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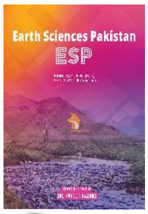

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RESEARCH ARTICLE

FIELD AND PETROGRAPHIC EVIDENCES OF GRANITOIDS AND MAFIC MAGMAS INTERACTION IN THE NEOPROTEROZOIC CENTRAL AFRICAN FOLD BELT IN CAMEROON (MAKENENE AREA)

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ABSTRACT

Field and petrographic studies of the Makenene area in the Central African Fold Belt in Cameroon reveals several features testifying the mafic and felsic magmas interactions and their coeval nature. They are: (1) the Mafic Magmatic Enclaves (MMEs) scattered throughout the Makenene granitoid pluton and displaying sub-rounded shape and back veining, (2) flow structures consisting of schlierens at the tails of MMEs, folded MMEs along with felsic host granitoids with hinge indicating the flow direction, (3) irregular or cuspate boundary between MMEs and host granitoids, (4) quenching of apatite and biotites minerals, (5) MMEs enclosing other MMEs or felsic host granitoids. The mafic magma injection operated during at least four stages (from early to late crystallization state of the host magma) leading respectively to the formation of homogenized granitoid; sub-spherical MMEs scattered in the pluton; dismembered dyke and undisturbed synplutonic mafic dyke. The Makenene area registered four deformation phases (D_1 to D_4). The first two deformation phases occurred before the magmatism and migmatization events. The third phase is coeval to the magmatism and the migmatization period (at the Eburnean orogeny (2.08-2.07 Ga)). The fourth phase is related to the Panafrican orogeny.

KEYWORDS

Makenene granitoids, Mafic Magmatic Enclaves (MMEs), synplutonic mafic dyke, magma interactions, deformation phases.

1. INTRODUCTION

Worldwide, several studies concerning mafic dyke's interactions with host crustal rock/magma and their emplacement process has been done (Vermon et al., 1988; Frost and Mahood, 1987; Andersson, 1991; Neves and Vauchez, 1995; Marcus et al., 1997; Piochi et al., 1999; Baxter and Feely, 2002; Santhosh and Vikoleno, 2006). It has been shown that, in several granitoid plutons, mafic dykes or enclaves more often host deformation structures formed during their ascent and emplacement in the crust following faults or shear axis (Ntieche et al., 2017; Ntieche et al., 2021). Mafic and felsic magmas are also generally used as petrological indicators of magama chamber process such as mixing or mingling (Jayananda et al., 2019; Jayananda et al., 2014; Elangovan et al., 2017; Jessica et al., 2002; Marcus et al., 1997; Piochi et al., 1999). They are indeed also known to be the source of compositionally intermediate granitoids. The magma mixing, also known as chemical mixing is characterized by a chemical exchange of elements between the two magmas (mafic and felsic). The magma mingling refers to mechanical or physical mixing by which two or more magmas settle together without chemical exchange of element or materials between them. It has been demonstrated that the difference between two magma viscosities results in the increase of the mingling effect (Grasset and Albarede, 1994; Poli et al., 1996; Perugini and Poli, 2005; Flinders and Clemens, 1996). So, the viscosity contrast between two different types of magmas results generally to the occurrence of physical or textural heterogeneities on the outcrop. That feature being the most common evidence for magma mixing in igneous rocks (Didier and Barbarin, 1991; De Rosa et al., 2002; Perugini et al., 2007; Perugini and Poli, 2012; Pritchard et al., 2013; Morgavi et al., 2016).

The Central African Fold Belt (CAFB) which constitutes the northwestern edge of the Congo craton is a continental collision zone of several kilometers stretching from Borborema Province in Brazil in America to Sudan in Africa (Van et al., 2008). It is a NE-SW oriented belt containing several granitoid plutons and considered by several researchers to be the result of the Panafrican collision of the West African craton and the Congo craton (Poidevin, 1983; Toteu et al., 1991; Castaing et al., 1994; Abdelsalam et al., 2002; Liégeois et al., 2013; Oliveira et al., 2006; Ngako et al., 2008).

The Cameroonian part of this mega-structure is subdivided into three geological domains, namely the Northern domain, the Adamawa Yade domain and the Southern domain (Figure 1).

The Makenene area, which belongs to the southern part of the Adamawa Yade domain, is made up of Eburnean to Panafrican granitoids containing

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mafic enclaves, mafic dykes, and gneisses more or less migmatized or mylonitized. Those mafic enclaves and dykes present several characteristics (mechanical mixing and deformation) testifying to the interactions with host granitoids. No previous studies have been done on interaction of mafic enclaves with the granitoid magma. In this paper, the term Mafic Magmatic Enclaves (MME) will be more often used instead of mafic enclaves. The aim of this study is to provide field and petrographic studies of those physical interactions well represented on the Makenene granitoids. For the first time in the Central African Fold Belt in Cameroon, new constraints about the Makenene mafic rocks and granitoids petrography, deformation structures and magma interaction will be provided in order to understand firstly the relationship between mafic rocks and granitoids and secondly the granitoids and associated mafic rocks emplacement process. More emphasis will be put on magma mingling process compared to magma mixing because of the absence of the whole rock and mineral chemistry data.

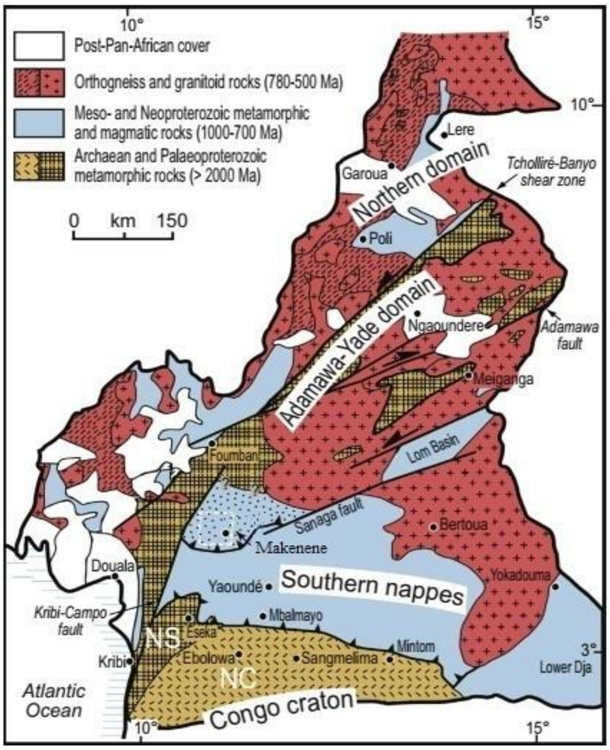

Figure 1: Geological map of the Central African Fold Belt in Cameroon and its main units showing the location of the Makenene area (modified from Nkoumbou et al., 2014). NC = Ntem complex, NS = Nyong series.

2. Geological Settings and Previous Work

The Central African Fold Belt (CAFB) in Cameroon is subdivided into three lithotectonic domains namely, the Northern domain, the Central domain also called the Adamawa Yade domain and the Southern domain.

The Northern domain is situated to the west of the Tchollirè–Banyo fault (TBF). It is made up of medium- to high-grade schists and gneisses of the ~700 Ma Poli series, the ~660–580 Ma calc-alkaline granitoids (diorite, granodiorite, and granite), anorogenic alkaline granitoids, and low-grade sedimentary and volcanic rocks (Toteu et al., 2004; Van et al., 2008). The Adamawa-Yade domain is bounded to the north by the Tchollirè-Banyo Shear Zone and to the south by the Sanaga fault (Toteu et al., 2001; Toteu et al., 2004; Toteu et al., 2006a; Van et al., 2008; Ganwa et al., 2016; Negue et al., 2017) (Figure 1). It is made up of 640–610 Ma, syn- to late-collisional high-K calc-alkaline granitoids associated to high-grade Palaeoproterozoic gneisses (Toteu et al., 2004; Van et al., 2008). The Southern domain also called southern nappes is made up of several Neoproterozoic metasedimentary units, which stretch from SE to NW Cameroon (Figure 1). These units are the Lower Dja, Mintom formation, Yokadouma and Nola series , Mbalmayo series, and the Yaoundé series. The Lower Dja, Yokadouma and Nola series consist of pelites, quartzites and basalt flows and dykes similar to continental tholeiits (Vicat et al., 1997; Caron et al., 2010). The Mintom formation consists of the diamictite, which is Cryogenian to lower Ediacaran sediments covered with cap-carbonates (Alvarez, 1995; Caron et al., 2010).

The Mbalmayo series and the Yaounde series are respectively low grade and medium to high grade and are mainly formed of clastic sedimentary rocks resulting from the reworking of a Paleoproterozoic to Archean continental crust and young Neoproterozoic volcanic deposits (Nédélec et al., 1986; Nzenti et al., 1988; Penaye et al., 1993; Nkoumbou et al., 2014). These formations were affected by a metamorphism between 620 to 600 Ma, during the Panafrican orogeny (Ball et al., 1984; Nzenti et al., 1988; Tchakounté et al., 2007; Caron et al., 2010; Yonta-Ngouné et al., 2010; Owona et al., 2011, 2012).

The Makenene area, located in the southern part of the Adamawa Yade domain in Cameroon at the contact zone between the nappes of the southern part of the CAFB and the western part of the Adamawa-Yadé domain (Figure 1). Zircon grains of migmatitic gneiss basement of the west of Makenene, gave upper and lower intercept ages of 692 ± 113 Ma and 2018 ± 9 Ma respectively (Tchakounte et al., 2007). These dates have been interpreted as corresponding to the times of the Panafrican intrusion and partial fusion, respectively (Toteu et al., 2001). A date of ca. 2.3 Ga (whole rock isochron Rb / Sr) was also obtained on Makenene migmatites (Nzolang, 2005).

Based on field and isotopic studies on paragneiss from the Kombé-II and Bayomen, suggested that the Bafia group (to which belongs the Makenene area) would represent a Neoproterozoic metasedimentary sequence formed of mica-schist, quartzite, paragneiss and migmatite, with interlayered amphibolite (Tchakounte et al., 2007; Ganwa et al., 2008). According to these same authors, that metasedimentary sequence results from the erosion of an older basement, involving sources of different ages. The zircon grain dating from the Bafia group metasedimentary rocks gave an imprecise lower intercept U - Pb date of 607 ± 66 Ma (ID-TIMS). This date overlaps the dates of 628 ± 68 and 674 ± 87 Ma, obtained by isochronous Sm - Nd whole rock - garnet dating and is interpreted as corresponding to the Panafrican metamorphic event (Tchakounte et al., 2007).

According to (Weecksteen, 1957), the tectonic history of the Bafia group is governed by two phases of deformation including a ductile phase, represented by a syn-metamorphic folding and a brittle phase, dominated by vertical movements giving rise to faults and joints. Moreover, suggested two ductile deformation phases D_1 and D_2 in the Bafia zone and a brittle phase D_3. (Ganwa, 2008; Tchakounté et al., 2007). Subsequently, comes to complete by showing that the “gneisses of Bafia” are affected by three phases of ductile deformation D_1, D_2 and D_3 including two compressive phases D_1 and D_3 with maximum shortening striking E-W to NW-SE and a decompressive phase D_2 with maximum extension striking N-S to NE-SW. The fourth phase of deformation (D_4), which is essentially a brittle phase, is characterized by a double network of conjugate fractures (Mvondo, 2009).

3. Methodology

For the field part of the work, a global positioning system (GPS), camera, clinometer, geological hammers and map was used. This phase involved foliation, lineation and shears measurements, collection of samples and mapping. A total of forty (40) samples were collected in the field.

The laboratory phase involved preparation of thin sections (including oriented thin sections) for petrographic study of selected samples. Five oriented thin sections for microstructure studies have been made at the National Geophysical Research Institute of Hyderabad in India. Twenty thin sections for petrography study (for sample for each type of rock) were done at the Geological and Mining Research Institute of Cameroon. Structural analyses and petrographic studies were done by observing thin sections under the polarized microscope at the geology laboratory of the Higher Teacher Training College of the University of Yaounde 1 in Cameroon. 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 non-coaxial strain (e.g. symmetry or asymmetry of shear bands, boudins, and tails around porphyroclasts, fault, and folds) were studied (Ntieche et al., 2017).

4. RESULTS

4.1 Field and petrographic identification's criteria for Mafic Magmatic Enclaves (MME)

The identification of Mafic Magmatic Enclaves is a bit complex because these rocks are most often confused with mafic xenoliths. The specific criteria for their identification are among other, their rounded or ovoid shape with igneous textures, and their darker color due to their enrichment in ferromagnesian minerals (Figure 4e). They generally bear finer-grained minerals than those of the host rock (Barbarin, 2005).

Xenoliths are fragments of rocks or mafic minerals found within host granitoids. They are distinguished from Mafic Magmatic Enclaves (MME) by their angular shape and their magmatic or metamorphic texture. Most often, they are folded, sheared and or fragmented by felsic veins.

Mafic dykes are intrusions of mafic rocks filling cracks or fractures left by the host rock (granitoid, being or completely crystallized).

According to a previous research, certain characteristics are essential for the identification of synplutonic mafic dykes (Pitcher, 1993). These are, for example, the shrinkage of the dyke along its length, the cuspate margins convex towards the host (Figure 4d), the frequently leucocratic back veining in the dyke and the dismemberment of the dyke into trains of angular enclaves (Figures 4e, 10b and 10c). The dykes are generally disturbed by the flow of the visco-plastic host, resulting in aligned MMEs (Figures 4e and 10b) (Pitcher, 1991).

4.2 Field relationships

The study area is made up of gneisses, migmatites, granitoids (diorite and granodiorites), mafic dykes, Mafic Magmatic Enclaves (MME) and pyroxenites (Figures 2, 3 and 4).

4.2.1 Gneisses and pyroxenites

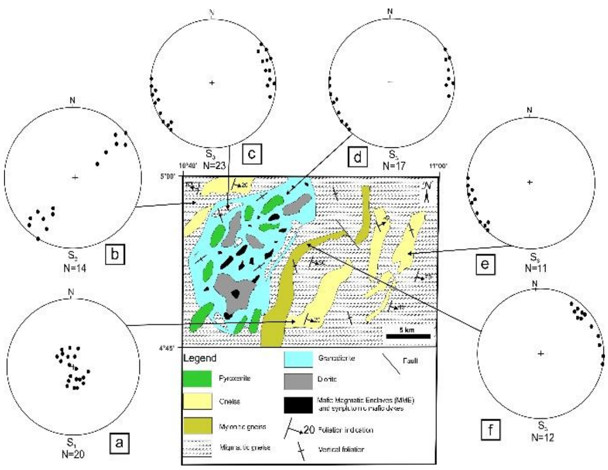

Figure 2: Simplify geological and structural sketch map of the Makenene area. Pole to foliation (a) S_1 on gneisses; (b) S_2 on migmatitic gneisses; (c) S_3 on migmatitic gneisses; (d) S_3 on granodiorite; (e) S_3 on gneisses and (f) S_3 on mylonitic gneisses.

Gneisses and pyroxenites constitute the metamorphic basement rock of the Makenene area. Gneisses are the most common rocks in the study area and are located in the East and West of the study area (Figure 2). From the East to the West of the study area, the outcrops are migmatitic gneisses and banded gneisses more or less mylonitized. Gneisses appear as a ball or dome and are characterized by foliation marked by alternating dark bands rich in ferromagnesian and light quartzofeldspathic bands (Figure 3a). In places the gneisses present faults, joints or veins. The mylonitized facies display the mylonitic foliation marked by the alternating dark ferromagnesian bands and clear quartzofeldspatic bands hosting mantled feldspar porphyroclasts (Figure 3b). In some places alkali feldspars porphyroclasts present a disk-shape (delta "θ" or sigma "σ"), symptomatic of a rotation of the rock in the senestral sense. The migmatitic facies consist of granite mobilizate mixed with the gneissic restite (Figure 3c). When the molten material is gneissic, the migmatite presents the gray appearance. Structures such as foliations or lineations are rare in migmatitic gnesses compared to mylonitic gneisses. Migmatites are spatially associated with granitoids and pyroxenites xenoliths.

Figure 3: Field photograph of rock types of the study area (basement rock). **(a)** Gneiss; **(b)** Mylonitic gneiss; **(c)** Migmatitic gneiss; **(d)** Pyroxenite

Pyroxenites occur in the form of blocks (Figure 3d) and also as mafic fragments of the basement rocks that are more or less metamorphosed. They occur in few places as xenoliths and are different from the Mafic Magmatic Enclaves by their angular shape and the presence of metamorphism evidences such as banding and shears.

4.2.2 Granitoids, Mafic Magmatic Enclaves and mafic dykes

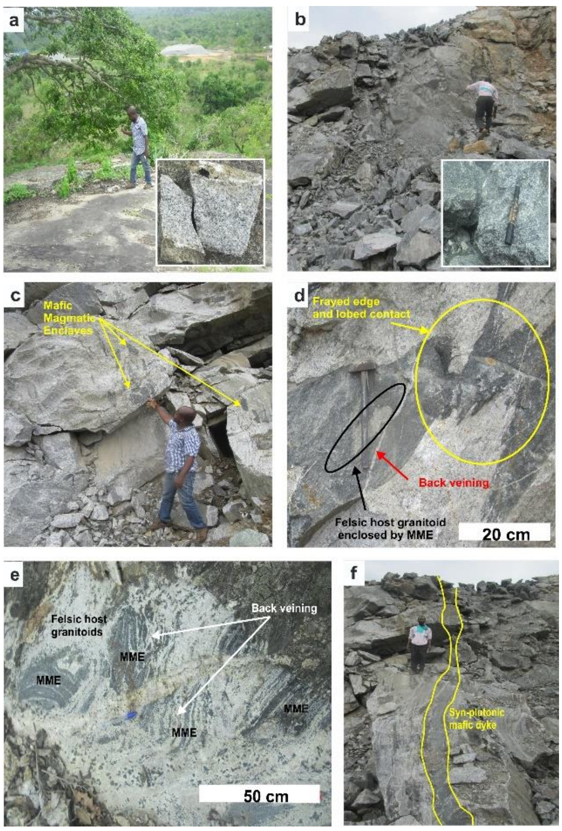

Figure 4: Field photograph of rock types and rock interaction features of the study area (intrusive rocks). **(a)** Granodiorite; **(b)** Diorite; **(c)** Mafic Magmatic Enclave (MME) occurring as blobs in the host felsic granitoids; **(d)** MME displaying frayed and lobed edges at their contact with the host granitoid. Note also granitoid rock enclosed by the MME; (e) Elliptical, rounded or sub-rounded MMEs exhibiting felsic veins (back veining) and following the flow direction of the crystallizing host magma; (f) Undisturbed synplutonic mafic dyke.

Granitoids occur in the East of the study area mainly at the Makenene quarry. Based on the color of the rock (due to the increasing abundance of ferromagnesian minerals) and the mineral composition of the rock, granitoids are here classified into granodiorite and diorite (Figures 4a and 4b, petrography section). They display fine, medium grained to coarse-grained texture and are macroscopically composed of quartz, alkali feldspar, plagioclase, biotite and pyroxene. The diorites are darker because they are more enriched in ferromagnesian minerals compared to the much lighter granodiorites. In places Mafic Magmatic Enclaves are molded and displaced by the felsic magmatic materials (Figure 4c). At the Makenene quarry, the phenomena of physical and progressive chemical mixing are observed. The physical mixtures are characterized by the presence of MMEs with sharp borders or the isolated sub-ronded mafic islets showing linear contact with the host granitoids (Figure 4c). At the Center and NE of the pluton, granitoids and MMEs are in places enclosed into each other (Figure 4d). In place, MMEs display frayed and lobed edges at their contact with the host granitoids (Figure 4d). The mixture is more or less macroscopically observed and consists of the gradual variation in the color of the rock, which ranges from light gray to dark gray depending on the abundance of the mafic magma within the felsic liquid. In some place, the boundaries between felsic and mafic facies are diffuse and characterized by the progressive mixing of the two magmas. This is materialized by the presence of diffuse schlierens in the felsic granitoids (Figure 11c). Magma flows evidences are common in the Makenene. They are the presence of elliptical rounded or sub-ronded enclaves oriented in the same preferential direction corresponding to the flow direction of the crystallizing magma, and exhibiting felsic veins (back veining) issued from the felsic magma surrounding the enclaves themselves (Figure 4e). Some Mafic Magmatic Enclaves with schlierens structures are folded and their hinges are giving the sense of the magma flow (Figure 11d). In place, some MMEs are less or not disturbed after filling the crystallized felsic magma, thus forming a syn-plutonic continue dyke (Figure 4f).

4.3 Petrography

4.3.1 Gneisses and migmatites

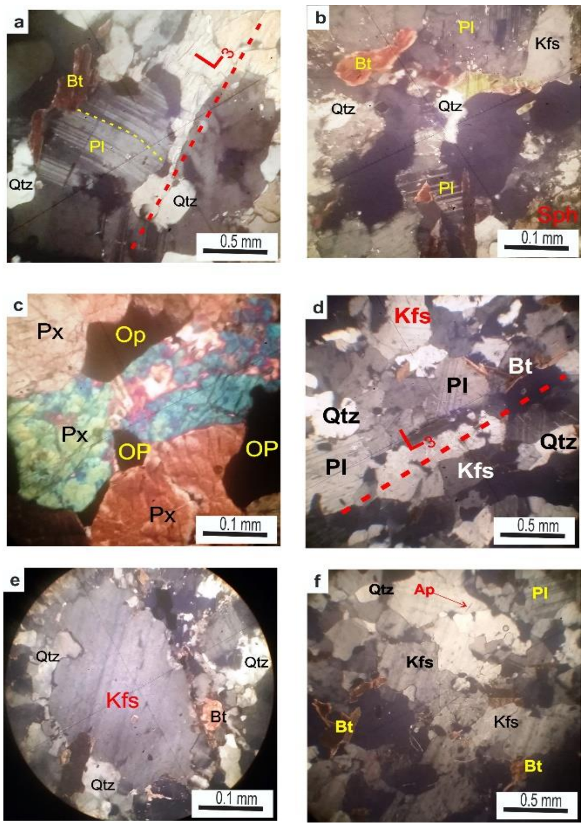

Figure 5: Thin sections microphotographs showing rock textures and features. (a) Granolepidoblastic texture in gneiss. Note the kink deformation on the plagioclase and the mineral lineation; (b) Granoblastic texture in migmatitic gneiss. Note the fine grained quartz filling interstices and mineral cracks; (c) Medium grained equigranular texture in pyroxenites; (d) Medium grained texture in granodiorite. Note also the overall mineral orientation due to magma flow; (e) Quartz absorbing the alkali feldspar boundary; (f) Apatite needle on alkali feldspar crystal.

Gneisses and migmatites display the granoblastic and granolepidoblastic textures and consist of aligned porphyroblasts of quartz (40-50%), alkali feldspar(20-35%), plagioclase (5-15%), and biotite (2-10%) following the gneissic foliation (Figure 5a). In gneisses, plagioclases are xenomorphic and show a preferential direction of alignment. Some plagioclase phenocrysts present kink deformation feature and also show polysynthetic twinning (Figure 5a). Quartz is xenomorphic and fills the interstices of alkali feldspars and plagioclases. Biotites are anhedral and fill mineral interstice along with quartz. Some flakes are included into plagioclases phenocrysts. In migmatites, quartz presents two shapes. The first is represented by anhedral crystals in places resorbing feldspar phenocrysts while the second one occurs in the form of inclusion in plagioclases and also as fine powders filling the fractures of alkali feldspars and plagioclases (Figure 5b). Mylonitic gneisses have the same mineral composition as the gneisses but display a mylonitic texture marked by mantled or sheared quartz and feldspar pophyroclasts (Figure 9a)

4.3.2 Pyroxenites

Pyroxenites are principally made up of pyroxenes (70-90%), and opaques (3-10%). Plagioclases (3-6%) are the accessory mineral phase while quartz (1-5%) is the secondary phase (Figure 5c). Pyroxenes are specifically othopyroxene and are sub-hedral to euhedral with clivages of about 90°. In place they present few quartz inclusions and are associated to plagioclases microcryts. Opaques are mostly subhedral and fill pyroxene interstices. They present linear contact with pyroxene (Figure 5c).

4.3.3 Granodiorites

The granodiorites show coarse to fine-grained textures (Fig. 5d). The principal minerals are quartz (30-45%), alkali feldspar (25-40%), plagioclase (5-8%) and biotite (4-7%). The accessory minerals are apatite (1-2%) and opaques (1-3%). Magmatic foliation is marked here by randomly aligned (L_3) feldspars and biotites minerals (Figure 5d). Alkali feldspars are subhedral and present lobed boundaries at their contact with quartz grains (Figure 5e). In places, apatite mineral are in the needle form and embedded on alkali feldspar phenocrysts (Figure 5f). The interstices of alkali feldspars are in places occupied by quartz. The quartz is anhedral and mostly occurs as microcrysts. Plagioclase is subhedral to anhedral and displays its characteristic polysynthetic twinning. In place they are associated with biotite. Biotites are less abundant in the rock and they occur as microflakes associated with feldspar, quartz and opaques microcrysts (Figure 5f).

4.3.4 Diorites

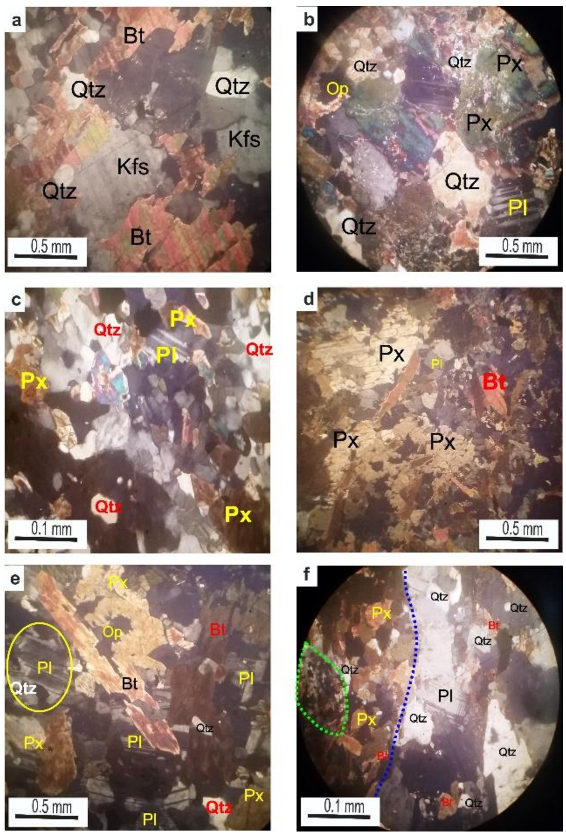

Figure 6: Microphotographs showing rock textures and features. **(a)** Medium grained texture on diorite; **(b)** Disequilibrium texture marked by replacement of feldspar and pyroxene by powder quartz in diorite; **(c)**

Fine grained texture on MME; **(d)** Pyroxene crystal in mafic dyke displaying irregular boundary and enclosing numerous opaque minerals; **(e)** Acicular biotite flake formed due to quenching of the mafic magma. Also note the plagioclase mineral progressively replaced by quartz (the circle in the thin section); **(f)** Sharp contact (blue dotted line) between MME and host granitoids. Note also the very fine grained MME enclosed in the medium grained MME (green dotted circle).

The diorites are more enriched in mafic minerals compared to granodiorite. They present medium grained texture and consist of biotite (30-45%), alkali feldspar (20-35%), pyroxene (15-25%), plagioclase (5-10%) and quartz (5-8%), as primary minerals and opaques (1-3%) as accessory phase (Figure 6a). In place the rock display equigranular texture (Figure 6b). Biotite is abundant in the rock and occurs as oriented flakes with irregular borders. Some biotite flakes display opaques as inclusions. Plagioclases present sub-ronded shaped and host quartz microcrysts inclusions. Quartz crystals occur as micro and phenocrysts. Microcrystals are anhedral and fill in pyroxenes and plagioclases cracks, while macrocrysts are subhedral and present sharp to diffuse contact with plagioclases, pyroxene and biotites. In places, quartz microcrysts are replacing plagioclase and pyroxene phenocrysts (Figure 6b).

4.3.5 Mafic dykes and Mafic Magmatic Enclaves

Mafic dykes and Mafic Magmatic Enclaves mostly present the same mineralogy. Their textures are ranging from medium to fine grained (Figures 6c, 6d, 6e, 6f). They consist of pyroxene (20-40%), biotite (15-30%), plagioclase (10-15%) and quartz (1-5%) as the main minerals. The accessory phase consists of opaques (1-5%). Pyroxenes are essentially clinopyroxene. They are anhedral and display frayed and irregular boundary and enclose numerous opaque inclusions (Figure 6d). In places the pyroxene are associated to biotite needles. Biotites occur as elongated flakes with local inclusions of opaques. Some biotite flakes are elongated in a preferential direction which may correspond to the magma flow direction (Figure 6e). Plagioclases are subhedral and less abundant in the rock. They are in place replaced by quartz crystals at their boundary (Figure 6e). Quartz is very rare and occurs as anhedral microcrystals at the margins of plagioclases or as fibers included in pyroxenes and plagioclases. In place some MMEs present sharp contact with host granitoid. The granitoids are more enriched in felsic minerals (quartz and feldspar) compared to the MME (Figure 6f).

4.4 Deformation structures

The macroscopic and microscopic observations of the rock and thin sections as well as the relative chronology of the emplacement of the deformation elements permitted to distinguish 04 deformation phases on the rocks of the Makenene area.

4.4.1 The first phase (D_1)

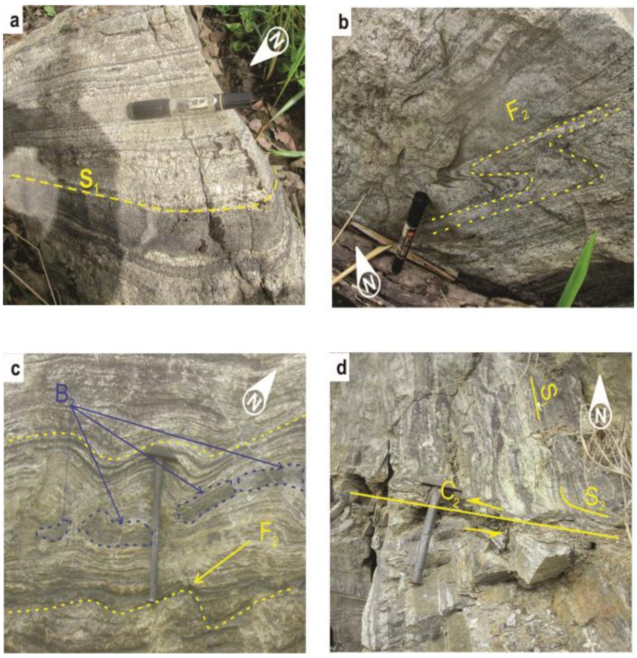

Figure 7: Deformation features of the D_1 and D_2 phases. **(a)** Foliation (S_1) on Makenene gneiss; **(b)** "S" type (F_2) fold on gneiss; **(c)** Boudin (B_2) and fold (F_2) on gneiss; **(d)** C_2 sinistral shear on migmatitic gneiss. Note the progressive transformation of S_1 foliation into S_2.

The first phase of deformation (D_1) is well marked on the gneisses while in other petrographic types it is very discrete or even absent. The first deformation phase is highlighted by the (S_1) foliation and the (L_1) lineation. The (S_1) foliation is penetrative and mostly subhorizontal within the gneisses outcrops and is striking N45-60E and display low dips (0-20°) to NW and SE (Figure 2a). It is marked in places either by thin dark layers (1mm-1cm) made of ferromagnesians and clear quartzofeldspathic layers or by dark and light bands (2-10cm) of the same mineralogical composition as the thin layers (Figure 7a). The (L_1) mineral lineation is characterized by the alignment of biotite minerals in the dark bands or quartz and feldspars in the light bands. In the pyroxenite enclaves, foliation is very discrete and marked by the alternation of fine quartzofeldapatic injections of milimetric thickness and large centimetric dark bands made of ferromagnesians.

4.4.2 The second phase (D_2)

It is well marked on gneisses, and migmatitic gneisses. On the gneisses, the (D_2) is marked by the (F_2) folds and the B_2 boudins (Figures 7b and 7c), while on the migmatitic gneisses, it is marked by (S_2) foliation oriented N120-160E with variable dip (35-90°) toward NE and SW (Figure 2b) and the (C_2) shear. F_2 folds are reversed and characterized by long and short flanks lying toward the Est. They result from the folding of S_1 foliations in the form of "s" with thickened hinges (Figure 7b). (F_2) fold display a wide variationin dip (0-30°) towards West. The (C_2) shear is marked on migmatitic gneisses by the sinisterly displaced migmatitic bands (Figure 7d). The shear axis is NW-SE to E-W oriented.

4.4.3 The third phase (D_3)

It is represented on gneisses, migmatites, diorites and granodiorites and is marked by (S_3) foliation, (L_3) lineation, (F_3) folds and (C_3) shear. The (S_3) foliation is mostly represented on gneisses, migmatites and granodiorites compared to pyroxenites. (S_3) foliation (striking NW-SE to N-S) is mostly vertical (dipping 80-90° toward NE, SW, E or W) (Figures 2 c,d, e, f) and marked by lithologic layering represented by alternation of clear quartzofeldspathic and dark ferromagneisian bands (Figure 8a). At the Makenene quarry, gneisses display (S_2) foliation, in place folded into (F_3) fold with fold axes parallel to the quartz vein injection (Figure 8b). Granodiorite also present folded MME presenting quartzofeldpatic back vening (Figure 8c). Homogenous granodiorites are folded into "M" shape fold presenting intersected axial plans (Figure 8d). On the heterogeneous granodiorite (granodiorite with MME or xenoliths), (C_3) shears are registered on MME and the shear axes are filled with quartzofeldspatic material coming from the host granodiorite (Figure 8e). The mylonitic foliation are in place, defined by the subparallel alignment of sigma (σ) K-feldspar or plagioclase porphyrocrysts bands alternating with biotite flakes showing the sinistral shear sense to the mylonitic gneisses outcrop (Figure 8f). In place, the alignment of quartz, feldspar and biotites constitute the mineral lineation (L_3) striking (NW-SE to NE-SW) (Figures 3b, 5a and 5d). (C_3) shears are also marked on mylonitic gneisses by the presence of asymmetric feldspar porphyroclasts and displaced grain fragments indicating the sinistral shear sense to the rock (Figures 9a, 9b).

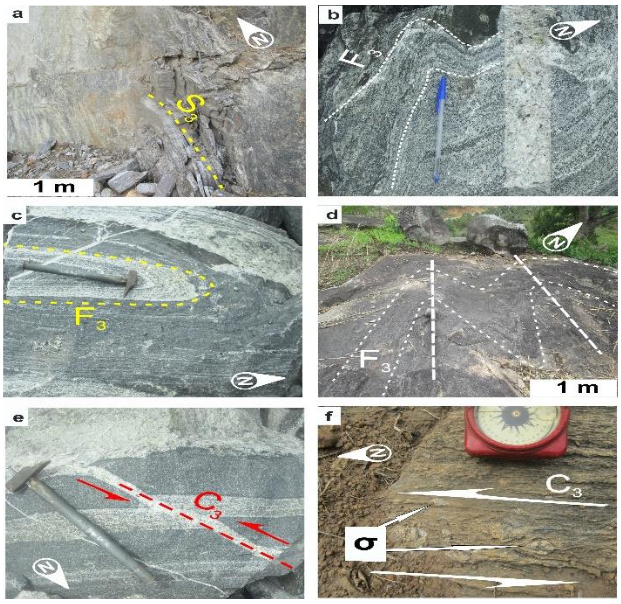

Figure 8: Deformation features of the D_3 phase. **(a)** S_3 vertical foliation on migmatitic gneiss; **(b)** (F_3) fold on the felsic granitoid; **(c)** F_3 lying fold affecting both the MME and the felsic granitoid. Note also the back felsic

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veins affecting the folded MME and the late vein crossing both MME and felsic host; **(d)** "M" type (F_3) fold on Makenene granitoid; **(e)** C_3 sinistral shear affecting the banded MME. The shear axe is filled with host granitoids magma testifying that the shearing and magmatism are coeval and occurred during the (D_3) deformation phase; **(f)** Sigma (σ) feldspar porphyrocrysts indicating the sinistral shear sense to the Makenene mylonitic gneiss outcrop.

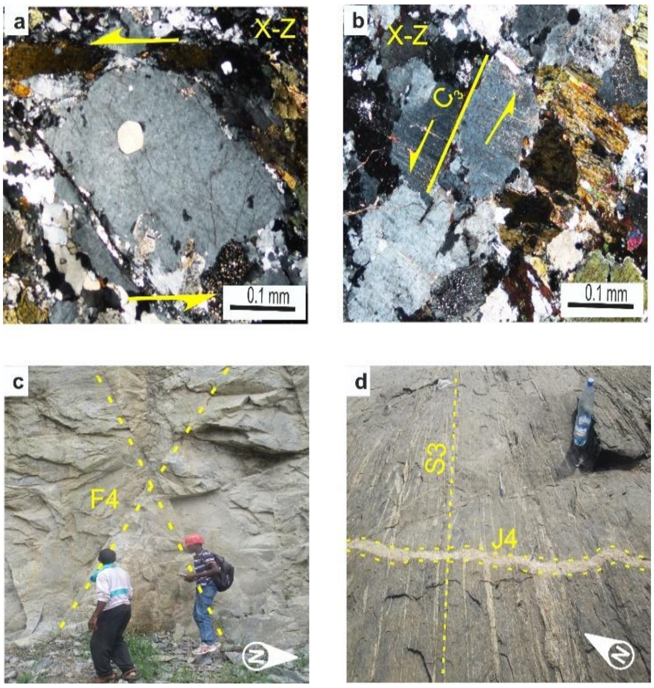

Figure 9: Deformation features of the D_3 and D_4 phases. **(a)** Delta porphyroclast showing the sinistral sense of shear on mylonitic gneiss; **(b)** C_3 sinistral shear on plagioclase porphyroclast; **(c)** Conjugated faults with a crossing angle of approximately 45° at the Makenene granitoids quarry; **(d)** Filled joint (J_4) on the mylonitic gneiss. Also note the S_3 vertical foliation.

4.4.4 The fourth Phase (D_4)

The (D_4) deformation phase is principally a brittle stage characterized by the presence of faults and joints. Faults and joints are found on all rock types in the study area. On migmatites and gneisses, the (S_3) foliation is crosscut by subhorizontal quartzofeldspatic veins or joints (J_4) (Figure 9d) while on diorite and granodiorite the foliation is intersected by fault N-S oriented or by conjugated faults with a crossing angle of approximately 45° (Figure 9d). The dry joints are found on all the petrographic types of the Makenene area.

5. Discussion

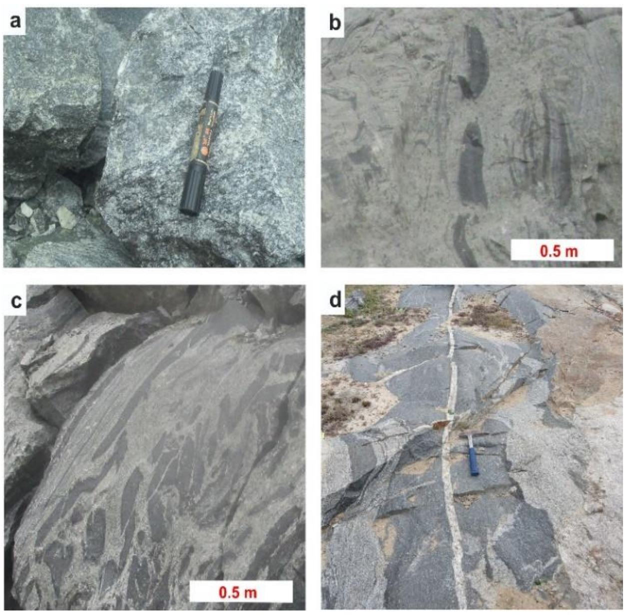

Figure 10: Magma interaction's products. **(a)** Mixing of felsic and mafic magmas leading to the formation of homogeneous hybrid (intermediate) rock (diorite); **(b)** Blobs of MME scattered in the host granitoids. This feature may be explained by the fact that mafic melt may have arrived slightly later after the beginning of the crystallization of felsic magma; **(c)** Mafic magma entering the host felsic granitoid later when it already partially crystallized. This has lead to composite fragmented mafic dykes; **(d)** Undisturbed synplutonic mafic dyke formed due to the intrusion of mafic magma in the fracture when the host granitoid already crystallized at about 90%. Also note the late felsic product intruding the mafic dykes.

5.1 Emplacement process and interaction of mafic and felsic magmas

According to several authors, (Barbarin and Didier, 1992; Hibbard and Watters, 1985; Furman and Spera, 1985) the diversity or variety of the morphologies of Mafic Magmatic Enclaves and mafic dykes may suggest several pulses or episodes of injection of mafic magma within the crystallizing or crystallized felsic magma. Thus, some study proposed four possible injection episodes for different types of MMEs and mafic dyke morphologies. The mafic rock morphologies of the Makenene granitoid pluton are consistent with the following four proposed injection episodes (Barbarin and Didier, 1992).

(1) When the mafic magma is introduced before the beginning of the crystallization of the felsic magma, a careful mixing is formed leading to the crystallization of granitoids of calc-alkaline character or to homogeneous hybrid magmas (Figure 10a). This type of mixing is generally favored by convection and occurs at depth. In the NE of the Makenene area, hybrid granitoids (granodiorite and diorite) are relatively homogeneous. The granodiorites crystallized from a magma mixture enriched in felsic magma compared to the mafic magma. They display few drops of unmixed mafic magma, which gives the rock a speckled appearance. Diorite is issued from a magma mixture enriched in mafic magma compared to felsic magma and completely homogenized. Those homogenous hybrids (diorite) come from the total mixing or chemical interaction of the felsic and mafic magmas due to low degree of crystallinity (Jayananda et al., 2014, Barbarin and Didier, 1990).

(2) When the mafic magma is introduced a little later, after the beginning of the crystallization of the felsic magma, the viscosities of the two magmas may be sufficiently different and therefore not allow mixing. The mafic magma is therefore likely to decompose into droplets or balls and be dispersed in the felsic magma thus forming the Mafic Magmatic Enclaves (MME). These features are present at the Center of the Makenene granitoid pluton, precisely at the quarry area. It is characterized by felsic granitoids carrying elongated balls or droplets of MMEs of variable size (2 cm to 1 m long) (Figure 10b). In place, the Mafic Magmatic Enclaves follow their host granitoids magma by moving through the fractures and then became slightly flattened or elongated without leaving the fracture.

(3) On the other hand, if the mafic magma is injected when the felsic magma is largely crystallized, the mafic magma will probably be channeled into the early fractures of the nearly rigid host felsic rock and interact with the last liquids of the felsic magma locally to form a composite or fragmented dykes. This is the case at the northwestern part of the Makenene pluton where the mafic dykes are disturbed by felsic granitoids liquid not yet crystallized. They are characterized by elongated mafic bodies traversed in places by back veins originating from the local magma (host granitoids) (Figure 10c).

(4) Finally, if the injection of mafic magma happens later in the cracks of the totally solidified host felsic rock (granitoid), a continuous or undisturbed mafic dyke occurs. This is because the rheology of the two magmas (mafic and felsic) are so different that most of the exchanges are inhibited. At the Center of the pluton, are located the undisturbed dykes filling the cracks of the previously crystallized granitoids (Figures 10d). These dykes have thicknesses varying between 10 cm and 50 cm and lengths of up to 20 m.

Base on the field observation, other parameters such as the deformation acted during the magmas emplacement. This is highlighted by the presence of folding and shearing on both MMEs and surrounding granitoids magmas (Figures 8c, 8e, 11a and 11d). The presence of some folds both in granitoids and mafic rocks of the Makenene pluton indicates that the folding and the magmatism are coeval, and also that the "cuspate-lobed form" along the contacts of the mafic enclaves are not only due to the magma (mafic and felsic) interactions, but also to the participation of the compressive deformation (Figures 8c, 11a and 11d).

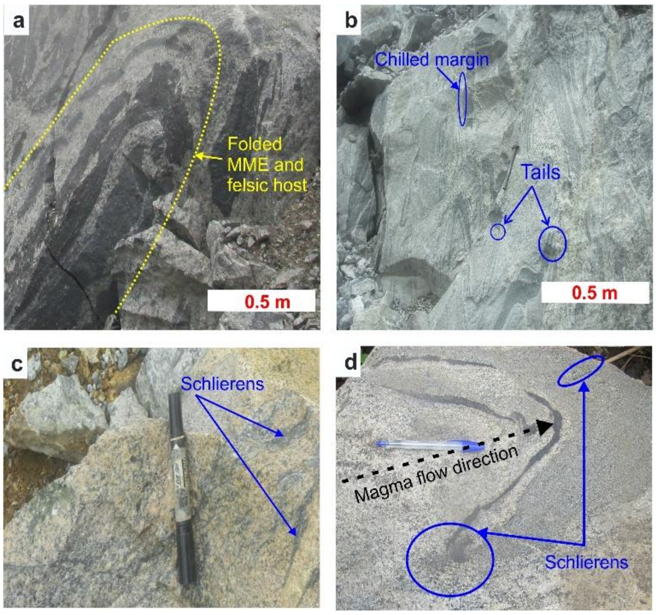

Figure 11: Magma interaction's products. **(a)** Folded MME and host felsic granitoid; **(b)** Chilled margin of the MME and flow structure materialized by MME tails; **(c)** Diffused schlierens highlighting the progressive mixing of MME with the felsic host rock; **(d)** Foldel MME. Note the flow direction indicated by the fold hinge. Also note some schlierens made of mafic minerals partially mixed with the felsic host.

Several other evidences of the mafic and felsic magma interactions were identified in the granitoids of the Makenene zone. Those evidences are the developments of fine-grained and lobed margins in mafic enclaves, thus reflecting the contrasts in temperature, viscosity and rheology (Bacon, 1986) between mafic enclaves and the felsic host magma. The chilled margins of mafic enclaves with the host rock are also the evidence of mafic-felsic magmas interaction (Figure 11b). According to certain authors, (Didier, 1973; Huppert and Sparks, 1989; Wiebe, 1991) the chilled fine-grained margins of the MME would indicate the presence of the magmatic liquid and would limit subsequent chemical exchanges between the two magmas. Those chilled MME margin suggest the intrusion of the mafic magma in relatively cold crystallizing felsic granitoid magma. Some Magmatic Mafic Enclaves are reabsorbed or diluted when interacting with the host granitoid magma. They consequently form a local hybrid zone at the tail of the MME forming magma flow structures. In Makenene granitoids, some MME are getting diluted in the host granitoids leading to the formation of diffused schlierens structures (Figures 11c and 11d). The tail structures may be due to the movement of MME in the felsic crystallizing granitoids magma.

Schlieren structures made up of accumulation of mafic mineral such pyroxene and biotite flakes at the boundary of MME and host granitoid are common. The hinge of some lying folds affecting both the MME and the host granitoids is giving the sense of magma flow (Figure 11d). The presence of granitoid melt filling the (C_3) shear axis of the MME indicates that the magma mixing event is contemporaneous with the (C_3) shearing event (Figure 8e).

The elliptical shapes of the mafic enclaves in the granitoids host pluton and vice versa (Figures 4c, 4e, 10c) also imply that both magmas were still in liquid state during the mixing. This is confirmed by the presence of granitoids with irregular borders surrounded by mafic rock and the presence of some mafic melt enclosed in the mafic magma (Figure 4d). The MMEs showing cuspate contacts indicate their magmatic state as well as the contemporary emplacement of the mafic and felsic mixture (Figure 4d). It should be noted that as long as the viscosity of the MME is lower than the viscosity of the host, the MMEs can capture other enclaves or K-feldspar and quartz xenocrysts from the host and can also reabsorb some mineral phenocrysts (Vernon, 1983; Vermon, 1984; Gill, 2010). That feature is present even at the microscopic scale in the Makenene area where some MMEs enclose another mafic enclave (Figure 6f). Other evidences of magmas interaction in the Makenene granitoids plutons are the presence of the poikilitic textures of the plagioclases (Hibbard, 1991; Baxter and Feely, 2002), as well as the presence of acicular biotite and apatite crystals which result from the mixture of magmas and the quenching of MME in the felsic host due to the great thermal contrast between the two magmas (Vernon, 1983; Vernon, 1984) (Figures 5f and 6e). The plagioclase crystals resorbed at their edge by quartz microcrystals are also the evidence of the magma interaction phenomenon in the Makenene granitoid pluton (Figures 5e and 6e). All the above features described in the Makenene area are similar to those highlighted on the Kanker granites of the Bastar Craton in the Central India by (Elangovan et al. 2017), on the late archaean granitoids in the Eastern Dharwar Craton in india (Jayananda et al., 2009) and on the granites pluton from Gurgunta area, northern part of the Dharwar Craton in India (Prabhakar et al., 2009).

5.2 Deformation phases and relative emplacement chronology

Four deformation phases have been registered on the Makenene granitoids and associated mafic and felsic rocks. The first deformation phases is recorded on gneisses and is marked by foliation (S_1), then is followed by the second deformation phase which overprinted some first phase features. The second phase is mostly a compressive phase marked by (F_2) upright folds with nearly horizontal fold axes and NE–SW sinistral (C_2) shears (Figures. 7b 7c and 7d). The first two phases of deformation occurred directly after the formation of gneisses. The third phase is mostly the shearing phase although some lying or recumbent folds (F_3) are registered (Figures 8b and 8c). That phase is marked by the felsic melt (back veining) injections filling the (C_3) sinistral shears axes and fractures on mafic dykes, MMEs, granitoids and gneisses (Figure 8e).

The third deformation phase corresponds to the magmatism and migmatization events. Contrarily to this study, the migmatization is reported to been occurred progressively during the (D_2) deformation phase in the Ngaoundere area from the Adamawa Yade domain (Tchameni et al., 2006).

U-Pb dating on zircon from migmatitic gray gneisses of Makenene area has shown evidence of protholith Archean-age (2.55 Ga) (Tchakounte et al., 2017). This dating would indicate the emplacement of protoliths of certain granotoids from the Makenene region at approx. 3.0–2.5 Ga, and those protoliths were affected by partial melting leading to migmatization at approximately 2.08–2.07 Ga, during the Eburnean orogeny (Toteu et al., 2001). It has also been demonstrated by the same authors that certain magmatic events occurred during the Panafrican orogeny (Toteu et al., 2001) and were affected by metamorphism at the same period (0.64 to 0.61 Ga). Panafrican magmatism has also been obtained for the neighboring porphyritic metagranite at Elon in the south of Bafia (Toteu et al., 2006b). The fourth phase of deformation (D_4) is a brittle phase and is present on all the rock types from the study area. It is marked by faults and joints and is the last deformation phase observed in the study area (Figures. 9c and 9d).

Field and petrographic observations have demonstrated that the mylonitization of host granitoids and surrounding gneisses and the brittle deformation (at D4 phase) may have occurred during the same Panafrican period. Although migmatization and magmatism have been demonsrated to have occurred during two different periods (Toteu et al., 2001, Tchakounte et al., 2017), field observations of migmatitic melt interacting with mafic dykes and felsic granitoid magmas (Figure 3c) are the evidences that migmatization and magmatism were contemporaneous and occurred during the same deformation phase (third phase D_3). This is not in contradiction with the previous result of (Tchakounte et al., 2017: Toteu el al., 2001) mentioned above, because a single phase of deformation can take a relatively long time during which several geological events such as magmatism and migmatization can occur.

6. Conclusion

Field and petrographic observations of the Makenene ganitoids and mafic rocks permitted to highlight for the first time the mafic and felsic magma interactions in the exposed crustal levels of the Adamawa Yade Domain, Central African Fold Belt in Cameroon.

The mafic rocks consist of MME, synplutonic mafic dykes and pyroxenites while the felsic granitoids consist of granodiorite and diorite. The basement rock of the study area is made up of gneisses, pyroxenites, migmatitic gneisses and mylonitized gneisses. The field and petrographic observations show different stages of injection of the mafic magmas into crystallizing host granitoids melt.

Early injection resulted to homogenous granitoids while the later leaded to synplutonic mafic dykes. Evidences such a schlieren at the tail of MMEs, cuspate and lobed contact of the MME with host granitoids, acicular apatite and biotite in the MMEs testify to the mafic and felsic magma interaction in the Makenene pluton.

Four deformation phases were registered in the Makenene area: the first two deformation phases were observed on gneisses and occurred before the magmatism and migmatization. The migmatization and the magmatism are coeval with the third phase of deformation and occurred during the Eburnean orogeny. The fourth phase of deformation is present on all the rock types of the study area and is principally the brittle phase. It occurred during the Panafrican period.

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