The Numba ductile deformation zone (northwest Cameroon): A geometric analysis of folds based on the Fold Profiler method

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The Numba ductile deformation zone (NDDZ) is characterised by folds recorded during the three deformation phases that affected the banded amphibole gneiss. Fold-shape analyses using the program Fold Profiler with the aim to show the importance of folding events in the structural analysis of the NDDZ and its contribution to the Pan-African orogeny in central Africa have been made. Classical field method, conic sections method and Ramsay's fold classification method were applied to (i) have the general orientation of folds, (ii) analyze the fold shapes and (iii) classify the geometry of the folded bands. Fold axes in banded amphibole gneiss plunge moderately ($<15^\circ$) towards the NNE or SSW. The morphology of F_1 , F_2 and F_3 folds in the study area clearly points to (i) Z-shape folds with SE vergence and (ii) a dextral sense of shear motion. Conic section method reveals two dominant families: F_1 and F_3 folds belong to parabolic shape folds, while F_2 folds belong to parabolic shape and hyperbolic shape folds. Ramsay's scheme emphasizes class 1C (for F_1 , F_2 and F_3 folds) and class 3 (for F_2 folds) as main fold classes. The co-existence of the various fold shapes can be explained by (i) the structuration of the banded gneiss, (ii) the folding mechanisms that associate shear with a non-least compressive or flattening component in a ductile shear zone and (iii) the change in rheological properties of the band during the period of fold formation. These data allow us to conclude that the Numba region underwent ductile dextral shear and can be integrated (i) in a correlation model with the Central Cameroon Shear Zone (CCSZ) and associated syn-kinematic intrusions and (ii) into the tectonic model of Pan-African belt of central Africa in Cameroon.

1. Introduction

Different types of strain patterns appearing in folded regions and their geometrical evolution from initial, undeformed stage, to the final fold are a matter of significance to kinematic studies of folding (Aller *et al.* 2010). The Numba basement rock

has been affected by three ductile deformation events recorded in banded amphibole gneiss and are marked by several folding structures. Folds are the concrete structures that mark these different events. Up until now, apart from the recent research works of Ganno *et al.* (2010), the basement rock of the northern domain of the Central African

Keywords. Fold classification; Numba; Cameroon; Pan-African.

Pan-African Belt (CAPB) in Cameroon has not yet been characterised using folds analysis. The north-west Cameroon basement rock, part of the CAPB, is poorly documented. It is important to understand the tectonic evolution of the Pan-African in Cameroon, in general and its northern domain, in particular, to tilt on detailed description of different tectonic events. Fold geometry has been used since the last century as (i) key for the better understanding of the tectonic and (ii) basis for kinematical analysis (Ramsay 1967; Hudleston 1973; Ramsay and Huber 1987; Zagorcev 1993; Bastida *et al.* 1999; Bobillo-Ares *et al.* 2004). Fold analysis seems to be one of multiple methods of basement rocks analysis.

To describe and classify the shape of folded surfaces, certain authors have recommended different types of function (Hudleston 1973; Ramsay and Huber 1987; Bastida *et al.* 1999; Aller *et al.* 2004) and others have classified natural fold shapes by comparing them to cubic Bézier curves (Srivastava and Lisle 2004; Coelho *et al.* 2005). One of the four classification schemes: (1) cubic Bézier curves (Bézier 1966, 1967) uniquely defined by the position of points marking the ends of the curve and control points; (2) conic sections (Aller *et al.* 2004) based on a drawback of using eccentricity as a classification parameter; (3) superellipses (Gardner 1965) that describes a generalized equation of an ellipse; and (4) power functions (Bastida *et al.* 1999) based on the comparison with the profile shapes geological folds can be used to better characterise folds in a given study area.

Structural geologists seek ways of untying ductile strain in orogenic belts, but there are few reliable ways of measuring ductile strain in rocks that do not contain classical 'strain markers', or are folded (Shah and Srivastava 2006). In this situation, flattened parallel folds, developed by superimposition of a homogeneous strain on parallel folds, can be used as a potential indicator for revealing the flattening component of strain history (Mukhopadhyay 1965; Hudleston 1973; Gray and Durney 1979; Ramsay and Huber 1987).

In this study, due to the fact that folds are common structures in many ductile zones, we perform fold-shape analysis associated with field observations with the aim to show their contribution to the structural characterization of the Numba ductile deformation zone (NDDZ) associated with the Pan-African tectonic in central Africa.

2. Geological setting and previous work

The Pan-African Belt of central Africa (PBCA; Bessoles and Trompette 1980) is also known as (1) Neoproterozoic Central African Fold Belt (CAFB;

Penaye *et al.* 1993; Toteu *et al.* 2001) that will be preferentially used in this study or (2) Pan-African North Equatorial fold belt (Nzenti *et al.* 1988). It is connected with the Neoproterozoic Brasiliano fold belt (Brito Neves *et al.* 2002; Cordani *et al.* 2003) as shown in figure 1(a) from Caby *et al.* (1991). However, it is less well known. In Cameroon, the Pan-African tectonic evolution is characterised by large scale shear zones, such as the Adamaoua shear zone (ASZ), Buffle Noir Mayo Baléo (BNMB) shear zone also known as Tcholliré-Banyo fault (TBF), Sanaga shear zone (SSZ), Mayo Nolti shear zone (MNSZ), Rocher du Loup shear zone (RLSZ) and Godé-Gomaya shear zone (GGSZ) that have transposed earlier structures (figure 1b).

The CAFB is divided into three domains (figure 1b, Toteu *et al.* 2004):

- (1) the northern domain (or Poli domain or west Cameroon domain) limited to the south by the BNMB shear zone;
- (2) the central domain located between the BNMB shear zone to the north and the Sanaga shear zone (SSZ) to the south;
- (3) the southern domain (also known as Yaoundé domain) located between the SSZ to the north and the northern border of the Congo Craton to the south.

The northern domain comprises the sinistral N-S Godé-Gormaya and Mayo Nolti shear zones and the NE-SW Tcholliré-Banyo shear zone (figure 1b). This domain, which contains the study area, consists of Neoproterozoic volcanosedimentary schists, gneisses (with possible 2.1 Ga (U/Pb zircon; Penaye *et al.* 1993; Toteu *et al.* 1994, 2001) inheritance) and orthogneiss (Toteu 1990). The volcanic rocks display both tholeiitic and alkaline affinities. The northern domain comprises: the Poli region, the Mayo Baléo region in the south and the Tcholliré region in its eastern part. In the Poli region, E-W antiform and synform characterise gentle folding of a regional flat-lying foliation and lineation probably formed during an early thrust evolution. Sheath-like folds coeval with the early foliation materialise intense shear deformation during thrusting (Ngako and Njonfang 2011). The geometry of the folds varies eastwards, from open to tight profiles correlatively with a progressive change of the axial plane cleavage from crenulation to mylonitic at the contact zone with the BNMB shear zone (figure 1b). According to Ngako (1999), the Vallée des Roniers and the Demsa shear zones (both in the Poli domain) are coeval with down-slip movements parallel to the Godé Gormaya segments (figure 1b) both E-W and N-S mylonites determine a complex transtensive system. These shear zones seem to be coeval with the Z-shaped rotation

of the region, associated with N–S crenulation cleavage S_2/S_3 . Further to the south, in the Mayo Baléo region, these folds are overturned westwards, indicating large scale thrust movements coeval with E–W stretching lineations (Ngako *et al.* 2008). Pb–Pb evaporation ages of $ca\ 600\pm 27$ Ma on monozircons from syn-thrust intrusions in Mayo Baléo give an age approximation of this second folding phase (Ngako 1999). The Tcholliré region consists of poly-deformed biotite–amphibole gneiss and orthogneiss with minor occurrences of metapelites and garnet amphibolites. These formations are also observed in the Banyo region in the southern extension of the Poli region (Ngako 1999; Toteu *et al.* 2004). The tectonic evolution of the Tcholliré area comprises an early D_1 deformation with probably a flat-lying S_1 foliation followed by D_2 folding characterised by sub-vertical axial planar S_2 foliation. The last stage of deformation inducing the D_3 shear zones (e.g., Tcholliré–Banyo shear zone) controls the emplacement of late tectonic granitoids. The domain is then characterised by three deformation events with an earlier D_1 event of gentle folding of a regional flat-lying foliation, a D_2 folding event and D_3 event inducing shear zones.

The Numba ductile deformation zone is a dextral shear zone oriented NE–SW on the western and the northeastern borders of the Numba granitic pluton. It extends from Bokwa to the south to Bambi to the north. This shear zone is sub-parallel to the documented Fotouni–Fondjomekwet mylonitic zone (FFMZ; Njanko *et al.* 2010; Tcheumenak Kouémo *et al.* 2014) situated 75 km southeastern part of the Numba granitic pluton and constitutes the basement rock of the granitic pluton.

3. Materials and methods

In this study, we use classical field methods, Cubic Bézier curves method, conic sections method and Ramsay's fold classification method.

A total of 11 observation stations from Widikum, Bambi and Bokwa localities were distributed among the study area. Fold profiles of six representative pictures were chosen from six different stations. Measurements were collected in LGE (Laboratoire de Géologie de l'Environnement; University of Dschang, Cameroon) using Fold-Profiler program.

In classical field method, structural elements as folds (axial planes and axes), foliations and stretching lineations are recognizable at a metric or centimetric scale and their orientations (strike and dip) were measured. These data were statistically analyzed in the laboratory using Stereonet. Fold axes

have been plotted in lower hemisphere Schmidt diagrams using conventional technique (figure 2).

Two quantitative methods are commonly used to describe fold-shape classification by visual comparison: the Ramsay method based on the use of three concepts (orthogonal thickness, $t'\alpha$; thickness parallel to the axial plane, t_0 ; and dip isogons, α) and the mathematical function that fits folded surface. Although, the type of mathematical function used is different, there are many features: (i) classification of the shapes of individual limbs, rather than the shapes of the entire folds; (ii) the mathematical functions that form the basis of the fold description; (iii) two-fold shape classification parameters; and (iv) the way of converting the shape parameter. Lisle *et al.* (2006) have developed the Fold Profiler: A Matlab-based program for fold-shape classification that contains several methods, based on different mathematical functions which accurately fit natural fold profiles. This program incorporates four methods: cubic Bézier curves, conic sections, power functions and super-ellipses. Liu *et al.* (2009) have developed the Bézier–Fold Profiler method. We favour the cubic Bézier curves method compared with the conic sections method, due to the nature of the folds to be fitted and the aim of our study. The file containing the digital image of representative fold to be analyzed was imported into the Matlab Fold Profiler software and displayed on the screen. Following the onscreen instructions, each fold limb is analyzed separately as described by Srivastava and Lisle (2004) and Lisle *et al.* (2006). Ramsay's folded surfaces classification is based on thickness variations. On a profile plane view of a fold, we first mark the hinge points and inflection points on the two bounding surfaces of the folded layer, and then draw the tangents to the folded layer at the hinge points.

4. Field observations and characteristics of folds

The study area is made up of granitic pluton that intrudes a basement rock mostly made of banded amphibole gneiss (figure 2). It crops out in the form of flagstone in Widikum, Bambi and Bokwa. Grey in colour, the banded amphibole gneiss are medium- to fine-grained (average size <1.5 mm) with a preferred orientation of their minerals and a granoblastic texture. They are composed of biotite, hornblende, plagioclase, K-feldspar and quartz. Accessory minerals are sphene, zircon, apatite and oxides.

Gneissic foliation dips moderately to highly towards the NW and SE (figure 2) implying, at the regional scale, folded surfaces. Folding events

Figure 2. Geological map of the Numba area and projection diagrams for S_2 foliation poles and F_2 fold axes. bp = best pole; bl = best line.

observed in this area are linked to three deformation phases. Folds are clearly visible on the field where they occur generally as centimetre or metre size and show different morphological aspects: (i) recumbent folds; (ii) anisopaque folds, and (iii) disharmonic folds in Bokwa, Bambi and Widikum (figure 3). Most folds of the NDDZ are of Z-shape.

Their short limbs appear to have rotated clockwise with respect to their long limbs. Their wavelength varies from 0.42 to 1.5 m and the amplitude between 0.17 and 1 m. Most of them are closed folds with hinges thicker than the limbs. Regularly, short limbs are sheared, thin and defined a shear plane of dextral movement (figure 3).

F_1 folds are the result of the folding of an earlier S_1 E–W gneissic foliation that is progressively transposed into S_2 . They show asymmetric morphology and occur as centimetric to decimetric intrafolial folds. Their axes plunge $<15^\circ$ towards the NNE or SSW. The quartzo-feldspathic bands of the folds are thicker than ferromagnesian one and also, long limbs relatively to the short limbs.

F_2 folds are multi-layered with mostly asymmetric Z-shapes (figure 3c). Their sizes vary from centimetre to decametre scale. They show (i) an axial planar schistosity (mostly parallel to the L_2 stretching lineation) S_2 marked by stretched quartz crystals, biotite flakes and amphibole crystals and (ii) consistent asymmetry and SE vergence. F_2 fold axes in the Numba area have similar orientations with axes plunging 12° – 28° towards the NE or SW. Best lines are at 241/21 and 41/28 in Bambi and 23/18 in Bokwa.

F_3 folds are materialised by the folding of a fine grain granite vein in the Bokwa area (figure 3d). The size of the folds is in decimetre scale. The axial planar schistosity of F_3 folds (well developed in the hinges) is marked by stretched quartz crystals and biotite flakes. Most of F_3 fold axes plunge 56° – 72° towards the NE.

5. Results

5.1 Fold-shape analysis

In the study, three main parameters are obtained: aspect ratio (R), normalized area (a) and eccentricity (e). F_1 folds are mainly plotted in the parabolic shape fold domain (78% of the measurements) even if there are some measurements in the sine shape fold domain (figure 4a). Considering the

Figure 3. Representative fold shapes determined by Fold Profiler[®]. (a) F_1 folds from Bokwa; (b and c) F_2 folds from (b) Bambi and (c) Widikum, respectively and (d) F_3 folds from Bokwa.

normalized area and the eccentricity parameters, 83% of the measurements are grouped around the parabolic shape fold.

F_2 folds are plotted in the parabolic and sine shape fold domains. In fact, their normalized area values vary between 1.1 and 1.4 for 87% of the measurements (figure 4b). The aspect ratio values of F_2 folds vary between 0.4 and 3.1, while the variation of the eccentricity parameter (0.8–1.5) allow to plot 54% of the measurements in the parabolic shape fold domain and 41% in the hyperbolic fold shape domain.

F_3 folds are scattered between sine and parabolic shape fold domains where they represent

respectively 40% and 30% of the measurements (figure 4c). The eccentricity parameter values are comprised between 0.9 and 1.2, with 90% of the measurements plotted in the parabolic fold shape domain.

Folds from the study area are scattered in the sine shape fold (with 12%, 39% and 40% of the measurements corresponding respectively to F_1 , F_2 and F_3 folds), parabolic shape fold (with 78%, 48% and 30% of the measurements corresponding respectively to F_1 , F_2 and F_3 folds) and elliptical shape fold domains. Parabolic shape folds are mainly represented with 52% of the measurements, followed by sine shape folds (30% of the

Figure 4. Fold-shape analyses aspect ratio *vs.* normalized area (1) with corresponding histogram, (2) aspect ratio *vs.* eccentricity and (3) determined by conic sections method for (a) F_1 folds, (b) F_2 folds and (c) F_3 folds.

measurements) and elliptical shape folds are 18%. According to Aller *et al.* (2004), the best approximation of fold shape should take in consideration the eccentricity (e) of the conic section. Based on the aspect ratio *vs.* eccentricity diagram, the almost whole measurements seem to be regrouped around the parabolic shape folds event if some measurements plot in the hyperbolic shape fold domain, where they show a great value of eccentricity for low values of aspect ratio.

5.2 Geometric analysis of folded layers

The method using the $t'\alpha$ *vs.* α diagram (figure 5) of Ramsay and Huber (1987) is based on layer thickness variations. Folds from the study area are located in class 1C and class 3. F_1 and F_3 folds are ranged in class 1C field, while F_2 folds cover a large field ranging from class 1C, class 2 to class 3 fields. The Numba folds, developed in banded amphibole gneiss mostly characterised by alternation of competent quartzo-feldspathic bands with biotite–amphibole rich incompetent bands, indicate different folding behaviours for the two bands. Competent bands plot mostly in class 1C and class 3 while incompetent bands plot in class 1C and class 2 (?). F_1 and F_2 are materialized by the folding of gneissic bands, while F_3 folds are the result of folding of a fine-grained granitic vein intruding the banded amphibole gneiss (figure 3).

6. Interpretation and discussion

The Numba ductile deformation zone is characterised by banded amphibole gneiss in which fine-grained granitic veins are folded. The morphology of folds in the NDDZ (figure 3a–d) points to (i) asymmetric

fold shapes with dominant Z-folds and (ii) a dextral sense of shear motion. It is well demonstrated that fold geometry and folding mechanism depend on physical properties and physico-chemical conditions of the folded bands. The morphology of the NDDZ folds is similar to the morphology of those described and categorized by Carreras *et al.* (2005), in the dextral Cap De Creus shear zone. They show the typical geometry of synthetic folds characterised by a thinned short limb that occur in dextral ductile shear zone. Folds Profiler characterised folds from the NDDZ in the conic section plots (figure 4) as parabolic shape for F_1 folds, parabolic shape to hyperbolic shape for F_2 and F_3 folds based on the normalized fold area and/or eccentricity parameters. The co-existence of parabolic shape, hyperbolic shape and sine shape folds can be attributed to the increasing of the normalized fold area and fold amplitude both linked to the importance of the flattening component in the deformation.

Folds from NDDZ mostly belong to class 1C, class 2 and class 3 fields of the $t'\alpha$ *vs.* α diagram of Ramsay and Huber (1987) (figure 5). The slope of the curves obtained on the $t'\alpha$ *vs.* α diagram indicates that F_1 and F_3 folds belong to class 1C field, while F_2 folds have various shapes ranging from class 1C, class 2 and class 3 fields. According to Ramsay (1967), Lisle (1997) and Srivastava and Shah (2006, 2008), the formation of Ramsay class 1C folds is due to the flattening (superposition of homogeneous ductile strain) on a parallel fold. At high angle to the shear direction, folds display a rather open shape with axial plane forming moderate angle to the shear zone and they plot predominantly as type 1C of Ramsay's classification (Carreras *et al.* 2005). The class 3 fold shape involves the susceptibility of the less competent

Figure 5. $t'\alpha$ *vs.* α diagram of Ramsay classification for (a) F_1 , (b) F_2 and (c) F_3 folds.

nature bands (quartz and feldspar rich) opposite to the ferromagnesian more competent nature bands to ductile deformation. Fold shape in competent bands varies with ductility contrast between the competence of adjacent bands (Ramsay 1967).

The results obtained in this study clearly classified the folding of the basement rock in the study area and indicate that these data should be taken into account when characterizing the tectonic evolution of the western domain of the CAFB in Cameroon, in particular and of the whole central Pan-African belt, in general.

7. Conclusion

The NDDZ is characterised by banded amphibole gneiss that recorded three deformation phases recognizable by F_1 , F_2 and F_3 folds. The morphology of folds points to asymmetric fold shapes with dominant Z-shapes. The geometric analysis of the folds in the study area points preferably to parabolic shape and hyperbolic shape folds for F_1 , F_2 and F_3 folds. In the Ramsay classification diagram, F_1 and F_3 folds belong to class 1C field while F_2 folds belong to class 1C, class 2 and class 3 fields. Field observations and the fold shapes allow us to conclude that the NDDZ underwent ductile dextral shear movement that takes into account the banding of the banded amphibole gneiss and folding mechanisms that associate simple shear with an important compressive component. These results demand the need to take into consideration the folding events for the understanding of the tectonic evolution of the western domain of the CAFB.

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MS received 20 February 2015; revised 21 December 2015; accepted 19 October 2016

Corresponding editor: SAIBAL GUPTA