Chapter

Deformation Features and Structures in Some Igneous and Metamorphic Rocks: A Case Study of Central African Fold Belt in Cameroon

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Abstract

The first phase is marked by the S1 foliation. The second phase is marked by fold (F_2), lineation (L_2), and boudins (B_2). The third phase is marked by subvertical foliation (S_3), shear (C_3), and lineation (L_3). The fourth phase is essentially a brittle phase. Granites present mostly magmatic deformation features; meanwhile, granite mylonites and gneisses present submagmatic to nonmagmatic deformation features. Mylonitization occurred during a ductile-brittle transition phase. Coarse-grained granites emplaced in the lower crustal level, while protomylonites and mylonites occurred in the middle crust and ultramylonites in the upper crustal level. Fine-grained granite was filtered and channeled through the middle crust shear zone areas to be settled on an upper crustal level as irregular spot within the ultramylonites and gneisses. Granites and granites mylonites were syntectonically emplaced during the D_3 sinistral shearing phase.

Keywords: Mgbanji, granitoids, deformation, ductile-brittle, syntectonically, shearing

1. Introduction

Igneous, metamorphic, and sedimentary rocks generally host structures or features characterizing their condition or their emplacement environment. For igneous and metamorphic rocks, the deformation features provide information on the condition of the emplacement, the tectonic environment, and or the protolith nature. The Central African Fold belt to which belongs the Mgbanji area is situated

between the Congo-Saõ Francisco and the West African cratonic masses, and it is mostly composed of Neoproterozoic plutonic and Pan-African metamorphic rocks [1–3]. The Mgbanji granites and their host gneisses present several deformation features testifying multiple deformation phases underwent by the area and the complex rock emplacement mechanism.

In this chapter, we present structural and petrographic data derived from systematic geological mapping, detailed petrographic descriptions, and structural characterization carried out in outcrops and rock thin sections coupled with kinematic studies in order to determine the petrography, the deformation phases, the origin, and the emplacement condition of the rocks.

2. Geological setting

The Mgbanji area belongs to the eastern part of the Adamawa-Yade Domain in the Central African Fold Belt (CAFB) in Cameroon (**Figure 1**). The CAFB was formed as a result of the convergence of the West African and the Congo-São Francisco cratons as well as the Sahara Metacraton during the assembly of West Gondwana [5, 6]. The CAFB is a major collisional belt that underlies the region from the West African craton to East Africa [3, 7]. It underlies parts of Nigeria, Cameroon, Chad, and Central African Republic, and extends further eastward to Sudan and Uganda [7]. Also known as the Oubanguide Fold Belt or the Pan-African Equatorial Fold Belt (PANEFB: [8]), the Central African Fold Belt in Cameroon belongs to the orogenic belt of Central Africa. It is a mega-chain-oriented E-W with a length of more than 5000 km over a 300-km width.

Three lithological domains have been identified in the CAFB in Cameroon, namely the Adamawa-Yade Domain (AYD), the Yaounde Domain (YD), and Northwestern Cameroon Domains (NWC) [3, 9]. Moreover, in [1, 10–12], the PANEFB (or CAFB) is subdivided into three (03) distinct geodynamic domains separated by four main shear and fault zones. They are from North to South:

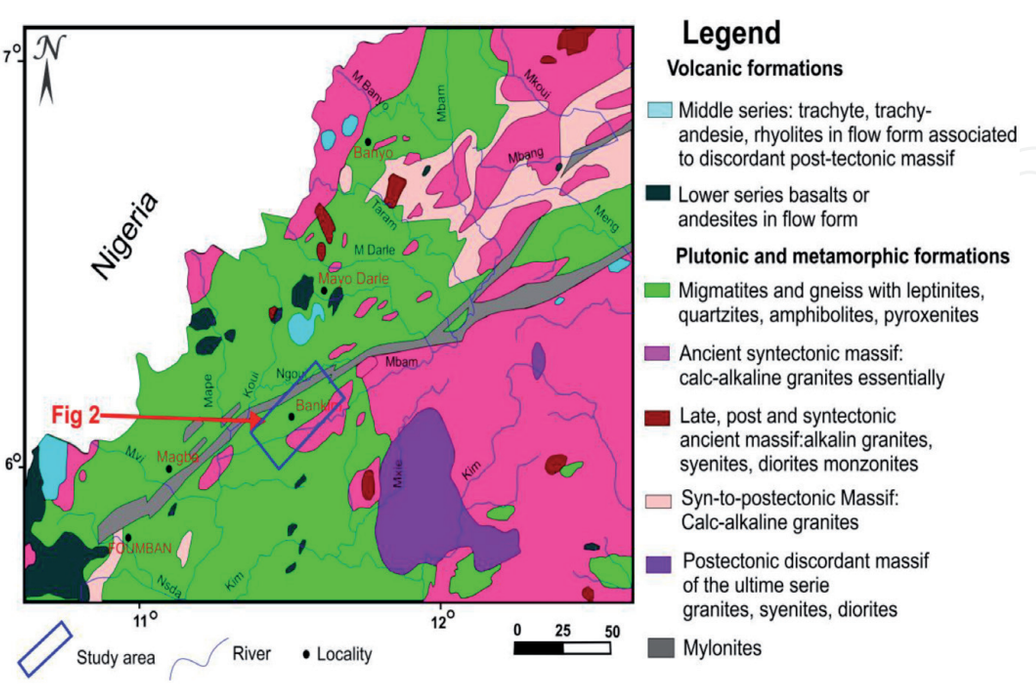

Figure 1.
Geological map of the western Adamawa Yade domain (modified from [4]).

the North Cameroon Domain, the Center Cameroon Domain, and the South Cameroon Domain.

The AYD [3, 9] or the Center Cameroon Domain [10] to which belongs our study area is the largest domain of the CAFB in Cameroon. It extends from the north of Bafia to the south of Poli. It is separated from the North by the Tchollire-Banyo fault (TBF), and its southern boundary is marked by the Sanaga fault. It displays syn to post-tetonic granitoids (leucogranites, granites, and syenites). These granitoids intrude high-grade gneisses that represent a Palaeoproterozoic basement, which was likely dismembered during the Pan-African assembly of western Gondwanaland [3, 9, 13]. According to [1, 10–12, 14], the geological formations of this domain are polycyclic and have been affected by three (03) deformation phases accompanied by metamorphic recrystallization in the amphibolite facies. The first phase D_1 is marked by a schistosity S_1, which carries a mineral line L_1; shear planes C_1; and the folds P_1. The metamorphism associated with this phase is characterized by the amphibolite facies assemblages from low to medium level. The second phase D_2 corresponds to a phase of transcurrent tectonics. It presents shear C_2, folds P_2, axial plane schistosity S_2, and lineation L_2. The associated metamorphism is characterized by assemblages of the amphibolite facies of high degree. Phase D_3 is a brittle tectonic phase, characterized by shear C_3 and large folds P_3.

Few geological works have been done in Mgbanji area. However, the early works taking into account the study area are mainly those done by [15–20]. Those studies demonstrated the presence of granites, gneisses, and mylonites on Foumban-Bankim shear zone that includes our study area. Those granitoids are igneous in nature and of calc-alkaline character. They are I-type and pre- to syn-tectonically emplaced [16, 19, 20]. Ntiéche et al. [20] demonstrated that the Magba area, adjacent to the Mgbanji area, underwent four phases of deformation under a transpressive tectonic regime.

3. Methods

For the field part of the work, a global positioning system (GPS), camera, clinometer, geological hammers, and map were used. This phase involved mapping, collection of samples, and investigation of structural elements on outcrops. A total of 30 samples were collected in the field. To assess the trend of structures, dip and strike measurements were taken. Other field assessment and tectonic features helped to determine the geotectonic setting of the rocks.

The laboratory phase involved the preparation of thin sections for petrographic study of selected samples. Structural analyses and petrographic studies were done by observing thin sections under the microscope. The deformation history and kinematic analysis of the whole area were deduced from the field measurements. Foliation and lineation, fault and shears trajectories along with meso-to-microscopic criteria of coaxial, or noncoaxial strain (e.g., symmetry or asymmetry of shear bands, boudins, and tails around porphyroclasts, fault, and folds) were studied.

4. Field relationship

Three main rock types are recorded in the Mgbanji area. They are granites, granite mylonites, and gneisses (**Figure 2**). Granites are mostly coarse-to-fine grained cropping in the hill top and the valley (**Figure 3(a)**). They are cropped in the form

of slab or dome of varying size (1–50 m long). They are gray or pink in color and host epidote veins in some outcrop (**Figure 3(b)**). Some outcrops present biotite flakes molding feldspar phenocrysts.

Medium- and fine-grained granites are mostly mylonitized and situated at the hill top or in the river bed. They are characterized by mantled and fractured feldspar porphyroclasts preferentially oriented.

Few coarse-grained granites outcrops show magmatic of stage (pre-full crystallization fabric (pfc)) marked by oriented feldspar porphyroclasts, while the mylonitized one show mostly solid-state deformation fabric.

Fine-grained granites display millimetric-sized quartz and feldspar with biotite flakes sparsely dotted in the rock.

Mylonitized granites are well represented in the study area. They occur as slabs or domes at the hill top and valley. Depending on the degree of crushing, granites mylonites can be classified into protomylonite, mylonites, and ultramylonites (**Figure 3(c)–(e)**). Some outcrops present banding or foliation marked by the

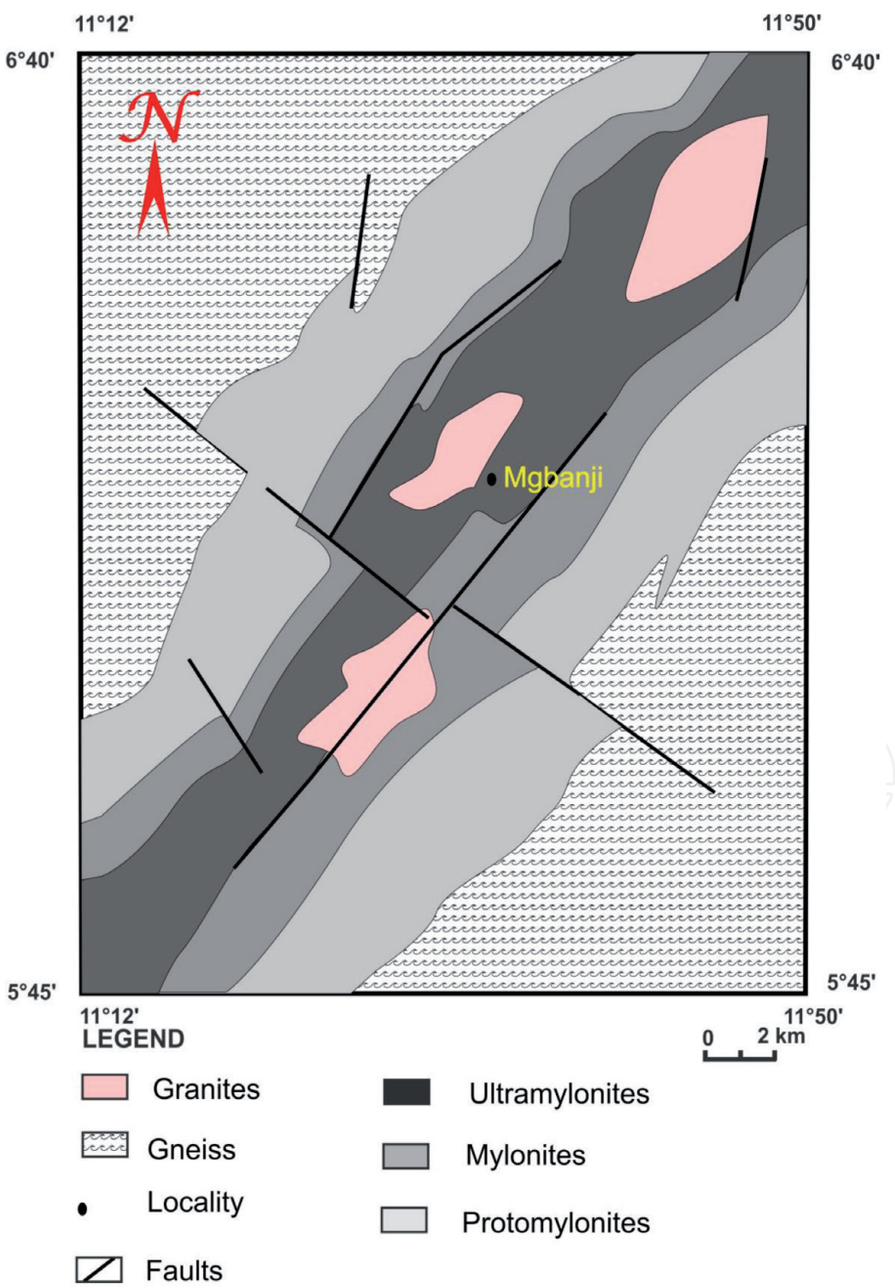

Figure 2.
Geological map of the study area.

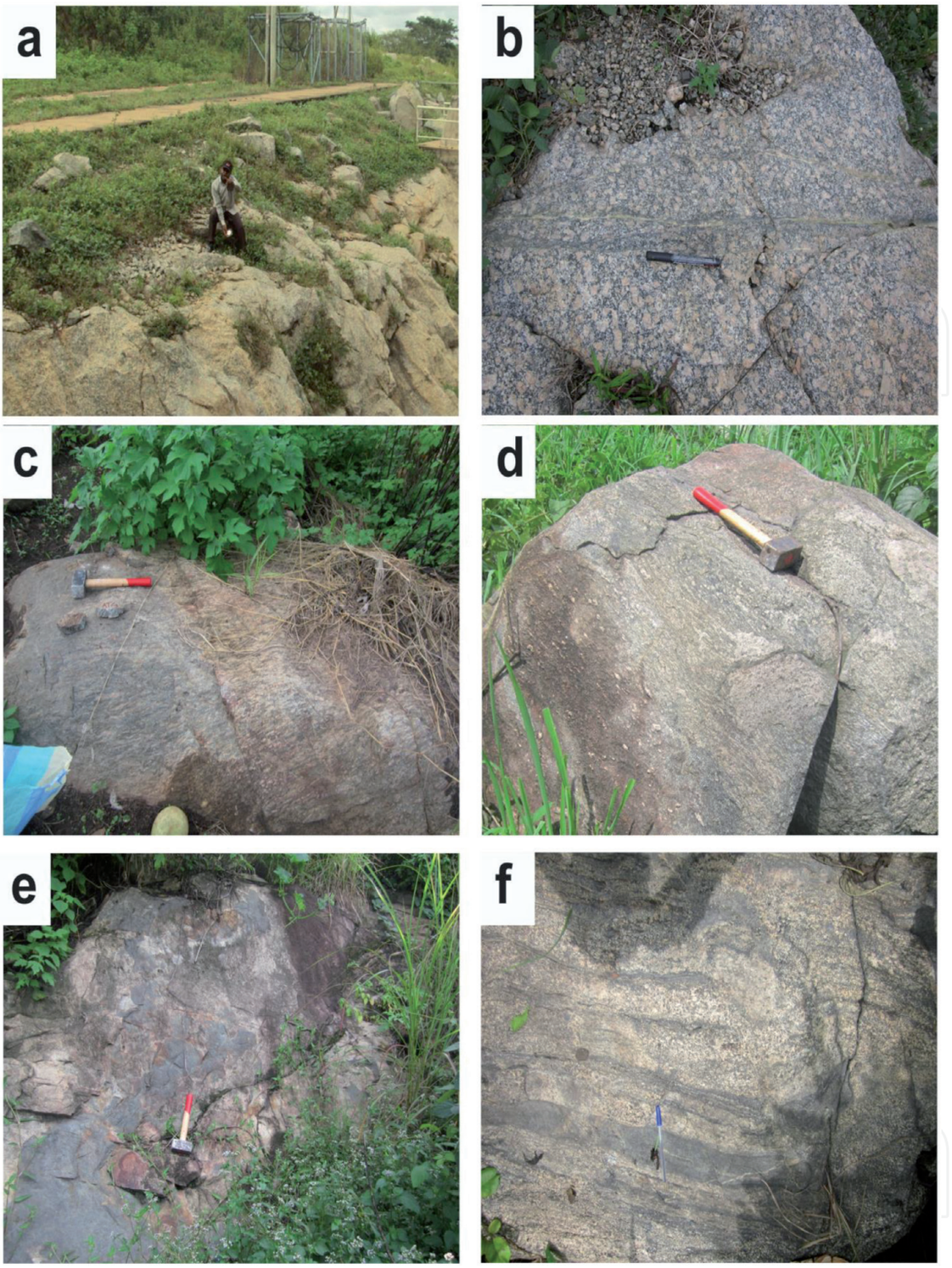

Figure 3.
Field photographs. (a) Fine-grained granite outcrop. (b) Coarse-grained granite outcrop. Note aligned and oriented euhedral K-feldspar megacrysts perpendicular to the epidote vein. (c) Protomylonite outcrop showing aligned deformed quartz and feldspar grains. (d) Mylonite outcrop with reduced quartz and feldspar grain size. (e) Ultramylonite outcrop presenting cataclasis marked by the reduction of the grain size to a pasty matrix. (f) Gneiss outcrop presenting foliation marked by alternation of amphibolites and quartzofeldspathic layers.

alternation of dark mafic and clear felsic bands. Clear bands present oriented sigma "σ" and delta "Θ" porphyroclasts, giving the sinistral sense of shear to the rock. They also present mineral lineation marked by aligned biotite, quartz, and feldspar porphyroclasts (**Figure 3(c)** and **(d)**). In some outcrops amphibolites injections are notice in the granite mylonite. The fine-grained mylonitized granites present some chlorite and epidote vein enrichments. The mylonitic foliation is outlined

by aligned biotite and quartz ribbons. In some places, the progressive increase in strain is marked by the presence of the protomylonite, mylonite, and ultramylonite subzones within the sheared granite.

Gneisses occur in a slab form and mostly confined to the hill slopes. They present foliation highlighted by alternating dark mafic and clear quartzofeldspathic bands (**Figure 3(f)**). In some places, lineations are characterized by the alignment of biotite flakes, quartz ribbons, and feldspar porphyroclasts.

Some gneiss outcrops present migmatitic features such as the combination of melted and unmelted gneissic components.

5. Microscopic features

5.1 Granites

Granites present coarse- to fine-grained texture and consist of quartz, feldspar, biotite pyroxene, and amphibole as principal minerals, while apatite, sphene, epidote, and opaques are the accessory mineral phase (**Figure 4(a)**). Sericite, perthite, myrmekite, and chlorite are the secondary minerals.

Quartz is fine- to coarse-grained and mostly anhedral and present in few places, tilled and imbricated porphyrocrysts. Quartz phenocrysts are associated to plagioclase and K-feldspar, while microcrysts are filling phenocrysts interstices. Some quartz grains develop from plagioclase porphyrocryst suggesting the incipient metasomatism during granite formation (**Figure 4(b)**). Plagioclases are predominantly subhedral and present twins. Some plagioclase laths are partially altered into sericite. K-feldspars are subhedral and mostly transformed into perthite. They are associated to quartz and plagioclase and present opaque inclusions in places. Biotites are subhedral and partially altered into chlorite. They fill quartz and feldspar interstices along with euhedral sphene (**Figure 4(a)**). Pyroxene and apatite are rare in the rock and occur respectively as subtabular and acicular crysts associated to amphibole and biotite.

5.2 Granites mylonites

Granites mylonites present granoclastic, cataclastic, and mylonitic texture (**Figure 4(c)**). They consist of quartz, K-feldspar, plagioclase, biotite, amphibole, pyroxene and microcline as principal mineral, chlorite and sericite as secondary minerals, and sphene and opaques as accessory minerals. The rock is marked by weakly to well-developed fabric characterized by elongated quartz and feldspar grains.

Quartz is in the form of polycrystalline ribbon preferably oriented and forming the clear band with feldspar. Some thin sections present also pasty or flame quartz molding feldspar and amphibole clasts. Some quartz and feldspar yield to brittle failure characterized by crystal fragmentation or shearing. In places, crystal underwent grain refinement through recrystallization. Some microclasts present waving or curved form testifying the deformation intensity (**Figure 4(c)**). Plagioclase and K-feldspar are subhedral to anhedral and present in places seritization reaction (**Figure 4(d)**). Plastic deformation is marked on feldspar by deformation lamellar, kinking or folding and the sigma "σ" and delta "Θ" porphyroclast giving the sense of shear to the rock. Mylonitic texture is developed in some thin sections and characterized by clear quartz and feldspar bands and dark ferromagnesian bands. In some places, subrounded feldspar and quartz are aligned in the clear band giving the ocellar mylonitic texture to the rock. Amphibole and biotite present flaky form or fish-like structure testifying the deformation of the rock. In some places,

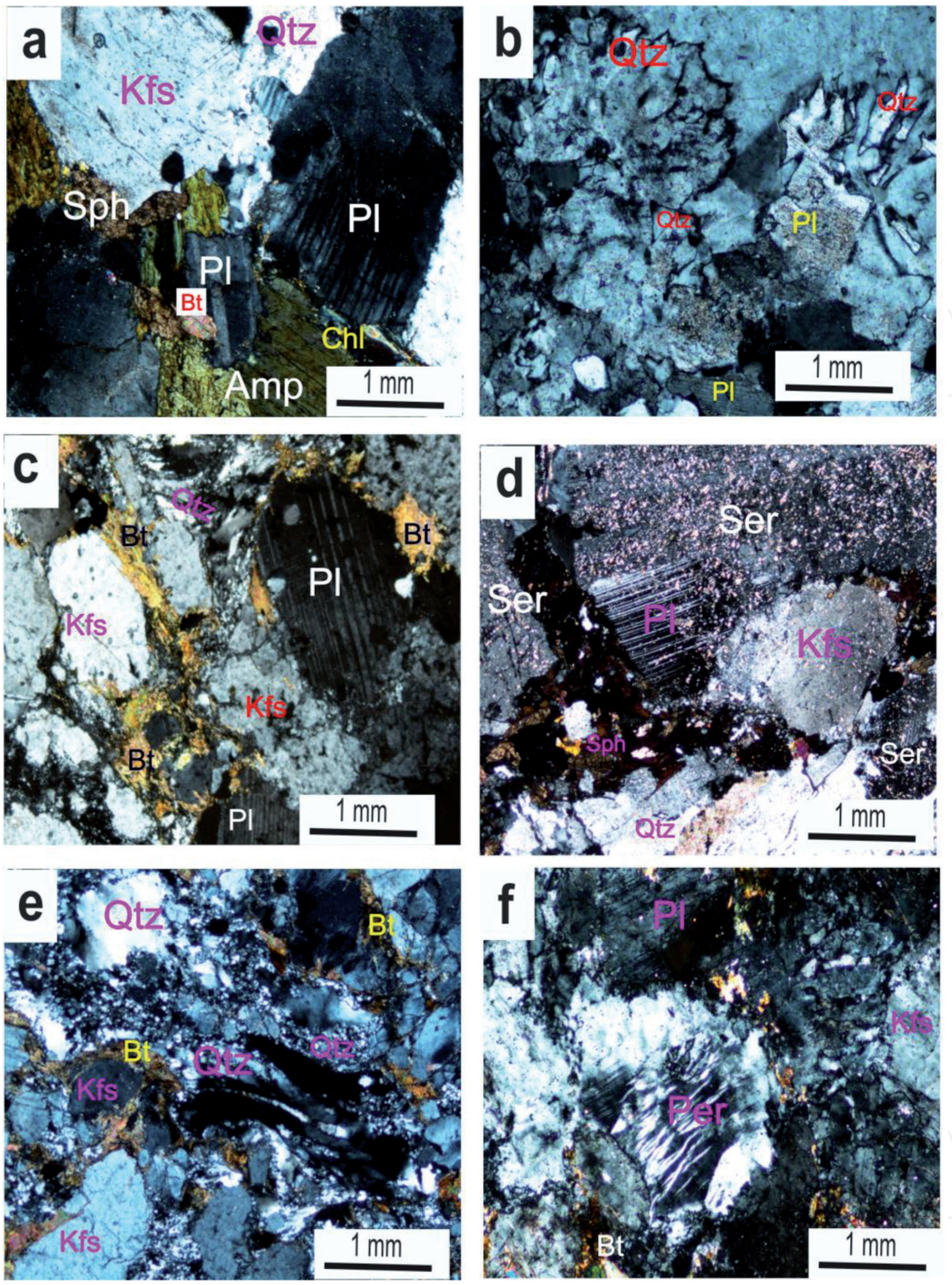

Figure 4.
Photomicrographs of mineral textures and reactions (cross-polarized light). (a) Coarse-grained texture marked by euhedral to subhedral feldspar, quartz, amphibole, and biotite. This is a typical evidence of magmatic structure in the rock. (b) Quartz replacing plagioclase in granite suggesting the incipient metasomatism by fluids derived from evolved crustal rocks. (c) Mylonitic texture marked by K-feldspar and plagioclase molded by biotite and quartz. Note the curved or waving quartz at the photo top and quartz grain embayment by plagioclase. (d) Sericitization reaction on plagioclase. Also note early sphene crystals trapped within the microfracture fillings in granite mylonite. (e) Grano-lepidoblastic texture on gneiss. Note the quartz and feldspar porphyroblasts in the matrix of fine-grained-elongated and recrystallized quartz with undulose extinction. (f) Perthitization reaction on K-feldspar in gneiss.

amphibole or biotite are altered into chlorite. Opaques and zircon are located in the mineral interstices or are present as inclusions in the center or the margins of some biotite minerals.

5.3 Gneisses

Gneisses present various textures. The principals are granoblastic and lepidoblatic textures (**Figure 4(e)**). Quartz, plagioclase, orthoclase, amphibole, and biotite are principal minerals; chlorite and perthite are secondary minerals, while sphene and epidote are the accessory phases.

Quartz is the most abundant mineral in the rock and is represented by two generations. The first generation is the porphyroblasts and the second generation is the microblasts (**Figure 4(e)**). The porphyroblasts are subhedral to anhedral and present boundary relationship with plagioclase and K-feldspar. The microblasts form the matrix and also fill the feldspar and hornblende interstices (**Figure 4(e)**). Both microblasts and porphyroblasts are generally confined and oriented in the clear microbands with some feldspar porphyroblasts. Plagioclases are in the form of elongated subhedral laths with polysynthetic twining. Some crystals present quartz crystal inclusions. The most represented feldspar is orthoclase. They are subhedral in some thin section, and mantled in the form of delta "Θ" porphyroblast. Perthitization reaction is common on feldspar porphyroblasts (**Figure 4(f)**). Amphiboles are anhedral and occur mostly in the form of amphibole fish. They are associated with biotite and sphene. Biotites are in the form of elongated flake in the dark microbands along with amphibole and sphene. Some flakes are totally or partially altered into chlorite.

6. Deformation features and kinematic indicators

Several deformations features and kinematic indicators are observed on Mgbanji granitoids in the Central African Fold Belt in Cameroon, either on outcrops scale or under the microscope. They are foliations, lineations, folds, faults, joints, delta "Θ," and sigma "σ" porphyroclasts, shears, boudins, kinking, micas, and amphibole fish.

On the outcrop scale, gneisses are of the rock types presenting all the deformation features observed on the study area. They are foliation, lineations, shears, joints, faults, and folds. The foliation is marked by the alternation of clear quartzofeldspathic and dark ferromagnesian bands. There are three different foliation generations on gneisses. The first is represented by parallel E-W-oriented horizontal bands (**Figure 5(a)**). The second is rare and is N-S oriented and results from the reorientation of the first foliation generation. It is mostly parallel to the isoclinals fold axes (**Figure 5(b)**). The third foliation generation is subvertical and oriented NE-SW (**Figure 5(c)** and **(d)**). It originated from the reorientation of the second generation foliation. Lineations follow mostly the foliation trend. Shears are mostly present on the third foliation generation and are mostly sinistral. Joints and faults are chronologically the last structures on all the rock types of the study area. Some joints are dry, while others are filled with quartzofeldspathic materials (**Figure 5(d)**).

Granites mylonites present several deformation features. Protomylonites and mylonites present some plastic deformation features, while ultramylonites present only brittle features such as faults, joints, and shears. Protomylonites present lineations marked by feldspar and quartz-oriented grains (**Figure 5(e)**). Foliation consists of alternation of quartzofeldspathic and ferromagnesian bands. S-C structures are in places seen on protomylonites and mylonites. Folds are rarely seen on ultramylonites but are common on protomylonites and mylonites. Fault and shears are present on all the mylonitic rocks.

Granites present lineations, faults, joints, and "false" boudins. Linenations consist of aligned feldspar porphyroclast on the outcrop, generally oriented

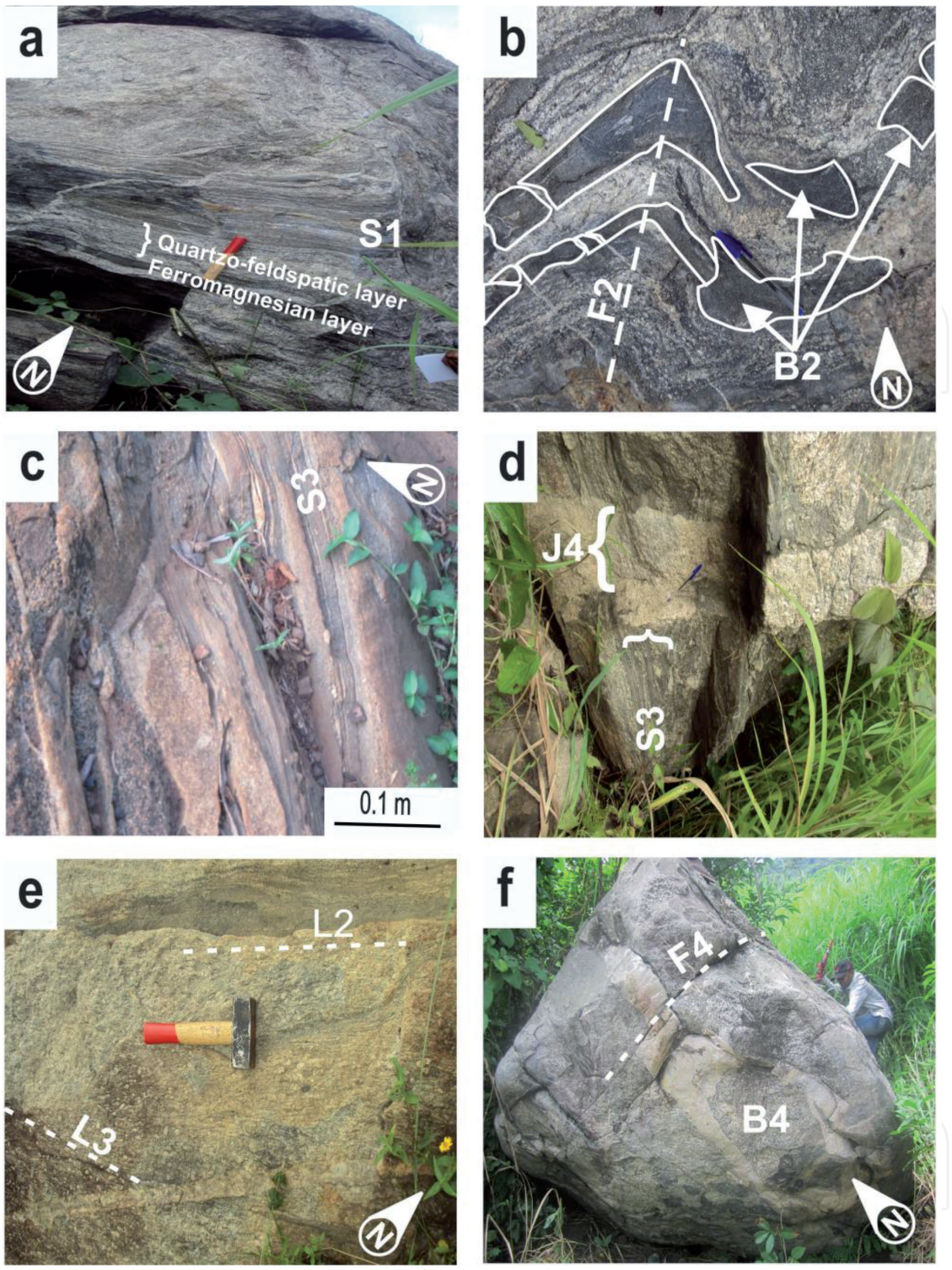

Figure 5.
Photomicrographs showing field deformation structures. (a) Foliation S_1 on gneiss; (b) F_2 folded asymmetric boudins B_2 on gneiss; (c) S_3 subvertical foliation on gneiss; (d) S_3 vertical gneissic foliation perpendicular to the J_4, quartzofeldspathic filled joint; (e) L_2 and L_3 lineations on granite mylonite; (f) F_4 fault on granite. Note also the "false" boudin B_4 made of quartzofeldspathic material encircling a portion of granite rock.

NE-SW. Faults are mostly normal faults. In some places, they are reduced to dry joints characterized by undisplaced component and empty fracture. Some joints are filled of quartzofeldspathic materials which are rarely boudinated. False boudins are made up of concentric quartzofeldspathic layers surrounding the granite material (**Figure 5(f)**). Depending on crosscutting relationship, faults and joints are the last deformation features on all the rock types in the study area.

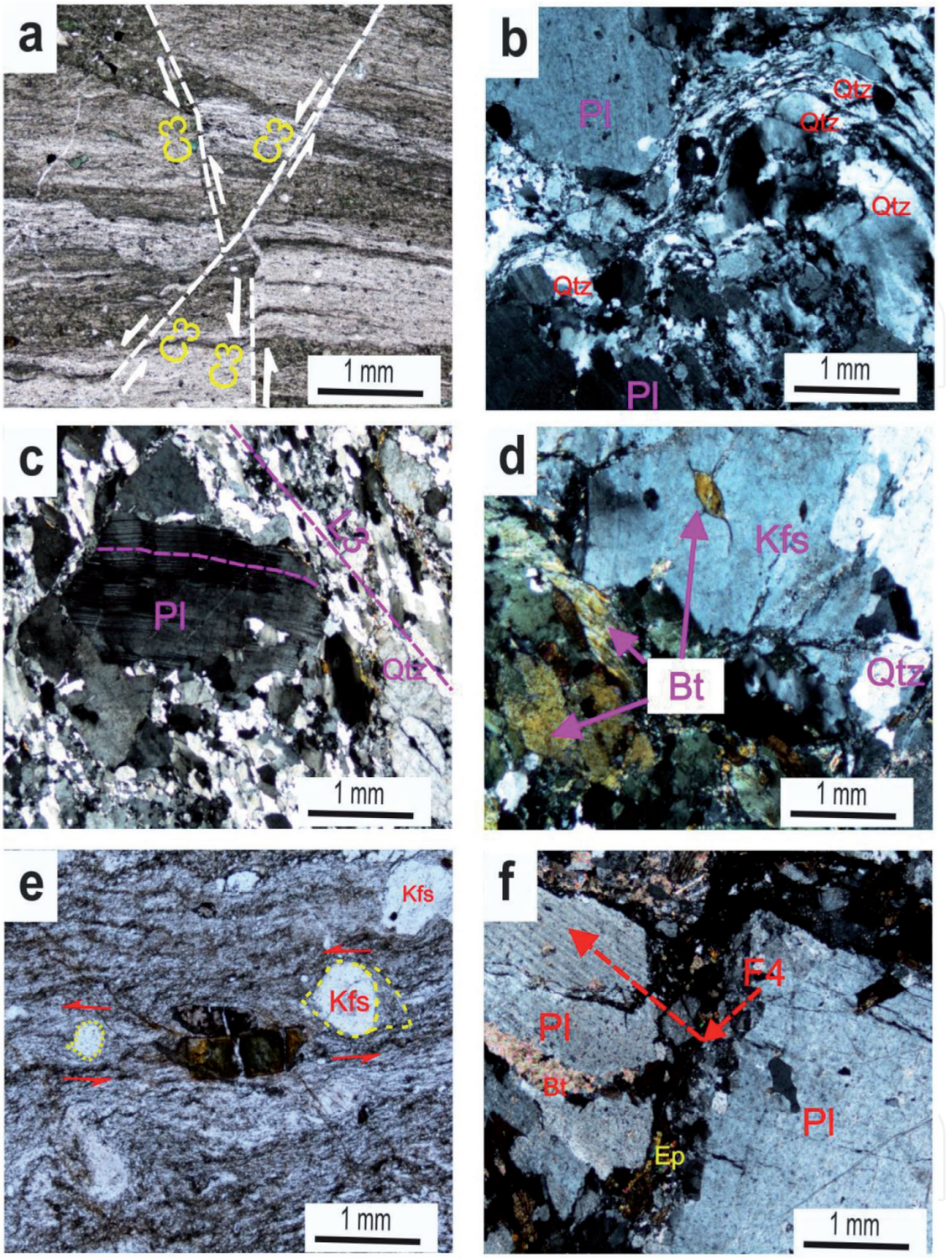

Figure 6.
Photomicrographs presenting microstructures and kinematic indicators ((b), (c), (d), and (f) = cross polarized light; (a) and (e) = plane polarized light). (a) Microfoliation marked by alternated clear quartzofeldspathic and dark ferromagnesian band crosscut by C_3 conjugated sinistral shear on granites ultramylonite; (b) stream quartz with undulatory extinction molding plagioclase and filling their cracks. Note also deformation lamellae in plagioclase; (c) kink deformation on plagioclase. The subeuhedral outline of the plagioclase phenocryst is oblique to aligned recrystallized quartz grain (lineation L3) giving the S-C fabric to the section. The plagioclase phenocryst is recrystallized along its margins, and present visible twins. The shape fabric and the intracrystalline deformation features can therefore be interpreted as submagmatic. This granite mylonite is syntectonically emplaced; (d) granite mylonite present embayed biotite fish on feldspar porphyroclasts; (e) "Θ" and "σ" porphyroclasts give the sinistral shear sense to the rocks. Also note the quiet pressure shadow around porphyroclast on the right; and (f) normal microfault on plagioclase megacryst. Note also the biotite mineral filling the plagioclase crack and epidote trapped in the fault fracture.

On thin sections, deformation structures are common. They are foliations, lineations, kink deformation on plagioclase, undulatory extinction on quartz, and deformation lamellae on feldspar, micas and amphibole fish, delta "Θ" and sigma "σ" porphyroclasts, and faults.

Foliation consists of alternation of quartzofeldspathic and ferromagnesian bands on mylonites. Bands are in place crosscut by conjugated sinistral shears (**Figure 6(a)**). Mylonites present flame and pasty quartz with undulatory extinction molding residual quartz grains. They also present feldspar porphyroclast with crystal deformation lamellae (**Figure 6(b)**). Mineral lineation is marked in mylonite by aligned recrystallized quartz crystals along with few biotite flakes. The feldspar porphyroclasts are in places recrystallized along their margins. They show kink deformation marks and visible polysynthetic twinning. The feldspar porphyroclast orientation is oblique to the recrystallized quartz mineral lineation, giving the microscopic S-C foliation to the rock section (**Figure 6(c)**). Biotite fish crystals are also present on mylonite. They are embayed on feldspar porphyroclasts and also seen at the feldspar edge (**Figure 6(d)**).

Granite mylonites in general host delta "Θ" and sigma "σ" porphyroclasts giving the shear sense of deformation to the outcrop. On ultramylonites, those porphyroclasts are located in the crushed matrix resulted from cataclasis (**Figure 6(e)**). They show a sinistral sense of shear as the conjugated shears are early described. The last deformation microstructure present in the Mgbanji granitoids is fault. On granite and granite mylonites, they are present on several minerals. The most faulted mineral is plagioclase. It presents normal microfault with sinistral sense of movement. The fault crack is more or less filled with epidote and sphene crystals which are a continuous phase in the rock matrix (**Figure 6(f)**).

7. Discussion

7.1 Deformation phases

Depending on crosscutting relationship, four deformation phases have been identified on studied rocks.

The first phase is exclusively represented on gneisses and is marked by the horizontal foliation (or banding) (S_1) and lineation (L_1). The foliation consists of the alternation of clear quartzofeldspathic and dark bands. They are mostly subhorizontal and oriented E-W (**Figure 5(c)**). Lineation is marked by randomly oriented quartz feldspar and biotite minerals. It is mostly parallel to foliation.

The second phase of deformation is recorded on gneisses and granite mylonites. That phase is characterized by folding (P_2), lineation (L_2), and boudin (B_2). Folds (P_2) are isoclinals with fold axes oriented principally N-S. The lineations are parallel to P_2 fold axes. Boudins (B_2) are complete and asymmetric. They are made of ferromagnesian layer (mostly amphibolites) and are folded in places (**Figure 5(b)**).

The third phase of deformation is represented on gneisses and granite mylonites. It seems to be the major phase on the field. It presents more deformation features compared to the other phases. Those features are resulting from the reorientation of previous phase's features. It hosts foliation (F_3), lineation (L_3), and shear (C_3). The foliation (S_3) is mostly subvertical and consists of alternated quartzofeldspathic and ferromagnesian bands oriented NE-SW (**Figure 5(c)** and **(d)**). Lineations (L_3) are hosted by foliation (S_3) and oriented in the same direction. Shears (C_3) consist of the

fracturation and displacement of foliation (S_3). The shear axes are mostly oriented NW-SE or NE-SW. They are observed both on outcrop and on thin sections. On thin section, D_3 deformation phase is marked by conjugated shears (C_3), lineation (L_3), and sinisterly oriented "Θ" and "σ" feldspar porphyroclasts (**Figure 6(a), (c)**, and **(e)**).

The fourth phase of deformation is present on all the three rock types of the study area, but it is mostly highlighted on granite. It is mostly a brittle phase. It is marked by dry and filled joints. The filled joints are made of quartzofeldspathic materials and may be qualified as a late D_3 phase. The filled joints crosscut the foliation (S_3) and are oriented E-W to NE-SW (**Figure 5(d)**). In some places, filled joints are circular and surround the granite material as a "false" boudin (B_4) (**Figure 5(f)**). The dry joints are chronologically the last feature on the study area of rocks. They are characterized by fractures classified as diaclase or fault (F_4) depending respectively on the tilling (diaclase) or the displacement (fault) of the component (**Figure 5(f)**). This chronology has been also mentioned in the recent study from the Central Cameroon Shear Zone [20].

7.2 Rock emplacement mechanism

Rocks within deformation areas are generally slightly, moderately, or highly strained and may exhibit very nice deformation microstructures. Deformed rocks present matrix with reduced grain size surrounding elongated faulted or sheared grains or grain aggregates. Many questions are steel a debate nowadays. Among them, we have the question of the identification of the presence or the absence of melt during deformation in rocks. Those questions are important for the problem of the melt extraction, the interpretation of plutonic magma ascent, and the mechanisms of emplacement. To have a good understanding of those questions, it is important to use macroscopic, mesoscopic, and microscopic structural criteria.

Coming to the present study, field relationships, mesoscopic and microscopic observations, and the structural data testify that Mgbanji granitoids were emplaced during the brittle-ductile deformation events occurring under the influence of an active strike-slip shear zone.

Conjugated mechanism may have acted simultaneously during the studied granitoid emplacement. They are cataclasis (microcracks, microfaults), diffusive mass transfer by solution (interpenetrating grain, pressure shadow), intracrystalline plasticity (deformation twin, odulatory extension, kink band, subgrain, grain shape fabric and ribbon, new grain), and solid-state diffuse mass transfer transformation (reaction rim, corona, relic mineral). All these mechanisms can be regrouped into magmatic, nonmagmatic (solid state), or submagmatic (few melt) deformation and can help to qualify the shear zone as magmatic, submagmatic, or nonmagmatic.

It is important to mention that nonmagmatic microstructures are those formed during deformation without any melt present. Such a deformation has previously been called subsolidus or solid-state deformation. Submagmatic deformation is characterized by the presence of few melt during deformation, while the magmatic deformation refers to the total presence of melt.

On Mgbanji granitoids, magmatic microstructures are only seen on granite. They are coarse-grained texture containing euhedral feldspar, amphibole, biotite, and sphene minerals (**Figure 4(a)**) and the presence of magmatic myrmekitic textures [21, 22]. In contrast to granites, granite mylonites (protomylonites, mylonites, and ultramylonites) present nonmagmatic to submagmatic deformation microstructures.

The nonmagmatic structures on Mgbanji granitoids are represented by plagioclase deformation lamellae, pressure shadows filled by epidote around megacrysts, and ribbon grains formed by intracrystalline plasticity in quartz, embayed, or overgrown grain boundaries [23, 24]. Granite mylonites contain new recrystallized quartz grains with higher frequencies of contacts between like grains (**Figure 7(b)**). This feature has been also revealed in [25] and is justified by the fact that new grains preferentially nucleate on the same phase.

The submagmatic structures on studied granite mylonites are highlighted by the tectonically induced myrmekites (**Figure 7(d)**) formed in volumes perpendicular to the shortening direction [21, 22].

The Mgbanji granite mylonites present elongated ribbons of quartz grains showing undulatory extinction. Quartz presents sutured margins on ribbons and some areas of small strain free polygonal grains. The new quartz or feldspar grains are in places concentrated in a mantle that partly surrounds the older mega feldspar grains, giving the core-and-mantle structure to the mineral (**Figure 7(a)**). These features are characteristic of syntectonic emplacement of the granite mylonites. Reaction rims of altered mineral around feldspar grains are present on granite mylonite. This texture may surely testify to DMT (**Figure 7(e)**).

The high frequency of undulose extinction in quartz within granites mylonites suggests that intracrystalline plasticity occurs during submagmatic deformation (**Figure 7(b)**). This assumption is mentioned here because quartz subgrain formation or recrystallization has been taken as an indicator of submagmatic deformation in rock where an overall igneous texture is preserved without any nonmagmatic deformation [26]. Plagioclase and calcite microcracks present biotite, quartz, and sphene or epidote trapped within the fillings (**Figure 7(a), (c),** and **(f)**). In some places, microcracks are intragranular and filled with pasty quartz suggesting that the plagioclase crystal was in contact with melt (**Figure 7(c)**). The microcracks filling is petrographycally continuous with groundmass phase of the rock.

Other submagmatic microstructures are the deformation twins and bent twins (kinking) in granite mylonites plagioclases. Such deformation features are known to be formed by intracrystalline plasticity in submagmatic phase (**Figures 6(c)** and **7(d)**).

Paradoxically, some authors demonstrated that the cataclasis of the crystal is not only occurring exclusively during the non-magmatic deformation but can also occur during sub-magmatic events [22, 27, 28]. Also, it has been proved that S-C fabrics may form either in submagmatic or nonmagmatic deformation [29].

On the field scale, the melt was localized in pressure shadows at the ends of boudins, and also faults and joints on Mgbanji granitoids were filled [30]. This observation coupled to the microscopic observation of some kinematic indicators ("σ" and "δ" porphyroclasts) indicate that the rock was syntectonically emplaced [31]. The presence of quartz replacing plagioclase in some granite mylonite samples suggests the possible incipient metasomatism by fluids derived from evolved crustal rocks (**Figure 4(b)**) [32].

Considering all abovementioned features, the granitoids of the Mgbanji area seem to be emplaced during plastic- to solid-state deformation stage.

It has been also demonstrated that intracrystalline plasticity and solid-state DMT are strongly controlled by temperature but relatively insensitive to pressure. That is why cataclasis is generally attributed to the upper crust (because of the low pressures at that level). Following that rule, crystal plasticity is supposed to occur in the lower crust or in the lithospheric mantle due to the high temperatures in deep earth areas.

The brittle-plastic transition (cataclasis—plasticity) results to intermediate deformation regime of semi-brittle behavior characterized by microfractures

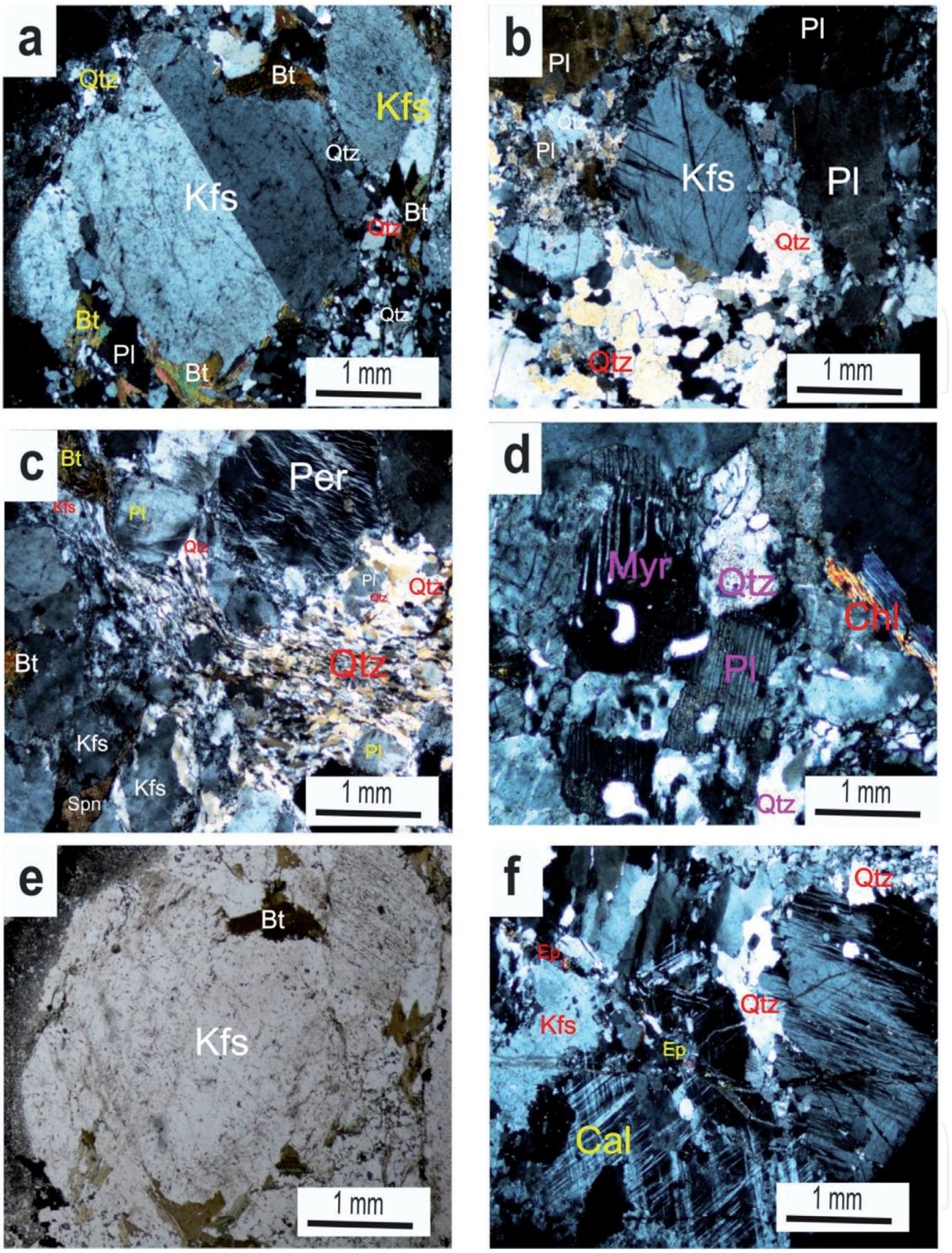

Figure 7.
Photomicrographs presenting microstructures ((a), (b), (c), (d), and (f) = cross-polarized light; (e) = plane polarized light). (a) Megacryst of feldspar (orthoclase) from granite mylonites presenting microcracks filled with biotite and quartz. The biotite and quartz are the same phases observed in the groundmass. Also note the core-mantle structure on plagioclase. (b) Typical feature of dynamic recrystallization in quartz involving grain boundary migration. Note the sutured margins on quartz ribbons and also domains of small strain free polygonal grains. Also note the K-feldspar presenting a leave like shape with unfilled microcracks (c) perthite exsolution and stream quartz molding K-feldspar porphyroblasts. Note the K-feldspar microcryst presenting microcrack filled with pasty quartz. (d) Tectonically induced myrmekites characterized by their grow in volumes perpendicular to the shortening direction. Also note exsolution lamellae on plagioclase. (e) Reaction rims of altered minerals around K-feldspar megacryst. This texture testifies to the transformation by diffusive mass transfer (DMT). Also note the biotite embayment and (f) calcite microveins filled with epidote and quartz.

interaction with intracrystalline plasticity [33, 34]. Two transitions in deformation mechanism, namely the brittle-semi-brittle transition and semi-brittle-plastic transition are registered with increasing depth respectively in the upper crust and

in the middle crust levels. But, even though it has been proved that high stresses may also cause cataclasis at greater depths or higher temperatures, the mechanism we suggest for the Mgbanji magma emplacement operates on three different crustal levels, namely lower, middle, and upper crustal levels (**Figure 8**).

In the lower crustal level, the granitic magma may have originated from the in situ crustal melting [35]. That level favored the formation of coarse-grained granite in the study area.

The middle level is characterized by the presence of mylonites and protomylonites, presenting submagmatic and mylonitic structures, typical of syntectonic magmatism. The presence of subvertical lineation on mylonites and protomylonites may indicate that the middle level zone reacted as feeder zones acting as melt collectors (**Figure 8**) [36].

The presence of both submagmatic and solid-state deformation features demonstrates that the strike-slip event may have been the active phenomenon during and after the total crystallization of the magma.

The magmatic to mylonitic fabric of the Mgbanji granitoids are in general parallel to the solid-state deformation features encountered in the country rocks, demonstrating that the Mgbanji granites seems coeval with the transcurrent tectonics in the Cameroon Central Shear Zone [20].

The upper crustal level or subsurface display spots of fine-grained granites (with homogeneous appearance in the field and few or no solid-state deformation features) surrounded progressively by ultramylonites, mylonites, and protomylonites (**Figure 8**). The fine-grained granite may be the outcome of tectonically driven solid-liquid partitioning, operating as filter-press, in the middle crust. At upper crustal levels, real magmatic fabrics are not common because of the higher temperature contrasts with the surrounding rocks, facilitating rapid magma cooling.

Magma intrusion may have been forced to flow toward local dilatational, low pressure sites, such as the boudin necks [37].

Field and microscopic observations of kinematic indicator point to the emplacement of the Mgbanji granitoids during the D_3 sinistral deformation within an active strike-slip shear zone.

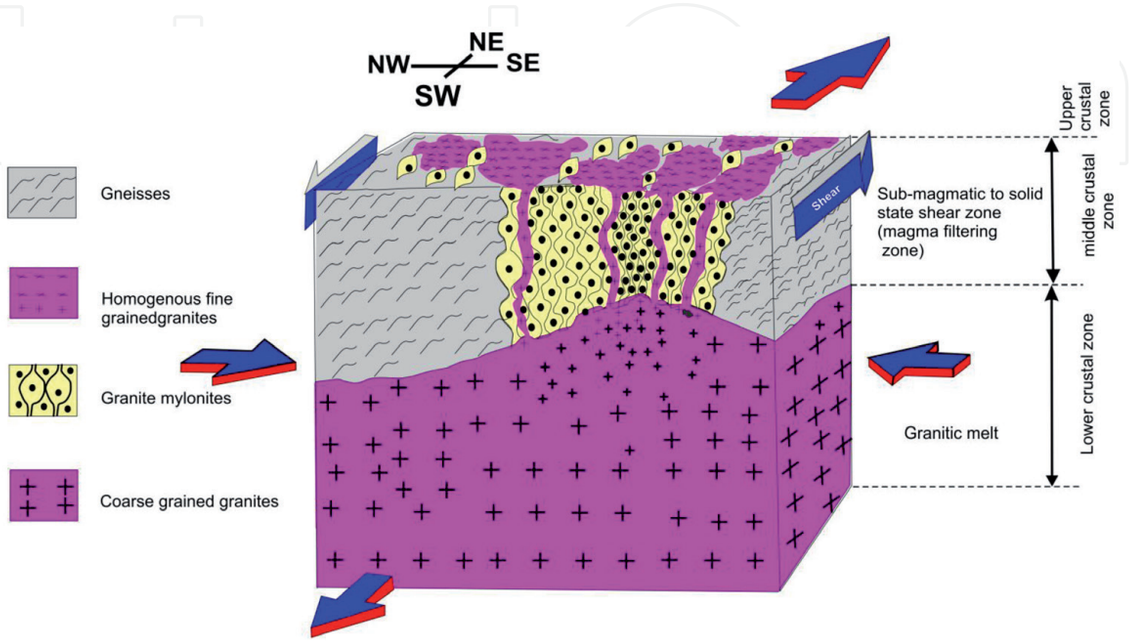

Figure 8.
A schematic model for the emplacement of the Mgbanji granitoids.

8. Conclusion

The Mgbanji area is made up of three main rock types, namely granite, granite mylonites, and gneisses. Field, mesoscopic and microscopic observations show coarse- to fine-grained texture for granites, granoclastic, cataclastic, and mylonitic texture for granite mylonites and granoblastic and lepidoblastic textures for gneisses.

Four deformation phases have been recorded in the study area's rocks. The first phase is marked by the foliation (S_1) which is mostly recognized on gneisses. The second phase is marked by fold (F_2), lineation (L_2), and boudins (B_2) on gneisses and granite mylonite. The third phase is marked by subvertical (S_3) foliation, shears (C_3), and lineations (L_3) recognized on granites mylonites and gneisses. The fourth phase is essentially a brittle phase and was recognized on all the three rock types of the study area.

Granites present mostly magmatic deformation features, while granite mylonites and gneisses present submagmatic to nonmagmatic deformation features. Mylonitization occurred on a brittle-ductile transition phase. Coarse-grained granites emplaced in the lower crustal level, while protomylonite and mylonites occurred in the middle crust and ultramylonites in the upper crust. Fine-grained granite was filtered and channeled through the middle crust shear's areas to be settled at the upper crustal level as irregular spot within the mylonites and gneisses. Deformation structures demonstrated that the studied area is a composite ductile-brittle shear zone. Granites and granites mylonites were syntectonically emplaced during the D_3 sinistral shearing phase.

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