet and pyroxene crystals. The D1 deformation phase is typically ductile and characterized by: a regional-scale S1 mylonitic foliation showing alternation of parallel compositional bands and lithological units, recumbent and intrafolial isoclinal folds, sub-horizontal stretching lineation, corresponded to tangential movements.

The D2 is the main deformation phase due to their diversity of structural elements. It is linked to the shear and folds; the deformation style of the D2 phase is heterogeneous affecting the previous D1 fabric by transposition. It is characterized by the development of axial plane S2 schistosity, abundant shear planes, upright and flanking folds F2 and boudinage. The D2 deformation phase consists of a coaxial and rotational deformation evolved in a trans-current tectonic regime.

The late- D2 deformation phase underlined by brittle features such as sub-vertical fractures, regional-scale joints and conjugated shear planes. At the regional scale, the chronology of the deformational phases in the Nyong serie is still controversies.

The structural evolution of the Nyong serie in Edea and Eseka area has similarities with the Ogooué metamorphics in Gabon and the Trans-Amazonian belt in Northeast Brazil. Therefore the Nyong serie is correlated with the collision belts (Ogooué metamorphics) of about the same age on the eastern margin of the Congo craton and with the Trans-Amazonian Orogenic Belt.

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