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RESEARCH PAPER

Local structural markers of the Batouri gold-bearing shear zone in Southeast Cameroon

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Abstract
The mining district of Batouri is located in the southeastern part of Cameroon and constitutes an integral part of the Adamaoua-Yadé domain of the Pan-African fold belt. This work aimed to highlight the structural and petrographic markers that characterize the auriferous shear zone. The investigations show that the rocks of the Batouri area suffered a ductile-brittle shear deformation in three directions (E-W, NE-SW, and NW-SE). These shear directions constitute the local extension of the Demza and the Balche shear zones of the Poli group, and the central Cameroon shear zone. Within these shear bands, the S_n schistosity and tension cracks present a sigmoidal geometry, which is justified by a variation in the direction and dip of the schistosity planes and veins. This shear zone displays a finite local extension (NNW-SSE) generated by an ENE-WSW compression. Intense shearing is observed within gold-bearing monzogranites and syenogranites. The gold mineralization is controlled by three main vein directions (NNW-SSE, E-W and NE-SW), which are closely associated with silicification, sulfidation, and K-alteration of the host granitoids.

Keywords: Shear Zone, Gold Mineralization, Structural Markers, Batouri Area, Cameroon.

Introduction

Shear zones are tabular or curvi-planar zones that are intensely deformed and adjacent to relatively weak deformation domains that accommodate lithospheric deformation (Mukherjee & Biswas, 2014). Based on the type of fabric displayed by these structures, three main shear zones (brittle, ductile-brittle, and ductile) were identified. Brittle shear zones are characterized by the presence of fabrics resulting from brittle deformation, notably fractures and faults. They appear between 5-10 km in the upper crust (Davis et al., 2011; Ali et al., 2023). The ductile-brittle shear zones are composed of ductile and brittle en echelon fabrics with a sigmoidal shape, whereas the ductile shear zones are without discontinuities. Ductile shear zones are long, narrow zones of relative displacement and are analogous to faults but without material rupture (Tiwari et al., 2020). They appear in the middle part of the crust at a depth of 10 to 15 km (Davis et al., 2011). The different brittle and ductile fabrics that characterize shear zones contribute to their permeability and become the true hydraulic drains for mineralized hydrothermal fluids that migrate to the surface during geological processes (Jolly & Cosgrove, 2003).

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In Cameroon, the complex tectonic structures have been extensively studied and mapped (Fig. 1). The "Central Cameroon Shear Zone" (CCSZ) is the southwest extension of the Central African Shear Zone, which extends from Cameroon to Sudan (Ngako et al., 2003; Adam et al., 2022; Seguem et al., 2022). It is composed of several components, including the Sanaga Fault (SF), the Adamaoua Fault (AF), and the Kribi Campo Fault (KCF) (Fig. 1a). Previous reports show that the Batouri mining district contains a voluminous Neoproterozoic mineralized granites (Asaah et al., 2015). Gold mineralization is disseminated in the syeno-monzogranite, granodiorite, and altered wall rock and controlled by quartzo-feldspathic stockwork veins along local shear zones.

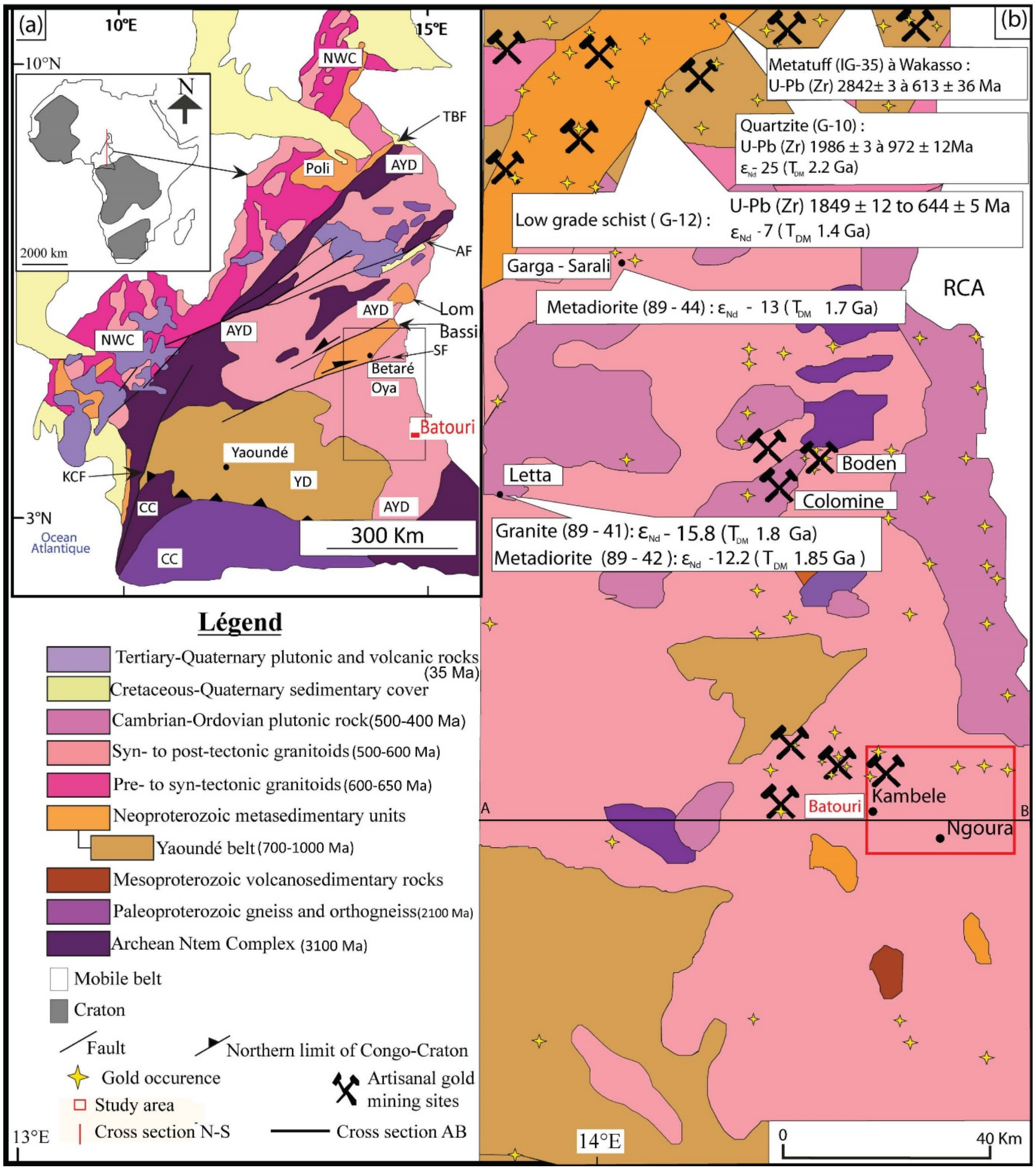

Figure 1. Geological map of Cameroon. (a) The Central African shear Zone is defined by a system of NE-trending faults comprising Tchollire-Banyo Fault (TBF), Adamawa Fault (AF), Sanaga Fault (SF), and Kribi-Campo Fault (KCF). The inserted square at the left is the map of the African continent, showing the location of Cameroon relative to the distribution of cratons and mobile belts., North-western Cameroon domain (NWC); Adamawa-Yade Domain (AYD); Yaounde Domain (YD) (Toteu et al., 2001); (b) gold index of the Batouri area (Asaah et al., 2015)

Looking at the presence of the shear zone and the intensity of deformation in the basement lithology, the question lies in what constitutes the local structural markers of shearing and the influence of these structures on the precipitation of the Batouri primary gold mineralization. Therefore, in this study, aspects of the deformation and evolution of shear zone activity relating to gold mineralization in the Batouri area were discussed. The findings will help to better understand the structural framework concerning gold mineralization in this district in Eastern Cameroon.

Geological Setting

The Batouri mining district is located to the south of the Colomine-Ngoura mining district in the East Region of Cameroon and is covered by the Batouri geological formations (Fig. 1a-b), which belong to the Adamaoua-Yadé domain (AYD) and the CCSZ (Toteu et al., 2004). The Adamawa Yadé domain, together with the North Western Doman (WCD) and the Yaounde Domain (YD), forms the three geotectonic units of the Central African Fold Belt (CAFB) in Cameroon (Ngako et al., 2003; Toteu et al., 2004). The CAFB was formed as a result of the convergence and subsequent collision of the *São*-Francisco Craton with the Congo Craton (Castaing et al., 1994).

The AYD contains relics of metasedimentary and orthogneiss from the Lom greenstones belt and the Yadé plutonic massif in the Central African Republic (Toteu et al., 2001). The related granitoids (monzo-syenogranite and granodiorite) are post-to-syn-collisional (610-640 Ma) with alkaline to calc-alkaline characteristics. They intruded into the high-grade gneisses that constitute the Paleoproterozoic basement affected by the Pan-African orogeny. Structurally, two deformation phases were defined in the AYD: (1) D_1 phase, marked by shallow dipping foliation that corresponds to the axial planes of isoclinal folds with lineations trending N110 and N140. The presence of asymmetric garnet porphyroclasts suggests a sinistral shear sense is associated with this phase (Kankeu et al., 2012); (2) the D_2 phase is characterized by the development of tight and stretched folds with axial plane schistosity. The directions of the D_2 fold axes and lineation's are NNE-SSW to NE-SW (Toteu et al., 2004). Spatial analysis of structures in the Betaré-Oya gold district north of Batouri shows that gold mineralization is controlled by NE-SE, ENE-WSW, and NNE-SSW faults (Nguemhe Fils et al., 2020).

The Batouri mining area contains widely distributed high-K calc-alkaline granitoids made up of syeno-monzogranites and granodiorites (Asaah et al., 2015). These lithologies are crosscut by NNE-SSW, NE-SW, ENE-WSW, and ESE-WNW generations of mineralized veins of pre-to-syn and post-tectonic age. These granitoids contain enclaves of monzonites, quartz monzonites, and quartz diorites that represent fragments of Paleoproterozoic to Archean basement or high-grade metasedimentary rocks (Van Schmus et al., 2008). Mineralized structures in this area include veins and pegmatite dykes that intrude the high-K calc-alkaline granitoids, while the barren structures mostly crosscut the basement lithologies (Asaah et al., 2015). Moreover, the gold mineralization is controlled by a network of quartz veins and associated wall-rock observed in the granitoids (Vishiti et al., 2015; Yannah et al., 2015).

Material and Methods

Local structural markers

Structural markers related to gold mineralization in Batouri, including mesostructures, microstructures, and petro-fabrics that characterize the sheared gold-bearing zones in the Emndobi, Kambele, Lala, and Ngoura sites (Fig. 1b), were investigated. These mesostructures, petro-fabrics, and structural characteristics (dip, strike, plunge, and overall trends) were measured and described at the outcrop level. Structural measurements for each mining site (Kambélé, Emndobi, Ngoura, and Lala) were obtained and analysed using steronet 10.2.9 software.

Mesostructures like granitic dykes and quartzo-feldspathic veins that outcrop at the Ngoura, Lala, and Emndobi sites were identified. These structures were studied using the descriptive methods of the structural geology of shear zone rocks (e.g., Ramsay & Graham, 1970; White, 1980; Davis et al., 2011). All mesostructures were subdivided into ductile, semi-brittle, and brittle deformations. The ductile indicators refer to C/S fabrics, schistosity (S_n), stretching lineation (Ln), and asymmetric porphyroclasts. The sigmoidal tension gashes and the shear joints define the ductile-brittle markers. Furthermore, brittle structures were represented by Riedel faults (R and R') and quartzo-feldspathic veins. The C/S fabrics, which correspond to kinematic features, indicate the sense of movement of the shear zone and were determined in the schistosity cusp zones (C-shear bands). En echelon veins (tension slots) were identified as a common minor structure associated with shear zones and are mineral-filled tension veins, where semi-brittle deformation is involved. These semi-brittle deformations, according to Davis et al. (2011), refer to brittle fractures in mode I (veins and joints). Often, the veins are arranged en echelon within the shear zone and open along the direction of the maximum instantaneous extension (Sibson, 1977). Riedel faults (R and R') refer to conjugate and en echelon faults within the main shear band (Ramsay & Graham, 1970).

To determine the spatial orientation of the structures, angular and cardinal annotations were used. A strike/dip angular notation was adopted for the attitudes of the schistosity planes (S_n), shear bands, Riedel faults (R and R'), and fracture planes. Attitudes of lineations (L_n) and paleo-stresses (σ), with azimuth/plunge were measured. A cardinal annotation was used to express the directions of the shear veins (or fault-fill veins) and tension gashes. This cardinal annotation was also used to designate the different branches of the shear zone and to express the directions of extension and compression in the discussion section. Structural data were oriented and collected using a Topochaix brand compass clinometer. The geometric representation of the planar and linear fabrics was done by stereographic projection via Stereonet 10.2.9, in the lower hemisphere of the Schmidt net and Wulf grids. From this projection, the directional rosettes, the poles of the planes, and the principal paleostresses σ_1, σ_2, and σ_3 were examined. Local maps were drawn using ArcGIS 10.4 and Adobe Illustrator C.S. software.

Petrographic investigation

This section identifies the C/S mylonite types and gold mineralization along shear zones. The preparation of the thin section was carried out in the laboratory of the Institute of Geological and Mining Research in Yaounde, Cameroon. The prepared thin sections were used to identify mineralogy and microstructures using an optical polarized microscope under the cross-polarized (PL) and plane-polarized (PPL) lights. Shear markers in the rock matrix were described. Attention was given to markers like σ, δ, and C/S structures and breccias.

A sketch of a geological cross-section of the Batouri area was established based on the N-S tectonic evolution of the North Equatorial Pan-African chain (Toteu et al., 2006). In this regard, an E-W cross section showing the variation of the local lithologies of the Batouri area was observed at the mining sites of Ngoura, Lala, Emndobi, and Kambele. This shows a gentle topography with an average altitude of 800 m, corresponding to the highest average altitude of the granite zones in Batouri. The area is generally covered by syn-to-post-tectonic granitoids with monzogranitic and syenogranitic compositions showing brittle-ductile shear deformation. This is marked by the presence of schistosity planes within mylonites with crosscutting veins and faults.

Results

Ductile markers

C/S fabrics

These meso-fabrics affect the deformed granites of the Lala, Emndobi, and Ngoura sites and reflect dextral and sinistral kinematics. In the Ngoura area, the right-lateral C-shear bands are represented mainly by N141E and N150E (mean: N140; n = 14) structures. These C-shear bands locally display a left-lateral sense of movement with main N121E and N130E (mean: N134E, n = 16) trends. In the Emndobi site, these structures turn to show a dextral sense of shearing and are represented by N91E and N100E trends. While the Lala area is generally characterized by right-lateral C-shear bands with recurrent N31E and N40E (mean: N58, n =1 2) trends (Fig. 2).

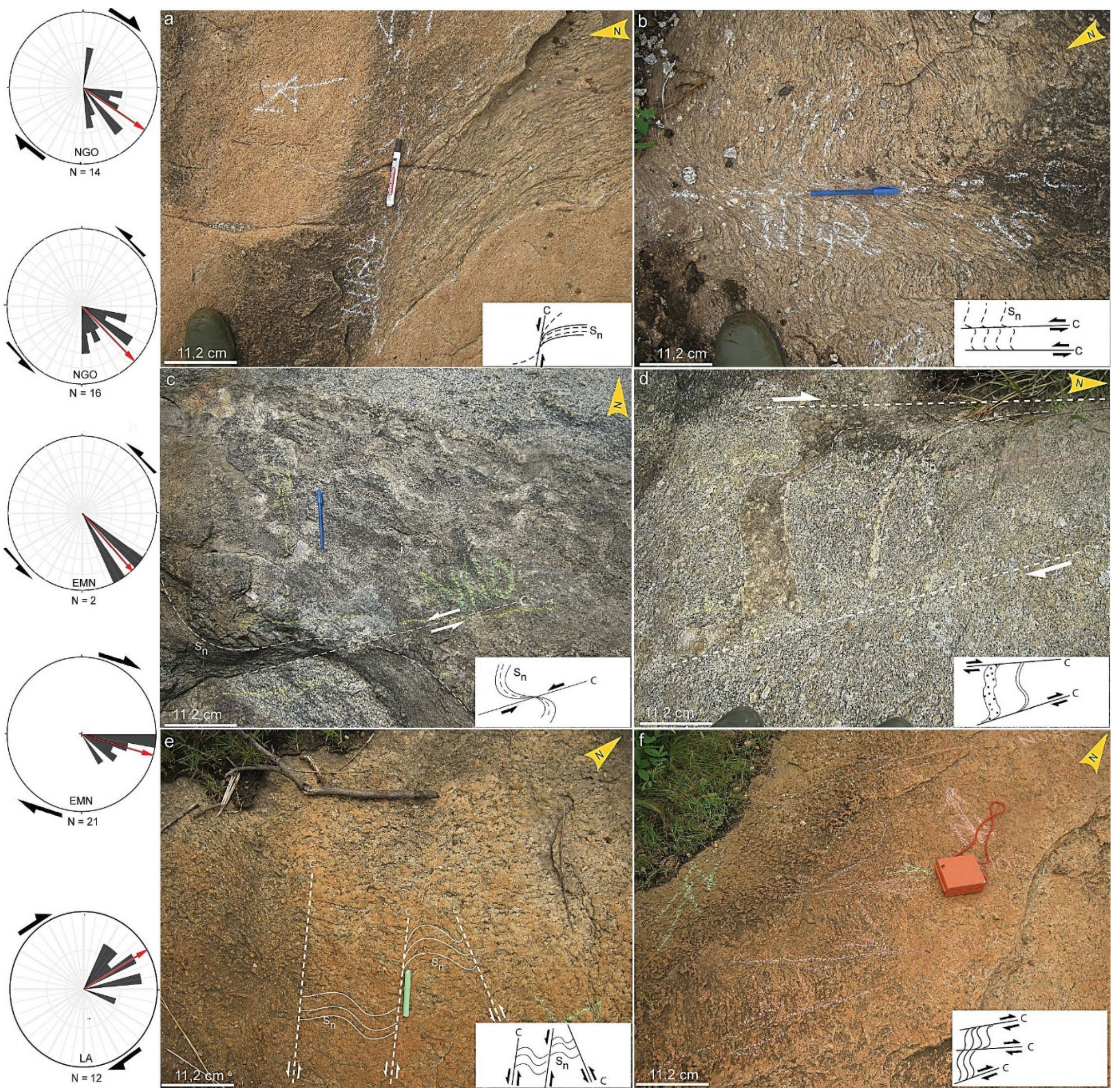

Figure 2. C-S ductile fabrics and directional rosettes of C shear bands. (a) dextral C/S fabric affecting deformed alkaline granites at the Emndobi site (EMN); (b, c) sinistral C/S fabric affecting deformed syenogranites at the Ngoura site (NGOU) and (d) sinistral C/S fabric affecting deformed leucogranites at Lala (LA)

Mylonitic schistosity S_n (XY)

The deformed granites are affected by S_n schistosity planes, with a sigmoidal configuration that is oblique to the C-shear plane. This schistosity defines mylonitic foliation and is characterized by alternating light millimetric and dark centimetric bands of quartzo-feldspathic and ferromagnesian minerals. At the Lala site, the orientation of the flattening S_n (XY) planes is oriented between the N30E and N54E directions, dipping between 32° and 45° to the NW and WNW. The best fit of poles along the XY planes is shown by stereographic plots, with the compression marker (σ_1) in the 256/24° and the extension marker (σ_3) in the 359/27° direction (Fig. 3).

At the Emndobi site, the S_n (XY) planes have an average trend of N40E with relatively gentle dips of 30°-31° to the NW. The best fit of the poles of these schistosity planes is N130E, which shows average compressional attitudes (σ_1) of 130/59° and maximum stretching (σ_3) of N040E (Figs. 3-4). The Ngoura site, on the other hand, shows an average foliation direction of the S_n (XY) of N74 ± 6.1E, with a prevalence of N60E and N70E trends. These moderately inclined planar fabrics have dip values between 19° and 90° to the NNW, NW, N, and NNE. They are associated with the Ln stretching lineations of feldspar minerals with a mean azimuth of N346 that plunges between 12° and 52° towards the NW and NNW (Figs. 3-4).

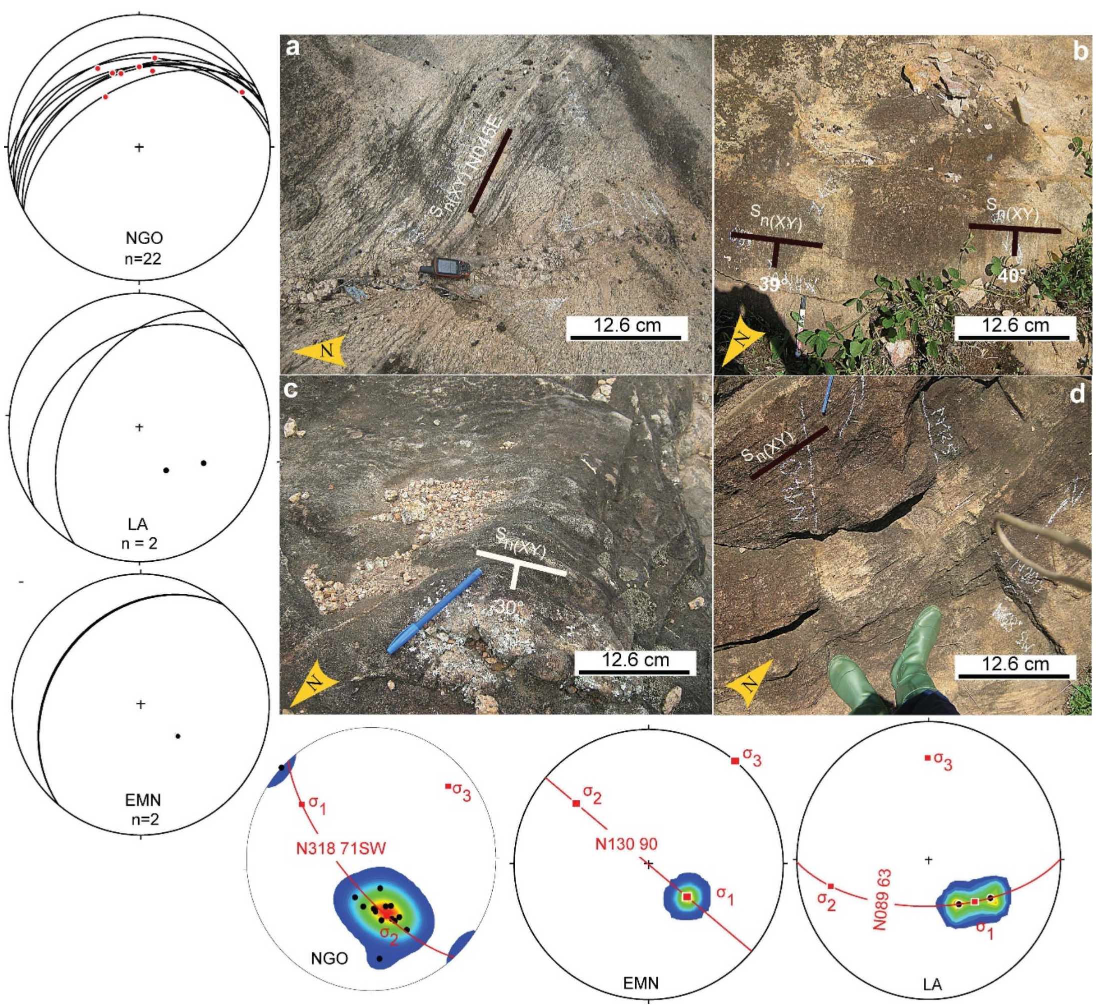

Figure 3. S_n (XY) schistosity and polar projection in the lower hemisphere of the Schimdt grid: (a, b and d) schistosity plane affecting the Ngoura syenogranites. (c) (XY) plane, affecting the basic formations of Emndobi

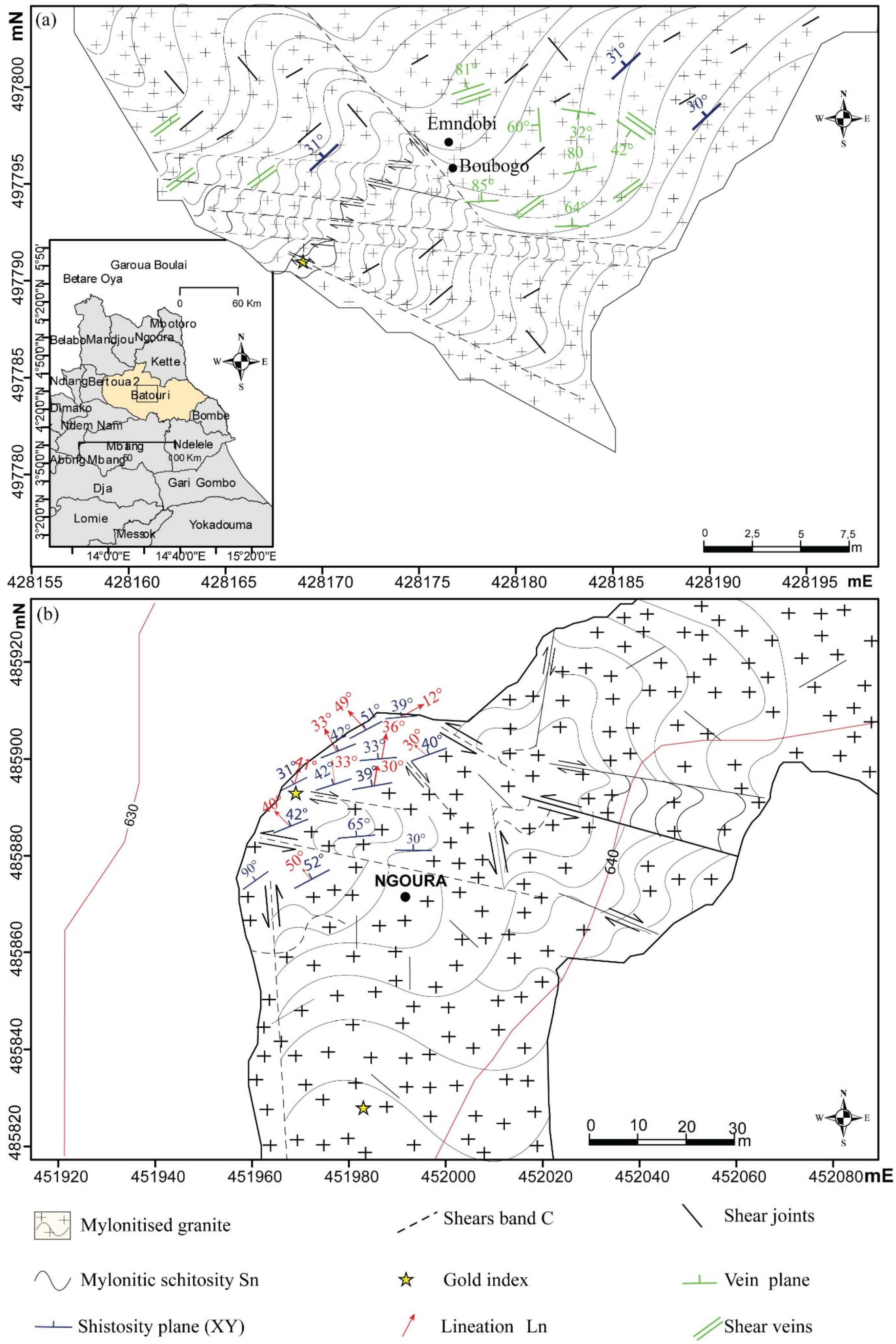

Figure 4. structural map of study area

The best fit obtained from the poles of the S_n (XY) schistosity planes shows a N138E and 71SW attitude, with a 306/31° maximum compression (σ_1) attitude and a 48/18° attitude of extension (σ_3) (Fig. 3).

Asymmetric grain features

These fabrics are observed in deformed syenogranites in the Ngoura area. They are defined by asymmetric feldspar porphyroclasts that illustrate a sinistral rotation within the intrafolial boudins bound by mylonitic schistosity (Fig. 5).

Semibrittle markers

Tension gashes

Semi-brittle fabrics in these formations are quartzo-feldspathic in composition and display maximum compressional orientation (σ_1). These sigmoidal planes show no visible dip plane on the outcrops. At the Emndobi site, these structures have an average direction of N117E. Meanwhile, the Ngoura site shows perfectly sigmoidal markers with an average trend of N58E (Fig. 6). The Lala structures are less sigmoidal and show an average direction of N036E. Following the variation in the trends of these structures, the Emndobi site belongs to a local ESE-WNW compression (σ_1) and NNE-SSW elongation (σ_3) (Fig. 6). The Ngoura sector, on the other hand, has experienced an average local ENE-WSW compression (σ_1) and a local NNW-SSE elongation (σ_3), whereas the Lala site suffered an ESE-WNW compression (σ_1) and an ENE-WSW extension (σ_3) (Fig. 6). Ngako et al. (2003) also identified tension gashes in the Ngoura gneisses (east of Cameroon), which were N150E and represented a sinister shear movement.

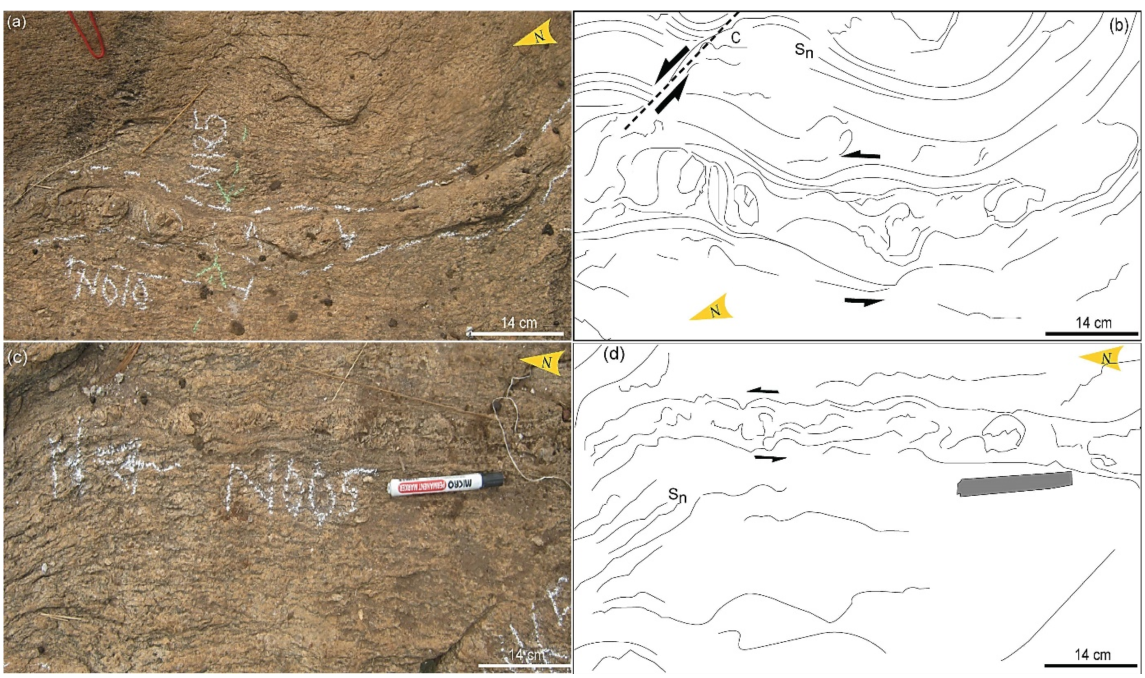

Figure 5. Asymmetric grain features. (a) dextral asymmetric porphyroclast within the intrafolial boudins at the Ngoura site (b) Illustration of the features of asymmetric grains

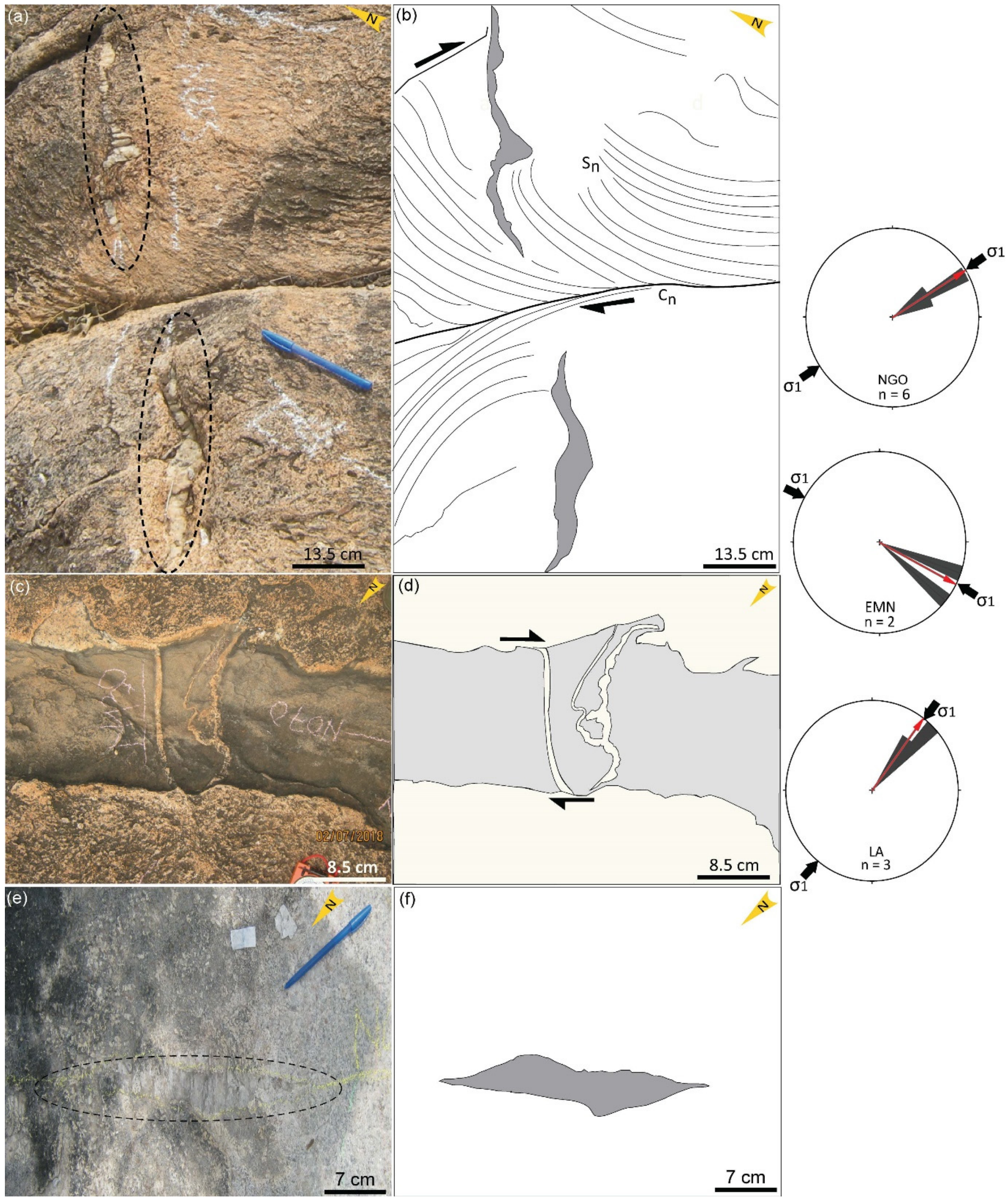

Figure 6. Tension gashes and associated directional rosettes. (a, b, c, and d) sigmoidal gashes in the deformed Syenogranites of Ngoura (NGO); (e) tensional gashes in the deformed leuco-granites of Lala (La) and (f) tensional gashes in a belt of mafic rocks at Emndobi (EMN) EMN= Emndobi, LA= Lala, NGO=Ngoura

Shear joints

These fabrics affect the Ngoura syenogranites and the quartzo-feldspathic veins of Emndobi and Lala. Directional rosettes in the Ngoura area show an average NW-SE trend with a recurrence of the WNW-ESE direction. They show three main orientations: NNE-SSW, WNW-ESE, and N-S (Fig. 7). At the Lala site, an average NE-SW trend with NNE-SSW and NE-SW structures is common (Fig. 7). In general, the fabric within the Lala site is directed NNE-SSW, NNW-SSE, NE-SW, ENE-WSW, and E-W (Fig. 7). Meanwhile, the Emndobi site shows joints with dominant NE-SW and ENE-WSW trends. These mesostructures are organized into E-W, N-S, NNE-SSW, and NE-SW trends. Overall, the three mining sites show the prevalence of NNE-SSW, NNW-SSE, NE-SW, and NW-SE directions of joints. The generations of joints are younger than the local mylonitic schistosity (S_n), as they are being intersected at these three sites. The NW-SE and NE-SW directions show parallelism with the directions of the tension cracks, which correspond to the two episodes of crustal compression σ_1: WNW-ESE and σ_1: NE-SW at the sites of Lala, Emndobi, and Ngoura. These different fabrics, which illustrate the beginning of the rupture of the different granitic intrusions subjected to stress, reflect a D_2 phase of partial deformation during the Pan-African orogeny.

Brittle mesostructures

Shear veins

These veins are mostly quartzo-feldspathic, displaying milky and pinkish appearances, and are common within the Emndobi site, where they are overturned by shearing (Fig. 7). In all mining sites, they cut through the duricrust top layer as well as the monzo- and syenogranites. These veins generally follow the C-shear planes defined by quartz recrystallization. In some cases, recrystallized quartz forms geodes-like features within reactivated structures that might have enhanced the remobilization of the quartzo-feldspathic fluids.

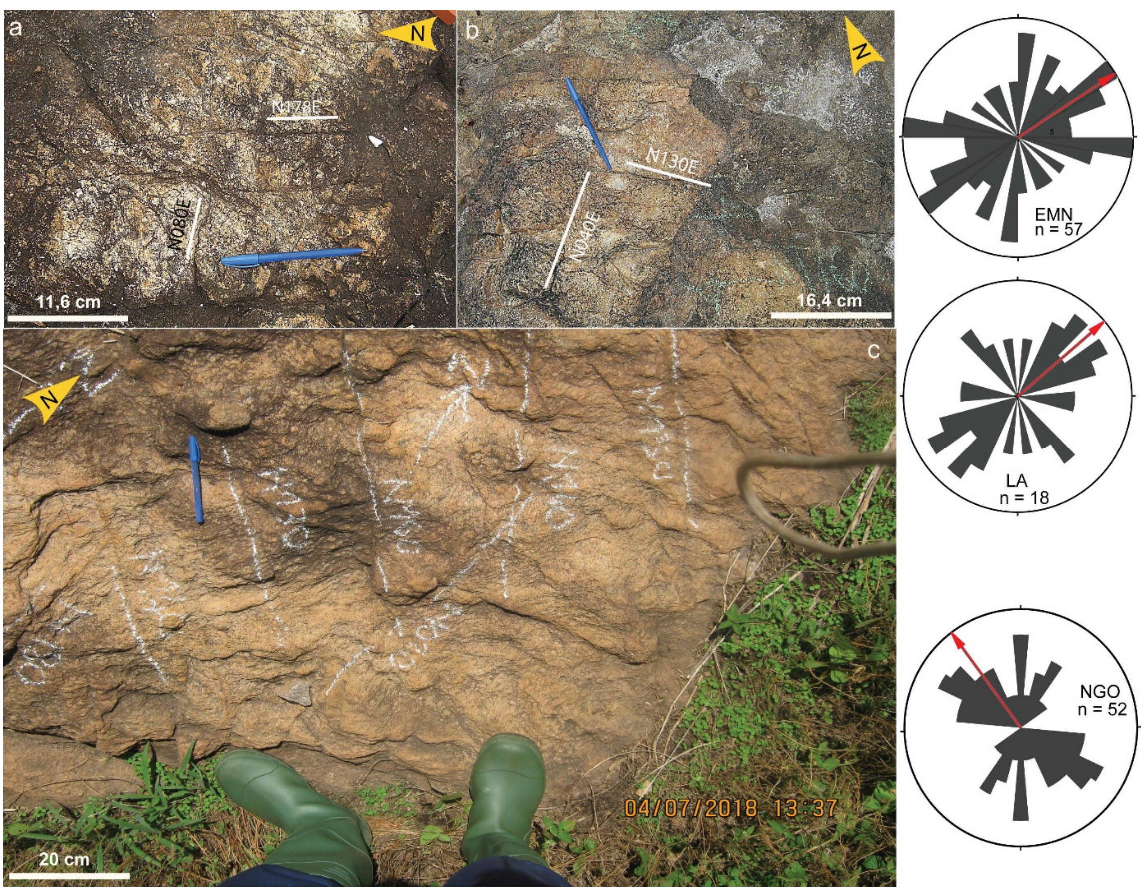

Figure 7. Shear joints and associated directional rosettes. (a) shear joints affecting quartzo-feldspathic veins at Emndobi, (b) shear joints affecting quartzo-feldspathic veins at Lala and (c) shear joints affecting schistosity on a granitic massif at Ngoura. EMN = Emndobi, LA = Lala, NGO = Ngoura

They display right-lateral and left-lateral kinematics. At this site, directional rosettes display NE-SW, NW-SE, E-W, and N-S vein orientations. The dominant directions are NE-SW and ENE-WSW, with an average NE-SW trend being recorded. The planes of these veins show E-W, NE-SW, N-S, and NW-SE directions, with high dip values between 76° and 90° to the N, W, NW, WNW, and E directions (Fig. 8).

The E-W direction corresponds to an alluvial gold mining site from which metric-sized quartzo-feldspathic veins emerge (Fig. 8f). At the Lala site, the veins present the following directions: NNE-SSW, N-S, and NW-SE trends, with a dominant NW-SE direction (Figs. 8). Meanwhile, the Ngoura veins are poorly represented. The stereographic analysis of the 31 vein planes reveals four generations of planes, with an average of N075 for N090, N120, N045, N061 and N070. These planes have a moderate to steep dip, with dip values ranging from 22° to 90° to the north, south, and east. The planes strike in the same direction as the slip planes, with dips between 01° and 32° towards the E, ENE, and SW directions (Fig. 8). The analysis of the poles of best fit gives planes N248.09 NW of finite compression σ1: 250/00° and finite extension σ3: 158/80 (Fig. 8). The variations in the directions of the vein and dip planes show the rotational character of the shearing deformation and are consistent with the sigmoidal configuration of the Sn mylonitic schistosity in the area. It should be noted that the veins trending NE-SW, ENE-WSW are syn-tectonic to the directions of the S_n mylonitic schistosity of the Ngoura sites. Whereas, the directions NW-SE, and NNE-SSW are syn-tectonic to the directions of the joints. The families of NE-SW and NW-SE trending veins are syn-tectonic with the tension cracks that define the initial crustal compression σ_1: NE-SW and σ_2: ENE-WNW. Meanwhile, the veins trending NE-SW, NW-SE, and E-W are the most mineralized.

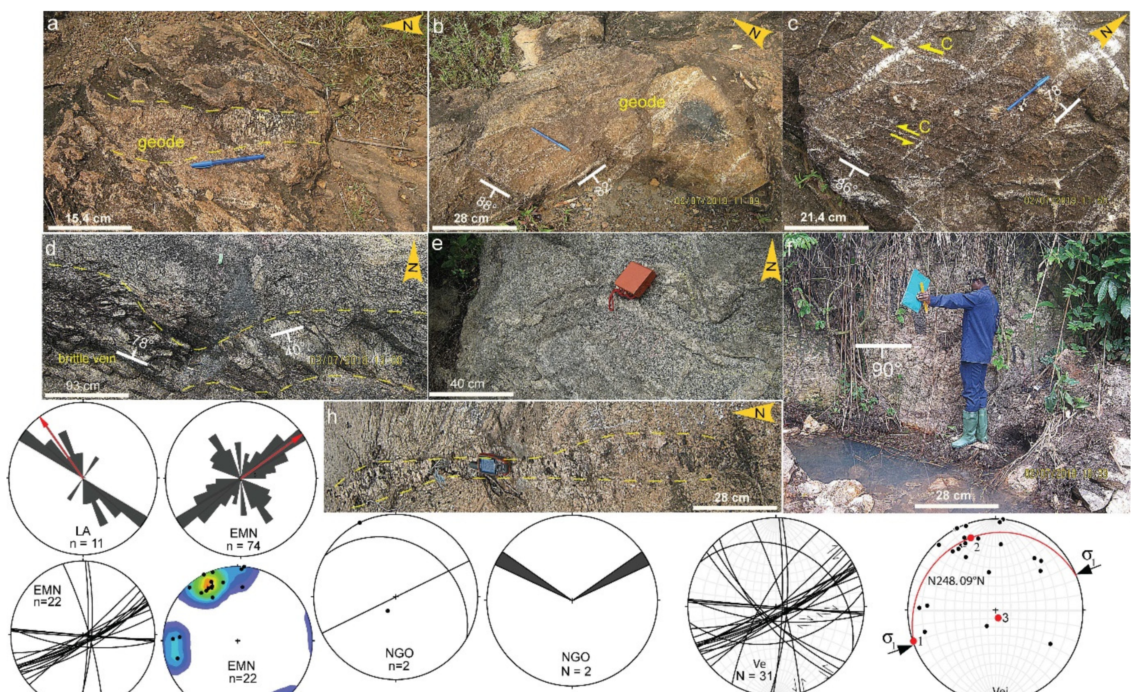

Figure 8. Shear veins and associated directional rosettes. (a, b,c) recrystallized quartz veins at the Emndobi site (EMN), (d,e) sheared veins at the Lala site (La), (f) E-W trending quartz-feldspar vein at the Emndobi site (EMN). The associate analyses stereographics and paleostress directions are those of the of synthesis of shear vein planes (Vei) from the sites Emndobi (a, b, c and f), Lala (d and e) and Ngoura (h); EMN-strerographics referred to stereographic analyses of shear plane veins of Emndobi (a, b, c and f)

Riedel faults

These brittle fabrics form an en-echelon within the right-lateral C-shear band, represented by the antithetic R' and synthetic R faults. The antithetic R' faults have a mean direction of N016E and form 75° angles with the main N91E band. The synthetic R faults of dextral polarity are oriented N084E. They are formed with the main shear band trending N91E at an angle of 7±5° (Fig. 9). The dihedral angles 2θ between the planes (R and R') are between 78° and 80° and admit σ1 as a bisector of direction N60. The presence of the Riedel faults and a strong dihedral angular value approaching 90° reveal extensional shearing.

Microstructures

Rock samples from the different studied sites show a dominant proportion of quartz phenocrysts, deformed feldspars, brecciated bands, and C/S kinematic fabrics within their matrices. These phenocrysts, which give a gritty porphyritic texture to the studied rocks, occur as stretched lenses and are haloed by mica minerals (Fig. 10b-e). The deformed quartz and feldspar minerals also display coiling minerals that form σ and δ structures in the shear bands (Fig. 10a-b). The sigmoidal S_n schistosity is expressed by feldspar and quartz minerals, which define S-bands on either side of the C-plane with which they form the composite C/S fabrics (Fig. 9a). Bands of quartz and k-feldspar breccia interleave the foliated in these deformed granitoids (NGU2) (Fig. 10h).

Petrofabrics

These are mylonitic fabrics common within deformed granites in this area. These granites form hills and range in colour from light in the Lala and Ngémo (north of Ngoura) GU2E2 and GU2 sites (Fig. 11) to pinkish at the Ngoura (NGO1E2) site (Fig. 11b-c). These petro-fabrics show foliations characterized by alternating light centimetric and dark millimetric bands (Fig. 11a-c). The light bands are composed of quartzo-feldspathic minerals, while the dark bands are defined by the preferred orientation of ferromagnesian minerals, including muscovite, biotite, and amphiboles. The matrix of these rocks presents at microscopic scale, with nearly 50% quartz and feldspar porphyroclasts (Fig. 10). Assah et al. (2015) identified monzogranites and syenogranites as the main granitic intrusions in the Batouri area. U-Pb and Ar-Ar dating of these rocks show an age between 620 and 640 Ma (Assah et al., 2015). The regional geological cross-section (Fig. 12a) showing the N-S evolution of the Pan-African NE chain (Toteu et al., 2004), coupled with the E-W local geological cross-section (Fig. 12b).

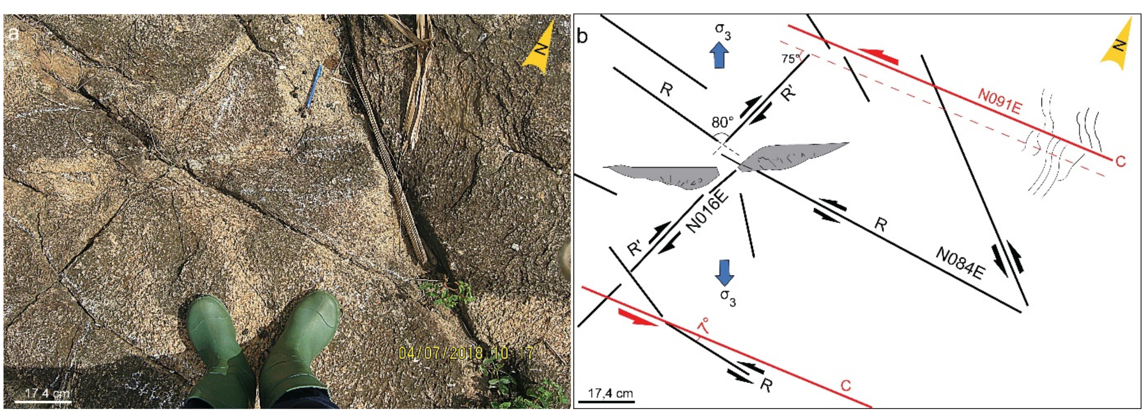

Figure 9. Brittle R and R’ faults. (a) R and R' synthetic and antithetic Riedel faults, respectively, and the main C shear band, affecting the Ngoura syenogranites; (b) geometric illustration of those faults

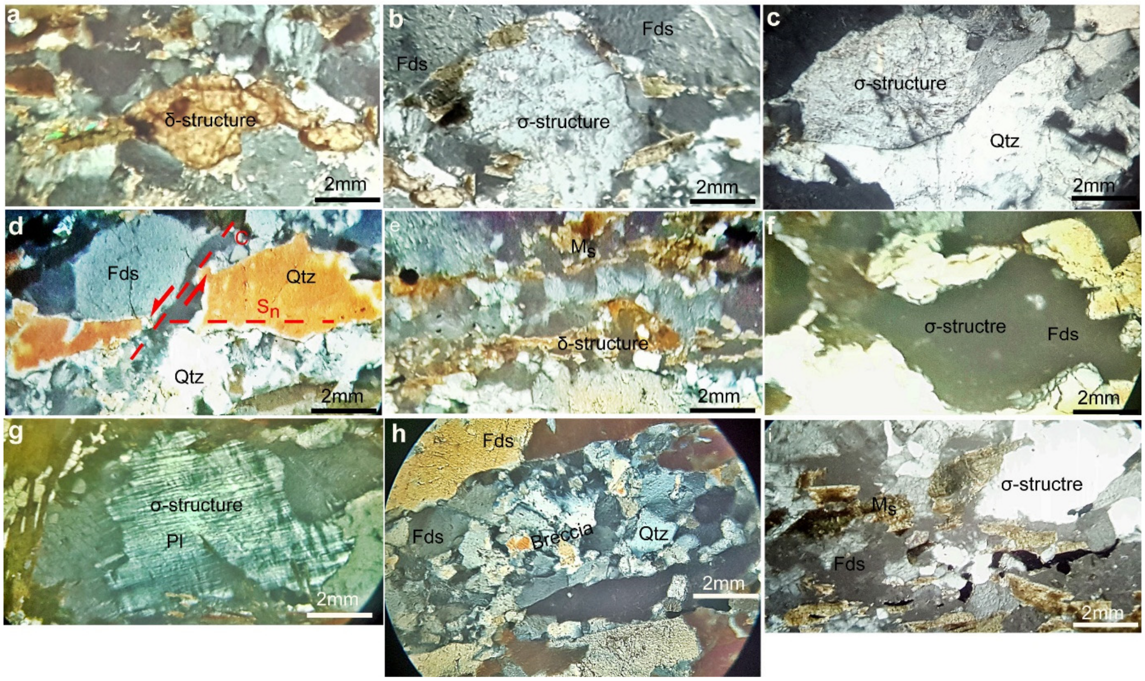

Figure 10. Photographs of the different microstructures observed at the investigated sites (a) δ-structures of feldspar, (b, c, f, g and i) σ-structures of quartz and feldspar, (d) C/S fabric materialized by quartz and feldspar minerals in the lens, (e) foliation and σ-structure of muscovite, (h) breccia band composed of quartz and feldspar minerals from Ngoura and Lala sites

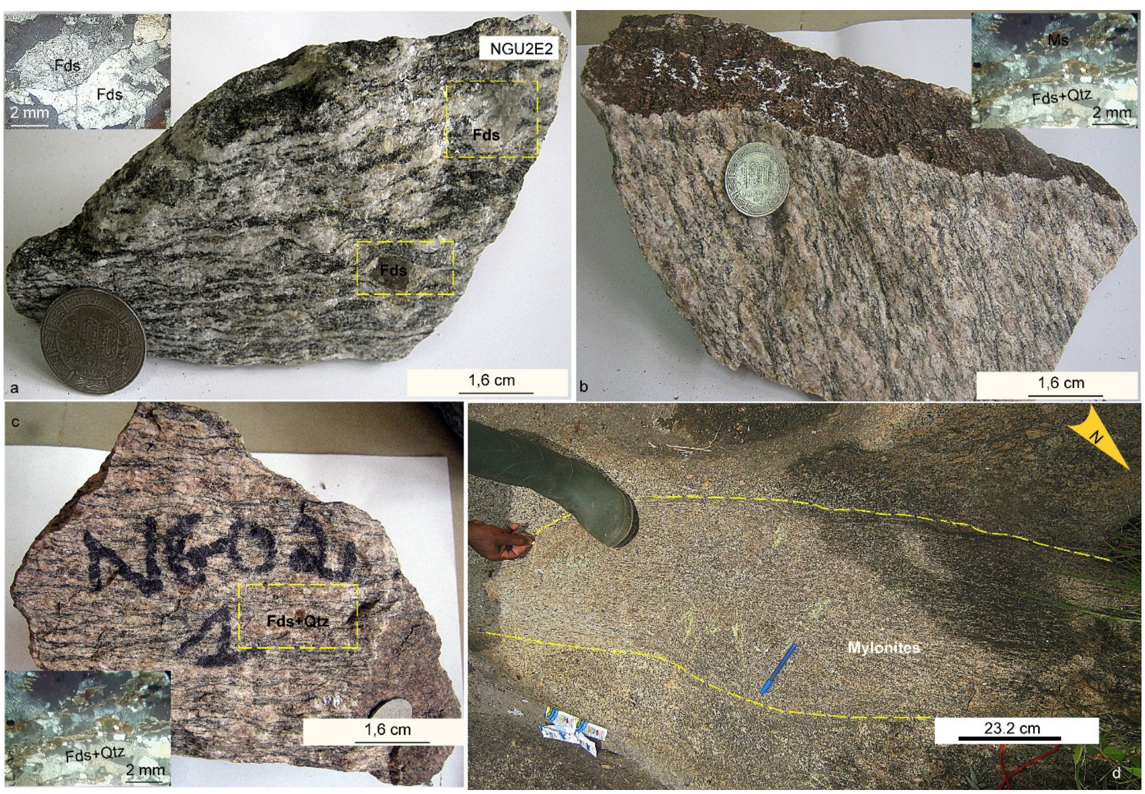

Figure 11. Mylonites. (a) Deformed granites with quartz and feldspar porphyroclasts; (d) N130E-trending mylonite band in the Lala site

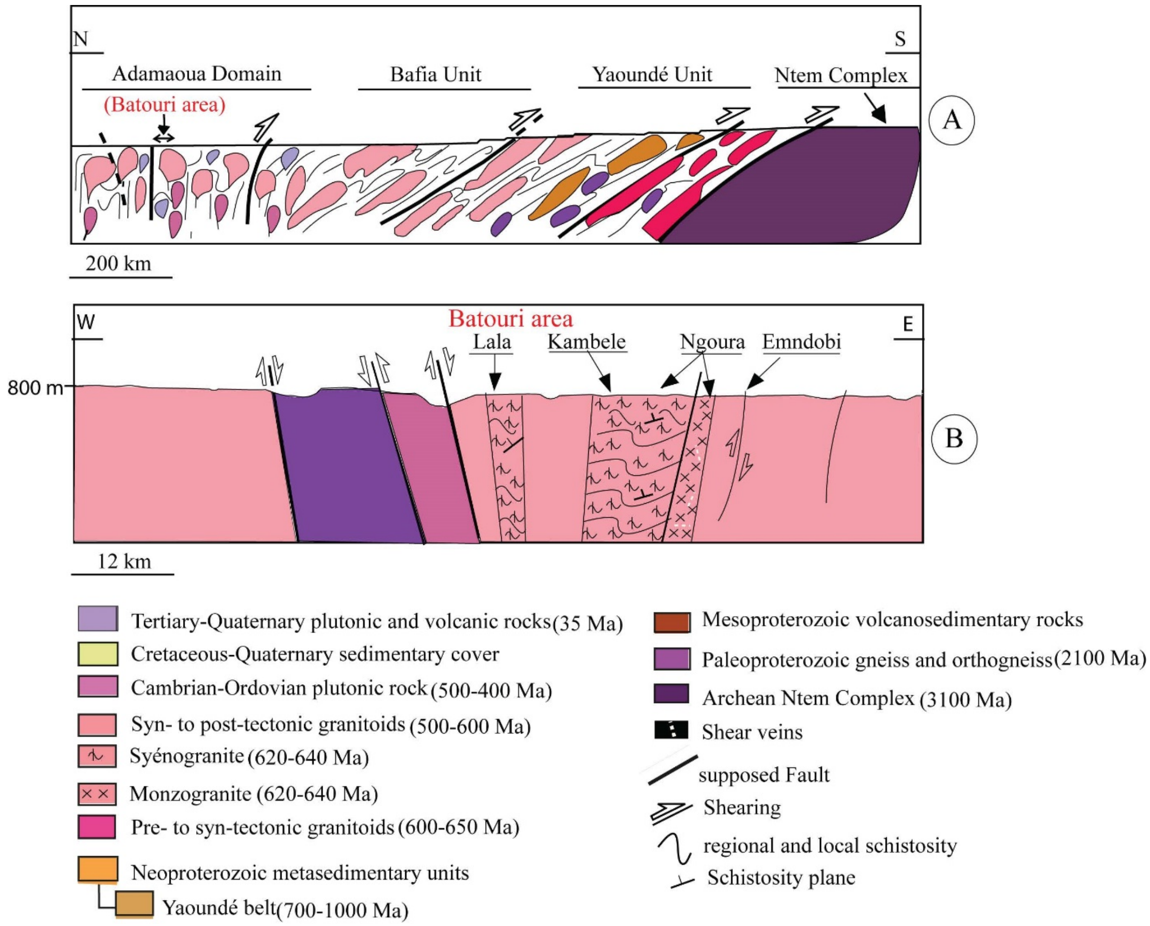

Figure 12. Illustration of regional and local geological sections. (A) Schematic representation of the evolution of the Pan-African chain in the Southern Cameroon Domain (Toteu et al., 2006b); (B) sketch of the E-W geological cross-section of the Batouri area

Moreover, it shows that the Batouri basement is essentially made of mylonitic monzogranites, with a band of mylonitic syenogranite visible at the Ngoura site. These shear fabrics are commonly crosscut by faults and veins.

Shear zone geometry

Mylonitic schistosity C/S

Referring to the mean C/S directions affecting the deformed granitoids of the study area (Figs. 2-4), it is observed that the three main shear directions, including N058E (Lala site), N91-100E (Emndobi site), and N140E (Ngoura) (Fig. 13), define the brittle-ductile shear movement in the area. The near rectilinear main shear directions delimit three main shear bands of identical average directions, which give the shear a geometry with three branches: NW-SW (Ngoura), NE-SW (Lala), and E-W (Emndobi) (Fig. 13). Inside these shear bands, which structure the local shear, an S-shaped sigmoidal schistosity develops. This sigmoidal character of the Sn schistosity is justified by a variation in the directions and dip of the schistosity, which vary from N030-040E in the Lala and Emndobi sites, and from N070-060E to Ngoura; the dip values vary between 30-32° to the NNW and NW in the Lala and Emndobi sites and between 19-90° to the NNW and NW in the Ngoura site (Figs. 3,4, and 8).

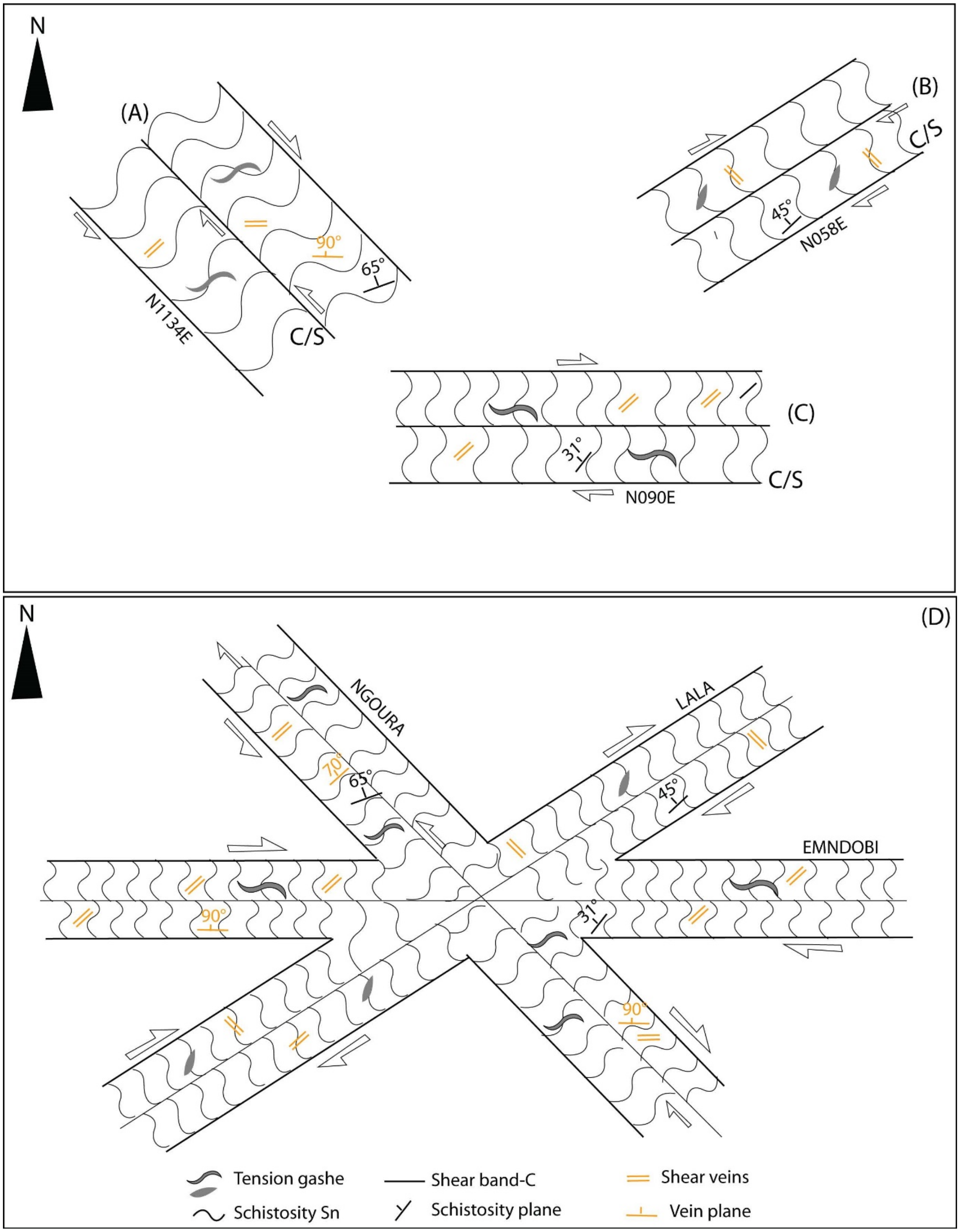

Figure 13. Shear zone geometry. (A) NW-SE band affecting the Ngoura area; (B) NE-SW band affecting the Lala zone, and (C) E-W band affecting the Emndobi zone and (D) overall geometry of the Batouri shear zone

Feldspar stretching lineations

Feldspar stretching lineation's show varying directions and dips due to shearing. At the Ngoura and Lala sites where they have been identified, these structures show respective trends between

N014E and N130E, with an average dip of 12° to the NNE at Lala, and 52° to the NW.

Deformation Conditions

The Batouri area forms part of the Adamawa-Yadé domain (AYD; Fig. 1) of the CAFB in Cameroon. This belt consists mainly of recycled and juvenile rocks that are specifically represented at Batouri by syn- to late-collision calc-alkaline granitoids. Shear deformation conditions of these granitoids result from high-grade metamorphism caused by the collision of the West African Craton with the Congo Craton (Toteu et al., 2004; Tanko Njiosseu et al., 2005; Van Schmus et al., 2008). This metamorphic gradient is related to the exhumation of high-grade metamorphic rocks. Previous reports (e.g., Ngako et al., 2003 and references therein) defined the thermobarometric parameters of this metamorphism at a temperature of 750-800°C and a pressure of 10-12 kbar. The shear fabrics within these granitoids and the chemical modifications they exhibit (Assah et al., 2015) indicate dominant plastic deformation, resulting from a high strain rate associated with mylonitization and syntectonic igneous intrusions (Bell & Johnson, 1989).

Alteration types

Silicification is marked by the presence of abundant quartz veins and quartzo-feldspathic tension gashes observed on outcrops and core samples. Disseminated quartz occurs at mineral interstices and grain boundaries and forms matrices in the rocks. Silicification is characterized by the association of quartz with pyrite and gold mineral assemblages.

Quartz blocks and the core samples show that sulfides and iron oxides form part of the alteration phases associated with this mineralization. These oxides are observed within quartz blocks, where they form a reddish coating around quartz, feldspars, and pyrite. Hematite occurs as the main oxide common around quartz vein margins and appears disseminated in the interstices between the feldspar minerals, thus giving the rock a reddish appearance. This alteration consists of quartz, pyrite, hematite, K-alteration, and a gold mineral assemblage (Fig. 14).

The recorded hydrothermal alterations identified in this study are marked by the progressive evolution of the deformation. The silicified zones, which are defined by veins and veinlets, occur in the host monzo and syenogranites. These structures correspond to the D_3 finite phase of ductile deformation. Based on the results, three directions of quartz veins defining silicification are common in the area. The NNW-SSE directions are represented by the Boumama mineralized watercourse; the NE-SW directions, which are syntectonic with the NE-SW branch of the CCSZ; and the E-W branch, which defines the Emndobi stream channel (Fig. 15).

Sulfuration and ferrugination are associated with zones of silicification and ductile C-S deformation. These are visible on the cores from the Kambele site and the mylonites from the Ngoura sites, in which pyrite and iron oxides occur in coarse-grained form (Fig. 14). This mineral alteration is syntectonic and also corresponds to the D_3 deformation. Potassium alteration is common within the syeno and monzogranite. This alteration is mainly controlled by the C-S shear fabric and corresponds to a D_2 ductile deformation phase. The gold nuggets alongside pyrite are disseminated in the quartzo-feldspathic veins that crosscut the Kambélé granitoids (Fig. 15a-c) and also in the sediments of the Mboumama stream trending NNW-SSE (Fig. 15b-d).

Relationship between ductile shearing and gold mineralization

The C-S fabrics that define the ductile shear markers are generally accompanied by a potassium alteration (Fig. 16).

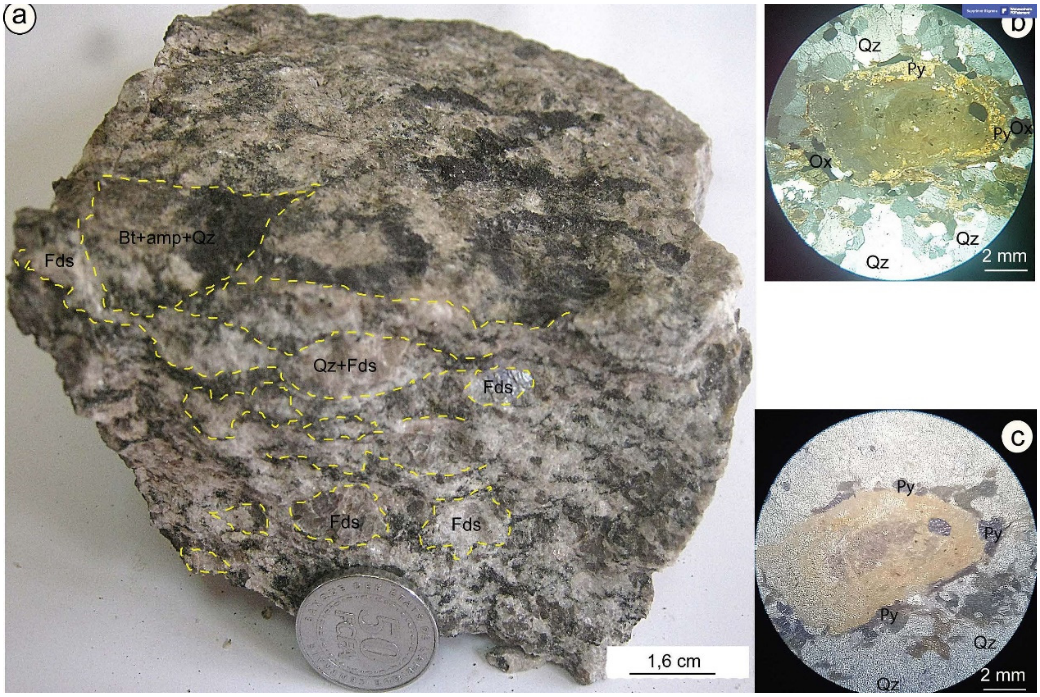

Figure 14. The presence of pyrite in a deformed monzogranite from the Ngoura site. (a) deformed monzogranite, (b-c) pyrite under the cross (PL) and plane (PPL) polarized lights

Figure 15. (a-c) Grains of gold disseminated in the quartzo-feldspathic veins of the Kambélé site; (b-d) gold nuggets from the pan bottoms of the Boubama stream

Figure 16. Drill cores from the Kambélé site show the relationship between ductile fabric and gold mining. (a-b-c) core showing feldspars and quartz veins which are accompanied by pinkish potassic alteration, (e-f) quartz fragments showing sulphides

This alteration is accompanied by gold mineralization found within the mylonite matrix, as observed in drill cores from the Kambelé site. These ductile fabrics are frequently cross-cut by mineralized veins that trend E-W, NNW-SSE, and NE-SW and postdate the C-S fabrics. Gold mineralization follows the C-S branches of the ductile shear bands trending E-W within the Emndobi site, NE-SW at the Lala site, and NW-SE at the Ngoura site (Fig. 16).

Discussion

Geometric configuration of the shear zone

Three conjugate shear zone branches

The Batouri local shear zone presents a geometry with three conjugate branches in the NE-SW, NW-SE, and E-W directions (Fig. 12). These three branches are justified by the analysis of the rosettes' directions, which show the direction of the average shear band C: N091E, N100E (Emndobi site), N058E (Lala site), and N140E (Ngoura site). These directions have also been described at a regional scale within the Poli group north of Batouri (Ngako & Njonfang, 2017). They are directed N050 of the sinistral shear zone at the Buffle Noir Mayo Baleo (BNMB) and to the E-W direction of the dextral shear zone of the Vallée des Roniers SZ (VRSZ), and Demsa (DSZ) from phase D3 (Fig. 17).

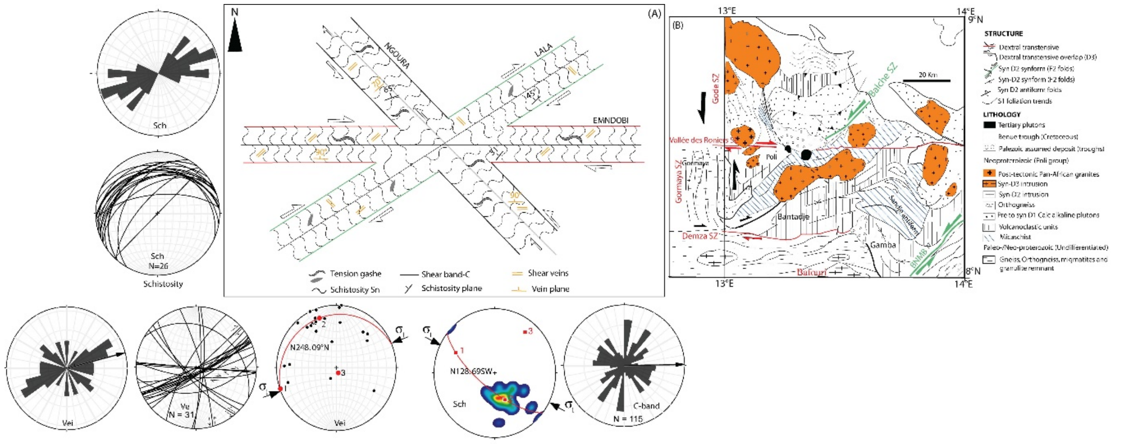

Figure 17. Structural synthesis. (a) overall shear geometry; (b) shear regional areas of the Poli group (Tchakounté et al., 2017), the associate analyses stereographics and paleostress directions are those of the synthesis of shear vein planes (Vei) from the sites Emndobi (a, b, c and f), Lala (d and e) and Ngoura (h). (1) maximum compressive stress; (2) intermediate principal stress and (3) minimum principal stress. At the level of the density diagram, Ve=shear vein, Sch= schistosity

Schistosity sigmoidal configuration

The stereographic synthesis of schistosity fabrics coupled with vein rosettes shows a variation in the direction of schistosity within shear bands (Figs. 2, 3, 4, and 12). These variations are justified by a variation in the direction of the schistosity ranging from N30-70°E, including dip values between 19° and 90° towards the north direction. These variant directions have also been reported within the Meigaga orthogneisses (Ngako et al., 2003), striking N030 and N060 with dips of 60°N. These directions are consistent with the regional directions N070 of the Sanaga and N050 of the Lom series.

Shear veins or brittle C bands

The shear bands (C) show directional similarities to the quartzo-feldspathic veins observed in this study area. At Lala, the shear bands (C) have directions N31E and N40E and are similar to the veins in the Emndobi and Lala sites. The N91E and N100E directions of the shear bands (C) at the Emndobi site are consistent with the vein orientations of the site (N141E and N150E), while the Ngoura site is identical to the trends of the Lala veins. These veins show recrystallization of quartz minerals (Fig. 8a), defining weak shear directions. At the north of Sanaga in the Meiganga locality, Ngako et al. (2003) showed that the N030E directions of the shear bands are consistent with the pegmatitic veins cross-cutting orthogneisses. The analysis of the vein planes shows the rotational character of the deformation caused by varying plane directions from N61-120E with dip values ranging from 22° to 90° towards the N, S, E, and W directions. Sigmoidal shearing can also be justified by local variations of compression and extension. These defined a finite compression and extension stress resulting from the planes of the veins σ1: 250/00° and σ3: 158/80°, against semi-finished compression and extension from the schistosity poles σ1: 296/00° and σ3: 038/80° (Fig. 8).

Riedel shears and extensive tectonic

Riedel shears are well expressed in the syenogranites at the Ngoura site. They are en echelon within the dextral C-band of direction N91E. The N84E-trending R faults are synthetic because they form a 7±5° angle with the main N91E band and are similar in polarity to the C-band (N91E). The R' faults of trend N16E are antithetic because they form an angle of 75° with the C-band and are polarized in the opposite direction as those of the main N91E band. The dihedral angles that emerge from the junction of the R and R' planes are between 78° and 80°. They show angular values varying between 65° and 75° for R' faults and 15° and 20° for R faults, similar to those developed in the models of Cloos (1955). Measured dihedral angles from 78° to 80° describe pure shear in the area. These values are closer to those experimentally described by Cloos (1955), with 60°, 120°, and 90° for compression, extension, and pure shear, respectively. It appears that the studied shear zone expresses extensive tectonics since the paleo-stress $\sigma 1$ in direction N61E forms with the C-band at an angle of 31°. This local extension is characterized by a finite NE-SW compression materialized by the trend of $\sigma 1$, and a NW-SE extension expressed by the orientation of $\sigma 3$ N29W. This extensive model involving local Riedel faults is similar to the Riedel model developed by Ngako et al. (2006), which defines extensive tectonics and the orientation of regional structures within the mobile belt in Cameroon.

Local extension of the CCSZ

Structural analysis of the C-fabrics shows a local repetition of the N40E and N31E directions (mean: N58E) in the Lala zone. The trend of structures conforms to C-fabric in the Meiganga orthogneisses north of the Sanaga and the Kadei orthogneisses in the Lom series to the north (Ngako et al., 2003). The same N50E structures defined a large, 6 km wide, and 60 km long mylonitic band in western Cameroon between Foumban and Bankim (Njonfang et al., 2006). Based on these reports, the structure corresponds to the extensive relays of the Sanaga fault, whose overall direction is N70E, closer to the N91E direction observed at the Emndobi sites. Thus, the main directions N40E and N58E are local extensions of the CCSZ, with a regional global direction of N70E (Cornacchia & Dars, 1983).

Influence of the shear zone on gold mineralization

The Batouri shear zone displays evidence of gold mineralization, which is disseminated in the host granitoids, veins, and petrofabrics (Figs. 11 and 14). These conform to previous reports on gold mineralization in the area where disseminated gold in the host granites and associated wall rock is structurally controlled by quartzo-feldspathic stockwork veins, lodes, and pegmatite dykes (Asaah et al., 2015; Yannah et al., 2015). The three directions of gold mineralization identified as NE-SW, E-W, and NE-SW, which correspond to the main directions of ductile deformation within pan-African terrains, are common. Similar directions of shears and silicification have been demonstrated by Njonfang et al. (2008) in the Magba and Adamaoua areas, where they have been interpreted as conjugate fault systems. These mineralized structures are also reported in the neighboring gold districts within the NE-trending Betaré-Oya area (Ndonfack et al., 2021). These brittle and ductile structures provide permeability and pathways that allow for hydrothermal fluids to circulate and precipitate mineralization (Benedicto et al., 2008). Thus, structural control played an integral part in gold mineralization in the Batouri area and can be correlated with other deposits such as the Quadrilatero shear zone in Brazil that controls gold mineralization and associated wall-rock alteration in the direction WNW-ESE (Fabricio-Silva et al., 2019). In east Africa, this shear structure correlates with the Wadi Hodein gold-bearing quartzo-feldspathic shear veins (Abd El-Wahed et al., 2021).

Conclusion

The Precambrian portion of Batouri is affected by a ductile-brittle deformation. This shear zone has a geometry with three branches of average cardinal directions (E-W, NE-SW, and NW-SE), inside which a sigmoid schistosity (S_n) develops. The E-W and NE-SW branches, respectively, constitute the extension at the regional scale of the shear zones of the Poli Group, which are the Demza and the Balche Shear Zones. Local-specific markers of progressive deformation define this ductile-brittle character in the deformed granitoids that are characterized by C/S fabrics, shear veins, sigmoidal tension gashes, shear joints, asymmetric porphyroclasts, and mylonites. The identified shear veins, which refer to the brittle C-shear directions, are directionally structured into three branches with average directions of N112E, N140E, and N58E, displaying dextral and sinistral polarity.

Riedel faults, which are evident in the Ngoura locality, show extensive deformation characterized by a local NNW-SSE elongation and a finite ENE-WSW shear. The trend of the shear structures indicates a local extension of the CCSZ with a mean direction of N70E. This is justified by the existence of local trends N58E, N40E, and N30E that are similar to the regional directions of this mega-shear zone, notably the directions N30E, N50E, and N40E reported in the Meiganga and Kadei orthogneisses in East Cameroon.

The mylonites that characterize the shear zones are well displayed at the Ngoura site and are derived from the deformation of the syenogranites and monzogranites in the area. Gold mineralization in Batouri is accompanied by hydrothermal alterations, including silicification and sulphidation/ferrugination. These mineralizations are confined within the NW-SE, NE-SW, and E-W silicification structures.

Mineralization indices occur as gold grains or nuggets in the quartz veins. This mineralization is controlled by shearing through quartzo-feldspathic veins and granitoids.

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