Structural Characterization of Outcrop-Scale Superposed Folding in the Kimbi Area (NW Cameroon): Implications for the Tectonic Evolution of the Pan-African North Equatorial Fold Belt

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Abstract: A study of predominantly folding structures was carried out on a number of outcrops in the Kimbi area. The main aim of this study is to provide a detailed structural characterization of the three folding events (F_1 , F_2 - F_3) recognized in this area, in order to improve our understanding of the deformation mechanisms that controlled the tectonic evolution of the Pan-African North Equatorial Fold belt. The F_1 folding is marked by decimetre-sized isoclinal folds with S_1 schistosity parallel to the axial plane of F_1 folds. The F_2 - F_3 folding is superposed on the F_1 older folds. Geometric shapes of F_2 - F_3 folds typically form Ramsay's type-3 interference patterns. The complex geometry of these folds suggests that they formed by shearing linked to the Central Cameroon shear zone (CCSZ). The Kimbi area superposed F_2 - F_3 folds have been interpreted as the result of progressive deformation dextral transpressive deformation caused by the oblique convergence between the Congo/São Francisco craton and the Eastern Saharan block.

Keywords: Superposed Folds, Type-3 Interference Patterns, Progressive Deformation, Transpressive Tectonic, Pan-African, Kimbi, Cameroon

1. Introduction

The study of fold structures is one of the most important fields of study with respect to orogenesis belts because they are relatively resilient to subsequent deformation and, once created, are difficult to destroy [1]. The common complexities of folds shape geometry are the results of superposed deformation. Superposed folds or fold interference patterns occur when one generation of folds is overprinted by a later generation [2]. The first attempt of the overall classification of interference patterns was proposed by Ramsay [3] but the

classic work of the fundamental concept of superposed folds was done by Weiss [4]. Folds are a fundamental structure of contractional orogens, and yet deciphering their kinematic history continues to be controversial [5]. The approach to the geometry and kinematical analysis of superposed folds has been mainly experimental [6, 7]. The disadvantage of these analogue models is that they do not accurately express the natural fold examples.

The Kimbi area, located at the western edge of the Central [8, 9] or Northwestern Cameroon [10] domain of the Cameroon Pan-African Fold Belt (Fig. 1), shows very conspicuous and spectacular examples of outcrop scale (< 20

m) fold structures. The main aim of this contribution is to provide a detailed description of superposed folds recorded in the Kimbi area. The results are then discussed within the context of (i) the geological evolution of north western Cameroon, and (ii) their implications for the tectonic evolution of Pan-African North Equatorial Fold Belt (PANEFB).

2. Geological Setting

The Pan-African North-Equatorial Fold Belt (PANEFB, Fig. 1A) or Central African orogenic belt is a major Pan-African orogen linked to the Trans-Saharan orogenic belt of Western-Africa and to the Brasiliano belt of NE Brazil. In Cameroon, the Pan-African realm [8, 9] is made up of three main domains (Fig. 1B):

- (1) The southern domain that is composed of high-pressure and high-temperature (HP-HT) metasedimentary rocks (ca. 800°C at 10-12 kbar [10]), deposited in a passive marginal basin. According to Penaye [11], the causative HP-HT metamorphism took

place at 620 Ma when these rocks were thrust upon the Archaean Congo craton to the south. This thrust continues towards the East, forming the Oubanguides Nappe in the Central African Republic [12].

- (2) The central domain that consists of Archaean to Palaeoproterozoic high-grade gneisses intruded by widespread Pan-African syntectonic plutonic rocks of high-K calc-alkaline affinities [13, 14]. These rocks are cut by major NE-striking transcurrent shear zones interpreted as extensions of major shear zones recorded in NE Brazil (Fig. 1A; [15]).
- (3) The northern domain consists of subordinate, 830 Ma metavolcanic rocks of tholeiitic and alkaline affinities associated with metasediments known as the Poli series [16]. Widespread 630-660 Ma calc-alkaline plutonic rocks, now exposed as orthogneisses, were emplaced during a major episode of crustal accretion. A Palaeoproterozoic crustal source in this region is attested by the presence of 2 Ga old inherited zircons in the plutonic rocks [16].

Figure 1. A) Pan-African and Brasiliano terranes (modified from [14]) and the location of the study area (marked by the asterisk) and major lithotectonic domains. B) Geologic map of Cameroon (modified from [9]) showing the location of the Kimbi area (marked by a box) and major lithotectonic domains, including the (1) southern, (2) central, and (3) northern domains. CCSZ: Central Cameroon Shear Zone; BOSZ: Betaré-Oya Shear Zone; ASZ: Adamaoua Shear Zone; SF: Sanaga Fault; TBF: Tibati Banyo Fault; BOSZ: Betaré Oya Shear Zone; PF: Patos Fault; DS: Dja Series; NS: Nyong Series; NT: Ntem Complex.

The study area, which forms part of the Central, or Northwestern Cameroon, domain [17], covers over 200 km². It is composed of two distinct lithotectonic units [18]: An older metamorphic assemblage and a younger magmatic one (Fig. 2). The metamorphic assemblage is composed of fine-grained and banded amphibolite, and gneiss, whereas the magmatic assemblage comprises of biotite-granite,

hornblende-biotite-granite and orthogneiss intruded by aplitic veins that intruded the older metamorphic rocks during the Neoproterozoic Pan-African orogeny at about 560 Ma [19]. As illustrated by the exceptional fold structures preserved in the Kimbi area, the rocks in this area were subjected to polyphase, ductile deformation, mostly attributed to the Pan-African orogeny [20, 21].

Figure 2. Geological sketch map of study area (modified from [20]).

3. Results

3.1. Main Characteristics of Deformational Phases

Basement (igneous and metamorphic) rocks in the Kimbi area was subjected to polyphase deformation, with three ductile deformation events (D_1 - D_3) and a later brittle (D_4) event having been recognized. These events are described elsewhere [22] but summarized here.

3.1.1. D_1 Event

The D_1 ductile event is only recorded in the older

metamorphic rocks and is associated with the development of an S_1 foliation, F_1 isoclinal folds and β_1 boudins. The S_1 foliation is outlined by a compositional banding and by the preferred orientation of biotite, amphibole and platy quartz. The S_1 foliation was progressively transposed by D_2 and it is recognizable only as relic at the microscopic scale. The foliation surfaces S_1 have gentle to moderate dips (0° to 50°), mainly to the NW and secondarily to the SE. The poles to S_1 from the main outcrops show a girdle distribution (see diagram of poles to S_1 in Fig. 3a) that implies folding around a gently NE plunging axis. The related lineation is conspicuous and corresponds to a mineral and stretching

lineation. It trends NE-SW with a gentle plunge ($0-10^\circ$) mainly towards the NE, although secondary SW plunging lineations are also observed (Fig. 3b). Clearly visible in the banded amphibolites, the β_1 boudins are developed on quartzofeldspathic layers. They have a symmetric shape and their long axes are parallel to the S_1 foliation.

3.1.2. D_2 Event

This tectonic phase is well-recorded in both the magmatic and metamorphic rocks units. It is characterised by a heterogeneous deformation affecting the previous D_1 fabric. D_2 deformation is associated with the development of S_2 mylonitic foliation, C_2 ductile shear zones, F_2 folds and L_2 stretching and mineral lineations. In magmatic rocks, the S_2 mylonitic plane is defined by biotite flakes, K-feldspar sigmoidal crystals, mica fish and platy quartz. The distribution

of S_2 surfaces from the main outcrops around Kimbi area show a girdle distribution. Their planes have moderate to high dips predominantly to the southeast (see diagram of poles to S_2 foliation on Fig. 3c). In metamorphic rocks, the S_2 planes are unequally distributed. They are mostly visible, in layered amphibolites and gneisses, as axial plane schistosity for the F_2 folds. At a microscopic scale, S_2 is marked by biotite flakes and hornblende needles. β_2 asymmetric boudins are developed in the banded amphibolite. C_2 shear zones appear as steep ductile zones that disrupt the S_1 foliation. Their dip is no less than 50° (average orientation $N130^\circ E$, $60^\circ SW$) and is nearly constant in the study area. The L_2 lineation is conspicuous and nearly perfectly oriented in the whole region. It has a $N028^\circ E$ - $N070^\circ E$ trend, parallel to F_2 fold axes. Its plunge can be up to 40° toward the NE.

Figure 3. Structural map of the Kimbi area and equal-area Schmidt lower hemisphere projections of structural data: (a): Poles to S_1 foliations; (b) L_1 mineral and stretching lineation; (c) Poles to S_2 foliations; (d) F_2 fold axis; and (e) Poles to S_3 foliation.

3.1.3. *D₃ Event*

This phase is typically a phase of superimposed folding. In fact the structures associated to this phase of deformation are the result of the transposition and reorientation of the *D₂* structures. *S₃* schistosity overprinted the pre-existing *S₂* schistosity. The *S₃* planes are equally distributed, trending N040-050°E with moderate dips (45-50°) toward the NW (see diagram of poles to *S₃* in Fig. 3e). They are mainly developed as an axial plane schistosity of the *F₃* folds. The *L₃* lineation is a stretching lineation defined by platy quartz, amphibole fish and feldspar rods. A *L₃* lineation associated with *S₃* is sub-parallel to the *F₃* fold axes with a gentle to moderate plunge toward the northeast (5-30°). The *C₃* shear plane is clearly visible in the Ndong river flagstone. The shear sense associated with *D₃* is dextral and, on average, trends N045°E and plunges 30° towards the SE.

3.1.4. *D₄ Event*

This phase is marked by three main types of late sub-vertical fractures marked by granitic veins, strike-slip, and micro-faults. The veins are either aplitic or pegmatitic. The *D₄* structures show three main orientations: (i) N30-40°E and parallel to the Cameroon Central shear zone; (ii) N70-80°E and equivalent to the Adamawa Faults; and, (iii) N140-150°E, a structural orientation that is also present in the central domain (Tombel basement) of the Pan-African fold belt and linked to the normal faulting associated with the opening of the Benue trough [8].

3.2. *Fold Description and Evidence for Type 3 Interference Pattern in Kimbi Area*

In the study area, three folding events (*F₁*, *F₂*-*F₃*) have been recognized [22]:

3.2.1. *F₁ Folds*

F₁ fold occurrences are few, probably due to the later phases that overprint the earlier structures. *F₁* folds occur as centimetric to decametric, intrafoliation folds with class 1C and Class 3 fold geometries [20]. Their axes, which trend NE to NNE and plunge moderately to the NE, are roughly parallel to *L₁* (Fig. 4a). The *S₁* axial planar schistosity is developed in the hinges of the *F₁* folds (Fig. 4a and Fig. 4b).

3.2.2. *F₂ Folds*

F₂ folds overprint the *D₁* structures and represent the main folding phase. They strongly affect the metamorphic basement and are clearly visible at megascopic, mesoscopic and microscopic scale. At megascopic scale (whole area) *F₂* folding displays antiformal and synformal structures with axes oriented NNE-SSW. The *F₂* mesoscopic folds have *S₂* as axial plane schistosity. Most of *F₂* are multi-layer folds, but single layer *F₂* folds are also found in the area. The *F₂* folds have various geometric shapes ranging from class 1B, class 1C to class 3 folds [20]. The axial trends are parallel and vary between N15°E and N70°E with gentle plunges (10-30°) toward the NE (Fig. 4d). The wavelengths of the many *F₂* folds vary from 15 cm to 30 cm with an amplitude of 10 to

20 cm. The axes of these folds are nearly parallel to the stretching lineation and could be large-scale sheath folds.

3.2.3. *F₃ Folds*

F₂ folds are refolded by the last folding event into *F₃* folds (Fig. 4c). These folds are polyharmonic with small scale *F₃* folds displaying either asymmetric or symmetric shapes depending on their location (hinge or limb zones) in the large scale fold (Fig. 4d).

F₂-*F₃* folds are superposed folds. Their geometric shapes typically form interference patterns that arise as a result of the development of later minor folds across the earlier *F₁* structures. The new small-scale folds have either asymmetric S- or Z-shapes or symmetric M- or W-shapes (type 3 interference patterns), depending upon their location in the large *F₂* folds (Figs. 4e, 4f, 4g and 4h). Common fold structures with 'S' or 'Z' asymmetric shapes are due to passive shearing. This is characteristic of shear-related folds [23].

4. Discussion

The superposed folds described in this paper are the result of a series of deformations whose understanding is essential for unravelling the tectonic evolution of their hosting orogen. According to Ramsay and Huber [24], two main processes can produce superposed folds in orogenic zones: (i) A change of the principal stress direction during the course of an orogeny; or (ii) single progressive deformation due to a systematic change in stress and incremental strain during deformation. Ramsay and Lisle [25] discuss the origin of type-3 interference patterns and consider that they occur when the axis of the pre-existing fold is perpendicular to the shear direction. Due to different strain and rotation rates, folds will generally become progressively more asymmetric. The superposed folds observed in the Kimbi area are asymmetric, with amplitude asymmetry greater than shape asymmetry [20]. The final asymmetry of these superposed folds could be a result of a complex deformational history that depends on the original orientation of earlier-formed folds with respect to the Central Cameroon shear zone (CCSZ). According to Carreras et al. [23], three types of shear related folds can be distinguished in shear zone settings:

- (i) *Sheared pre-existing folds* are folds of a previous deformation event that become involved in shear-related deformation. The final geometry of such folds is modified by the effect of shearing, and largely depends on the degree of mechanical behaviour of the folded layers or foliations.
- (ii) *Shear-related early folds* are folds in planar fabrics (i.e. layering or foliation) of a previous deformational event that become deflected towards parallelism with a shear zone.
- (iii) *Shear-related late folds* affect a newly formed shear zone-related foliation (e.g. a mylonitic foliation) or a stretched layer that becomes unstable during progressive shearing.

Figure 4. Observed fold structures: a and b): F_1 isoclinal folds with S_1 schistosity parallel to the axial fold plane; c) F_3 asymmetric folds; d): Superposition of F_3 folds on the F_2 folds; e, f, d & h): Type 3 interference patterns (Note the asymmetric shape “S” or “Z” and the symmetric shape “M” or “W” of F_3 folds and S_3 axial plane schistosity for the F_3 folds).

In the study area, the superposed folds are either asymmetric, or are cross cut by the shear plane, with dextral shear sense movement. This is characteristic of shear-related early folds and shear-related late folds. Thus the shearing predates and postdates the folding event. In effect, axial directions of folds, both the second and third phases, tend to be parallel or subparallel. This relationship implies that the deformation regime during D_2 and D_3 deformational phases was co-axial, with smooth change of stress and strain during deformation. Thus the fold axes were reoriented into

parallelism during progressive shearing. The Kimbi area superposed folds are consistent with their formation within a continental convergence zone. Their geometry and orientation is consistent with NE-SW oblique shortening within a dextral transpressive regime, probably during the oblique collision between the Congo/São Francisco craton and the Eastern Saharan block (Fig. 5). These results are similar to those obtained by [26] in Trans-Saharan belt of Eastern Nigeria and by [27, 28] in both the Eastern and northern part of the central domain of PANEFB in Cameroon.

Figure 5. Cross section deciphering regional tectonic model of Northwestern Cameroon Pan-African Fold Belt.

5. Conclusion

In the Kimbi area, three folding events have been recognized. F_2 - F_3 folds are phases of superposed folding. Detailed field observations and geometric description, are in accordance with the fact that the last two folding events represent two-phases of coaxial deformation with Ramsay's Type 3 interference fold patterns. The complex geometry of these folds can be related to shearing. The Kimbi area superposed folds are the result of progressive deformation in a dextral transpressive context, during the oblique convergence between Congo/São Francisco craton and the Eastern Saharan block.

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