

Structural Study of the Precambrian Basement of Kaele (Far North Cameroon): Contribution of Remote Sensing (Application of Landsat 8 OLI/TIRS Images) and Field Data

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Received December 14, 2022; Revised January 22, 2023; Accepted February 05, 2023

Abstract The Kaele is located in the northern domain of the Pan-African fold belt of Central Africa in Cameroon, north of Mayo- Kébbi domain. The structural study carried out in this area is based on Landsat 8 OLI/ TIRS image processing techniques and traditional geological prospection methods. The objective is to evaluate the contribution of landsat 8 OLI/TIRS image processing and field data in the structural mapping of the Kaélé region. The application of the 7×7 directional filters of the Sobel type in the N-S, E-W, NE-SW and NW-SE directions, to the ETM+3 channels gives better results. The rose diagram of the lineament map (obtained from image processing) shows a major E-W direction (N100E) and a secondary direction N-S (N10E). The studied area is affected by a polyphase deformation D1 to D4. The first phase of deformation (D1) is tangential and has set up the sub-horizontal dipping S1 schistosity which bears a composite L1 lineation (stretching, mineral). The D2 phase is constrictional and responsible for the establishment of the subvertical S2 axial plane foliation of the P2 folds, carrying the composite L2 lineation (stretching, mineral) and the B2 boudinage. The dextral-moving C2 shear cuts the S1 foliation, the P2 folds are asymmetrical isopach and anisopach. The third phase D3 is a constriction and set up the S3 schistosity which appears in syn -tectonic granite and highlight the C3 shear planes. The C3 shear is dextral and the P3 folds are isopach, anisopach, intrafolial and sheath fold. The last phase of deformation D4 is brittle and has set up faults and joints. There exist similarities between orientation of lineament from image processing and direction of D2, D3 and D4 deformational phases structures.

Keywords: remote sensing, lineaments, deformational phase, Precambrian basement, Kaele, Cameroon-Central Africa

Cite This Article: Bello Bienvenue, Ganwa Alembert Alexandre, Naimou Seguem, Simeni Wambo Armel Nicole, Amadou Diguim Kepnamou, Yingyang Wangbitching Raoul, and Haskandi Kalaza Josué, “Structural Study of the Precambrian Basement of Kaele (Far North Cameroon): Contribution of Remote Sensing (Application of Landsat 8 OLI/TIRS Images) and Field Data.” *Journal of Geosciences and Geomatics*, vol. 11, no. 1 (2023): 1-10. doi: 10.12691/jgg-11-1-1.

1. Introduction

The Central African fold belt (CAFB) (Figure 1a) is an elongated orogenic mega-belt trending E-W, more than 5000 km long and 300 km wide; it cover over Nigeria, Cameroon, Chad, Central African Republic

[1,2,3] and extends to the NE of Brazil in the province of Borborema by the Brazilian chain [4-9]. The CAFB is subdivided in Cameroon into three domains [10]: the Southern domain, the Central domain and the Northern domain. The Northern domain includes a NW sub-domain and a Mayo-Kébbi sub-domain [11] (Figure 1b). The study area is located in the Mayo- Kébbi sub-domain.

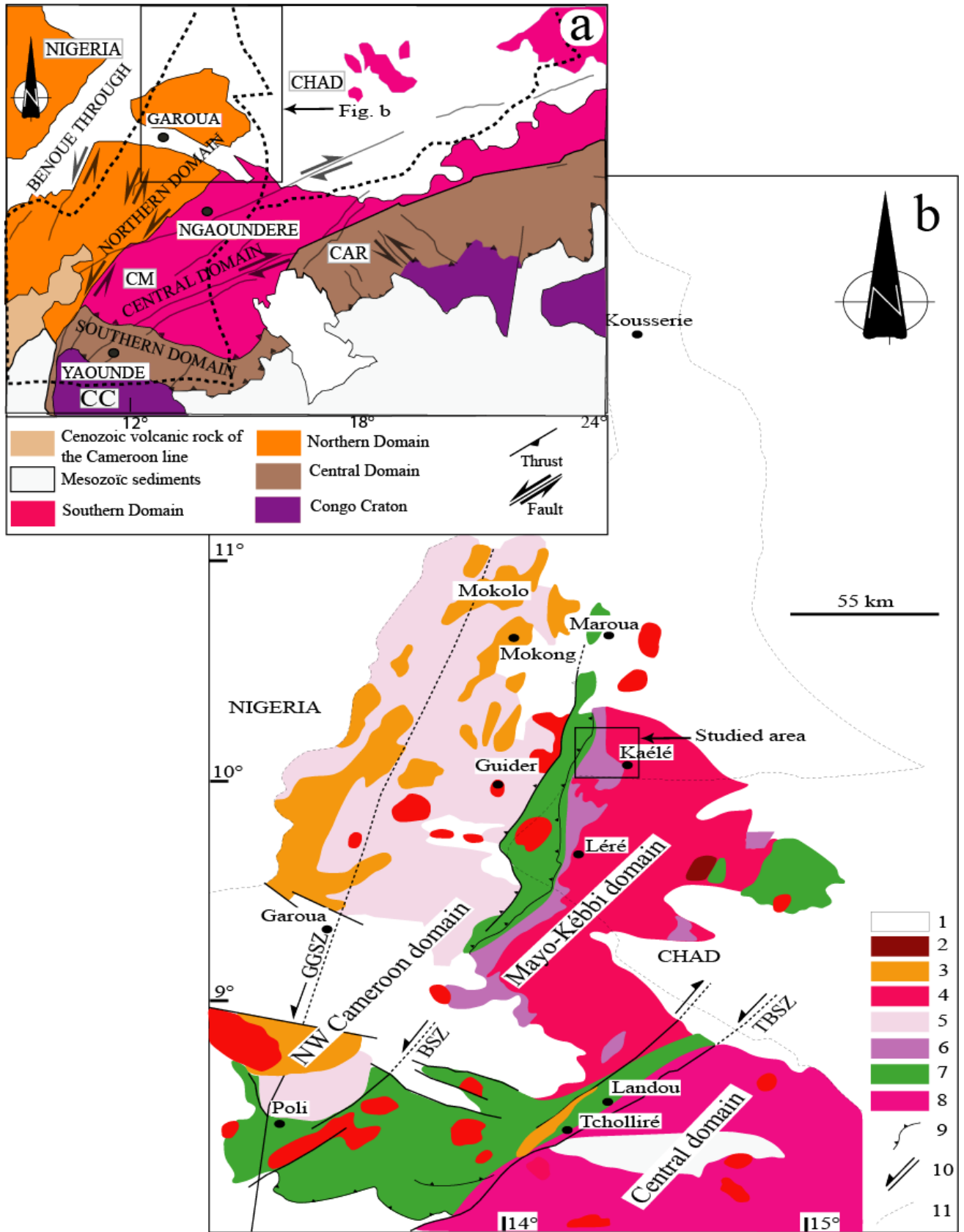


Figure 1. Map of the Central Africa Pan-African fold belt: a) Geological sketch of the Pan-African fold belt North of the Congo Craton showing the Northern Cameroon domain (modified from [10]), Congo craton (CC), Cameroon (CM), Central Africa Republic (CAR); b) Geological map of the Northern Cameroon domain (modified after [11,13,14]) showing the major lithological units and the study area: (1) Post-pan-African sediments; (2) Post to late tectonic Pan-African Granitoids; (3) Syntectonic granite; (4) Mayo-Kébbi Batholith; (5) medium to high grade Gneiss of the Northern domain; (6) Mafic complex of the Mayo-Kébbi domain (metadiorite and gabbro-diorite); (7) Neoproterozoic volcano-sedimentaries Sequences of the Poli-Léré group; (8) Adamaoua-Yade Paleoproterozoic domain; (9) thrust; (10) FTB= Tcholliré Banyo fault; FGG=Godé-Gormaya fault; (11) Border limit

Remote sensing and image processing have imposed themselves in recent years in geological mapping, due to the scarcity of outcrops, their discontinuity and the inaccessibility of their limits. The diversity of satellite sensors and their technical characteristics (spatial, spectral and temporal resolutions) provide additional information that can be combined with data from other sources [12], particularly field data. This study aims to apply remote sensing and field data in the structural study of the Kaélé region.

2. Geological Setting

The Mayo - Kébbi domain which covers Cameroon and Chad is an NE-SW elongated unit. It is located between the Adamawa-Yade domains and NW Cameroon domain (see Figure 1b). This domain is limited to the SE by the Tcholliré-Banyo fault in Cameroon and its extension, Massenia-Ounianga gravimetry anomaly, in Chad [11,15]. It is separated to the NW from the NW Cameroon domain by the volcano- sedimentary series of Zalbi, considered as a NE extension of the Poli group [8,11,16]. The Mayo-Kébbi domain differs from the Adamawa-Yade domain and NW Cameroon domain by its juvenile Neoproterozoic crust [11,17,18]. This domain corresponds to a magmatic arc zone which was formed between 800 Ma and 550 Ma by successive collision with the Central Cameroon and NW domains respectively [11,17,18]. It consists of: (1) the greenstone belts formed by the volcano-sedimentary series and the mafic to intermediate complex, (2) the Mayo- Kébbi batholith, and (3) the post-tectonic intrusions [11,17,18,19,20,21]. Study of the deformation highlights three tectonics phases D1, D2 and D3. There is a predominance of the NNE-SSW elongated direction. The first two are syn-schistose and the last is essentially strike-slip [19].

3. Materials and Methods

3.1. Materials

Envi 5.2, Geomatica 2015 and Qgis 3.18 softwares were used for multi-spectral image processing and analysis. Qgis 3.18 software was also used for

georeferencing, digitizing and adding maps to the database. StereoWin1.2 and CorelDraw12.0 software were used for field data processing.

3.2. Methods

3.2.1. Landsat 8+ Image Processing

3.2.1.1. Data Used

The cartographic database used for this study includes Landsat 8 image, the scene acquired between April 27, 2021 and May 01, 2021 under favorable climatic conditions to the visualization of geological elements on the ground (absence of clouds, relatively sparse vegetation cover). These orthorectified images appear very clear. The topographic map of Maroua 1:200 000 scale and the geological map of Leroy and Ciroteau [16] were also used.

3.2.1.2. Image Pre-Processing Method

The Landsat 8 image has undergone pre-processing, in particular radiometric correction [22] and atmospheric correction [23] to make exact overlay on topographic and geological maps, and convert the reflectances of the surface overlays to real reflectances.

3.2.1.3. Landsat Image Processing For Lineaments Mapping

Lineament mapping was carried out using digital processing from ETM+ band 3, which shows better results [24]. The principal component analysis (PCA) of the preprocessed channels makes it possible to transform the multispectral data into their principal component (PCA1). It highlights similarities and differences, thus reducing data redundancy [25]. The application of 7×7 directional filters of Sobel type (Table 1) in the NS, EW, NE-SW and NW-SE directions to the ETM+3 channels make it possible to accentuate the structural discontinuities and lithologies for a better discrimination of lineaments [26] and PCA1 makes it possible to enhance the image discontinuities corresponding to the lineaments. Automatic extraction has been used to extract lineaments because of its simplicity, speed, and it also offers high degrees of reproducibility compared to subjective manual extraction [27,28]. Only lineaments of structural origin are of interest in this study.

Table 1. Sobel in the four main directions

Sobel N-S							Sobel E-W						
1.0	1.0	1.0	0.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
1.0	1.0	1.0	0.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
1.0	1.0	1.0	0.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
1.0	1.0	1.0	-0.0	-1.0	-1.0	-1.0	0.0	0.0	0.0	0.0	-0.0	-0.0	-0.0
1.0	1.0	1.0	-0.0	-1.0	-1.0	-1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	-0.0	-1.0	-1.0	-1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	-0.0	-1.0	-1.0	-1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Sobel NE-SW							Sobel SE - NO						
-1.4	-1.4	-1.4	-0.7	0.0	0.0	0.0	0.0	0.0	0.0	-0.7	-1.4	-1.4	-1.4
-1.4	-1.4	-1.4	-0.7	0.0	0.0	0.0	0.0	0.0	0.0	-0.7	-1.4	-1.4	-1.4
-1.4	-1.4	-1.4	-0.7	0.0	0.0	0.0	0.0	0.0	0.0	-0.7	-1.4	-1.4	-1.4
-0.7	-0.7	-0.7	0.0	0.7	0.7	0.7	0.7	0.7	0.7	0.0	-0.7	-0.7	-0.7
0.0	0.0	0.0	0.7	1.4	1.4	1.4	1.4	1.4	1.4	0.7	0.0	0.0	0.0
0.0	0.0	0.0	0.7	1.4	1.4	1.4	1.4	1.4	1.4	0.7	0.0	0.0	0.0
0.0	0.0	0.0	0.7	1.4	1.4	1.4	1.4	1.4	1.4	0.7	0.0	0.0	0.0

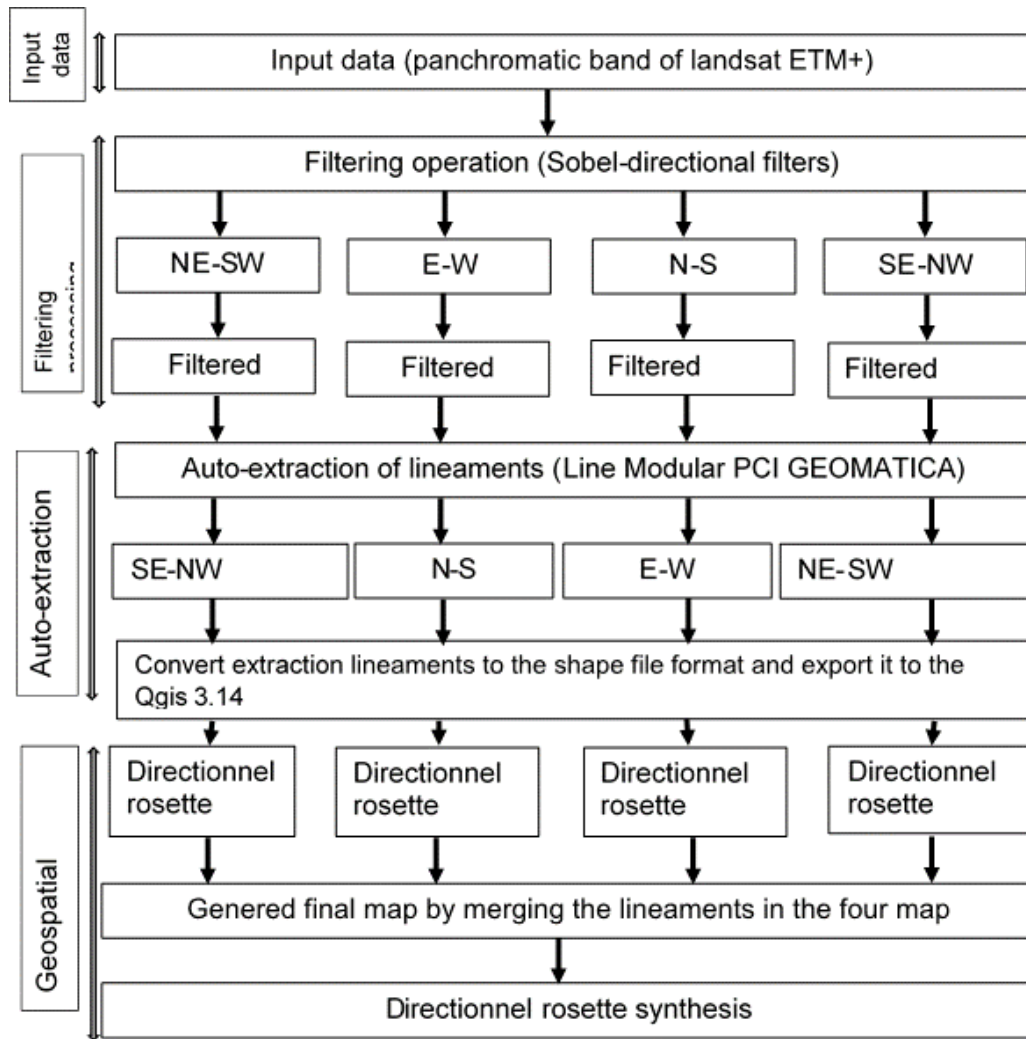


Figure 2. Flowchart shows of the study

The lineaments highlighted were analyzed and the main directions were firstly compared to those of known tectonic accidents in the region [11,13,14,17,18,19]. In order to validate the lineaments and give a structural interpretation. This step is fundamental in the validation of fractures resulting from the processing of satellite images [22]. In the second step, the lineaments extracted were compared to the lineaments of anthropic origin previously vectorized (asphalt roads, tracks, limits of forests or cultivated areas and the aligned houses) which were identified in all the lineaments and eliminated. Figure 2 shows different stages of this work which are similar to that of Rayan Gazi [29].

The lineament extraction algorithm was applied to panchromatic band 8 from geomatca software. The tuning values were selected from several tuning tests, the one that was used is recorded in Table 2.

Table 2. Suggested parameter values

Parameters Suggested	values
Filter radius (RADI)	10
Gradient threshold (GTHR)	100
Length threshold (LTHR)	30
Line fitting error threshold (FTHR)	3
Angular difference threshold (ATHR)	30
Linking distance threshold (DTHR)	20

4. Results

4.1. Mapping Lineaments

Lineaments are representations of linear geological features or alignments of geological objects, topographical discontinuities or geomorphological structures inherited from ancient topographies [30,31,32]. The images resulting from the processing by directional filters made it possible to draw up the lineament maps of the study area. The one that brings out the most discontinuities is the directional filter N-S, E-W, NE-SW, NW-SE with a 7×7 matrix applied to the band OLI 3 which gives the best result (Figure 3).

Lineaments extracted from different directional filter maps of Figure 3 allow to realize rose diagrams of Figure 4. The rose diagrams of the N-S, E-W, NE-SW, NW-SE directional filters show the major directions N-S (N100E), E-W (N10E), NE-SW (N140E), NW-SE (N40E), respectively.

A total of 3841 lineaments were obtained in the study area (Figure 5a) and they permit to obtain the rose diagram of Figure 5b, which shows E-W (N100E) major direction and N-S (N10E) secondary direction.

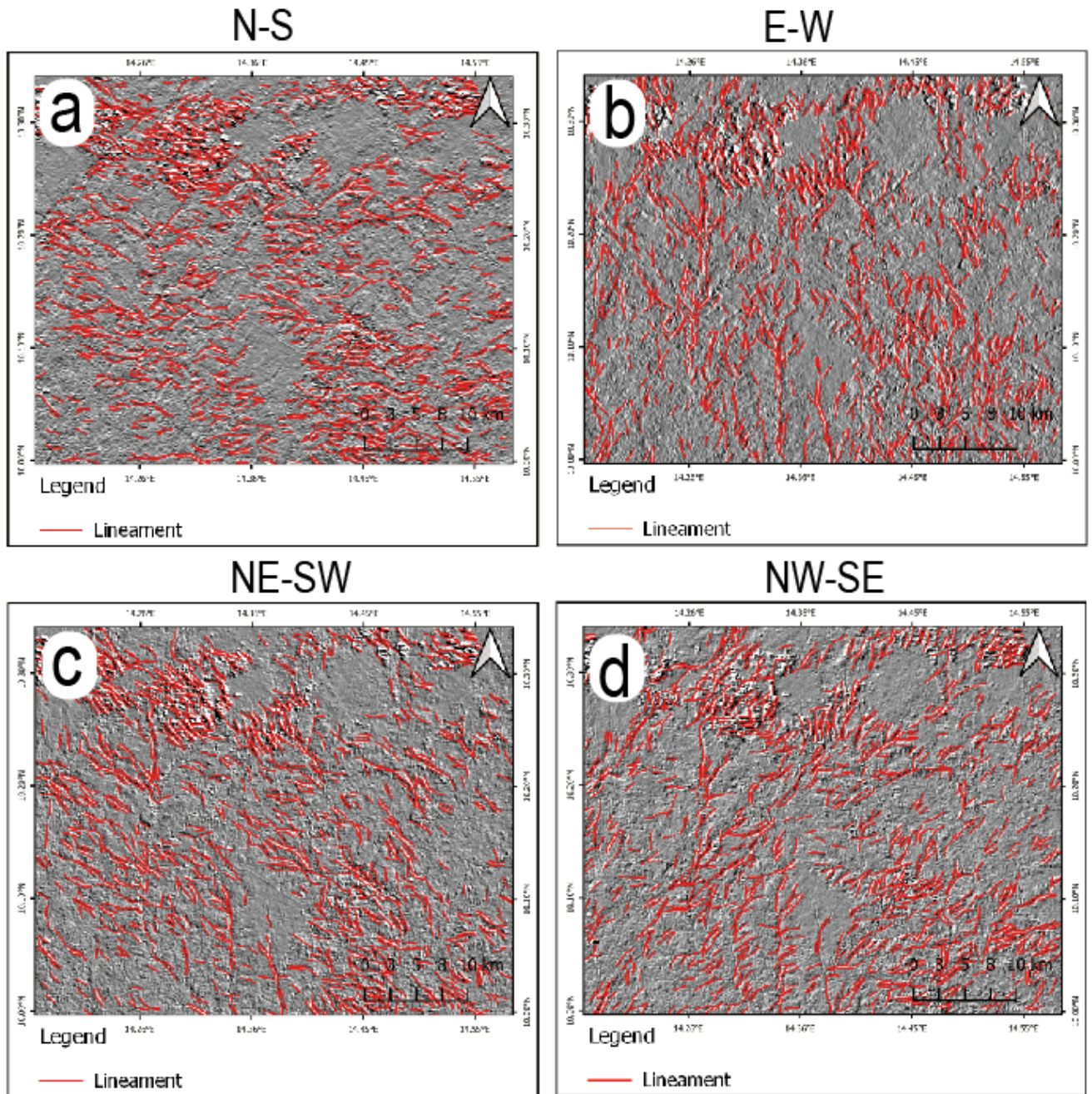


Figure 3. Four images from the Landsat 8 panchromatic band: a) discontinuities of the NS directional filter; b) discontinuities of the EW directional filter; c) discontinuities of the NE-SW directional filter; d) discontinuities of the NW-SE directional filter

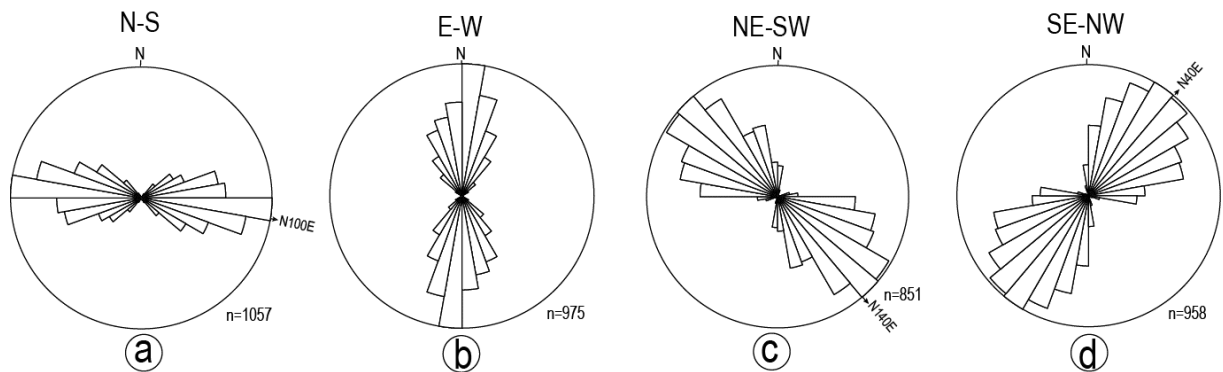


Figure 4. Lineament rose diagrams: a) rose diagram from the NS directional filter; b) rose diagram from the EW directional filter; c) rose diagram from the NE-SW directional filter; d) rose diagram from the NW-SE directional filter

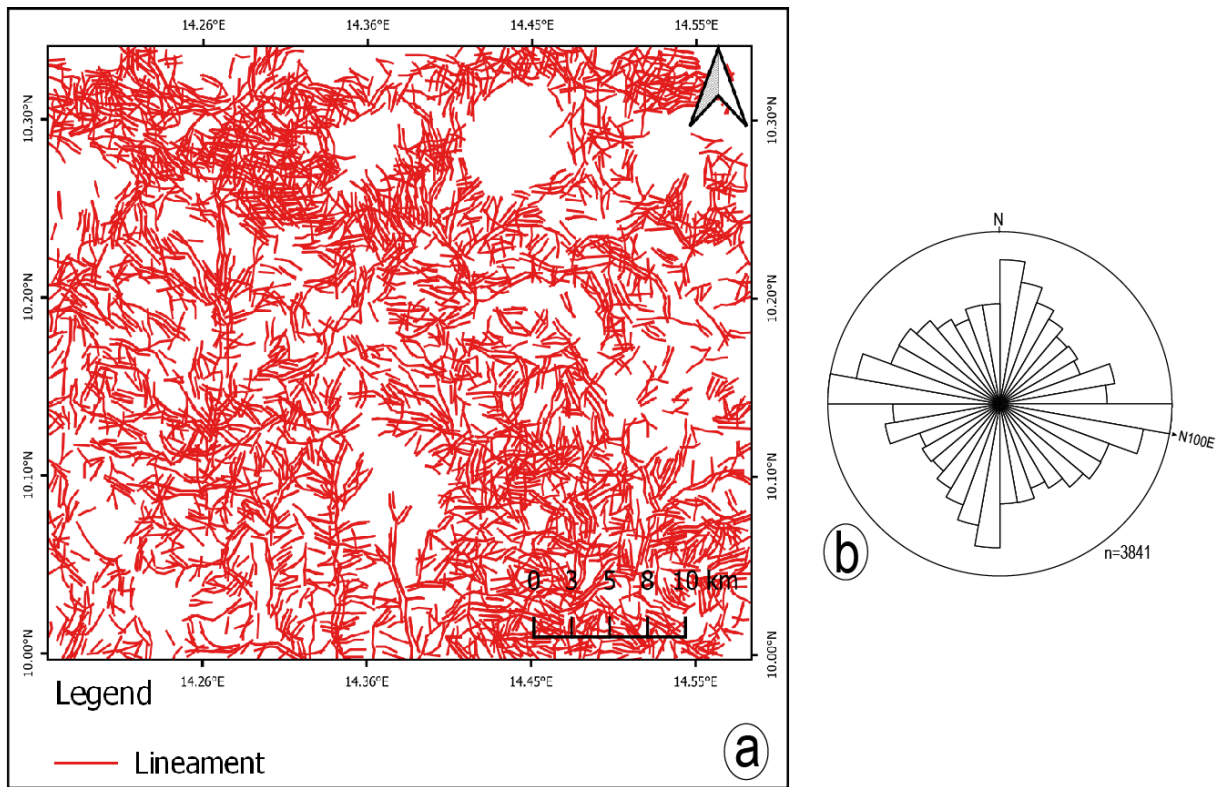


Figure 5. a) lineaments Map of Kaélé region; b) rose diagram of lineaments in the Kaélé region

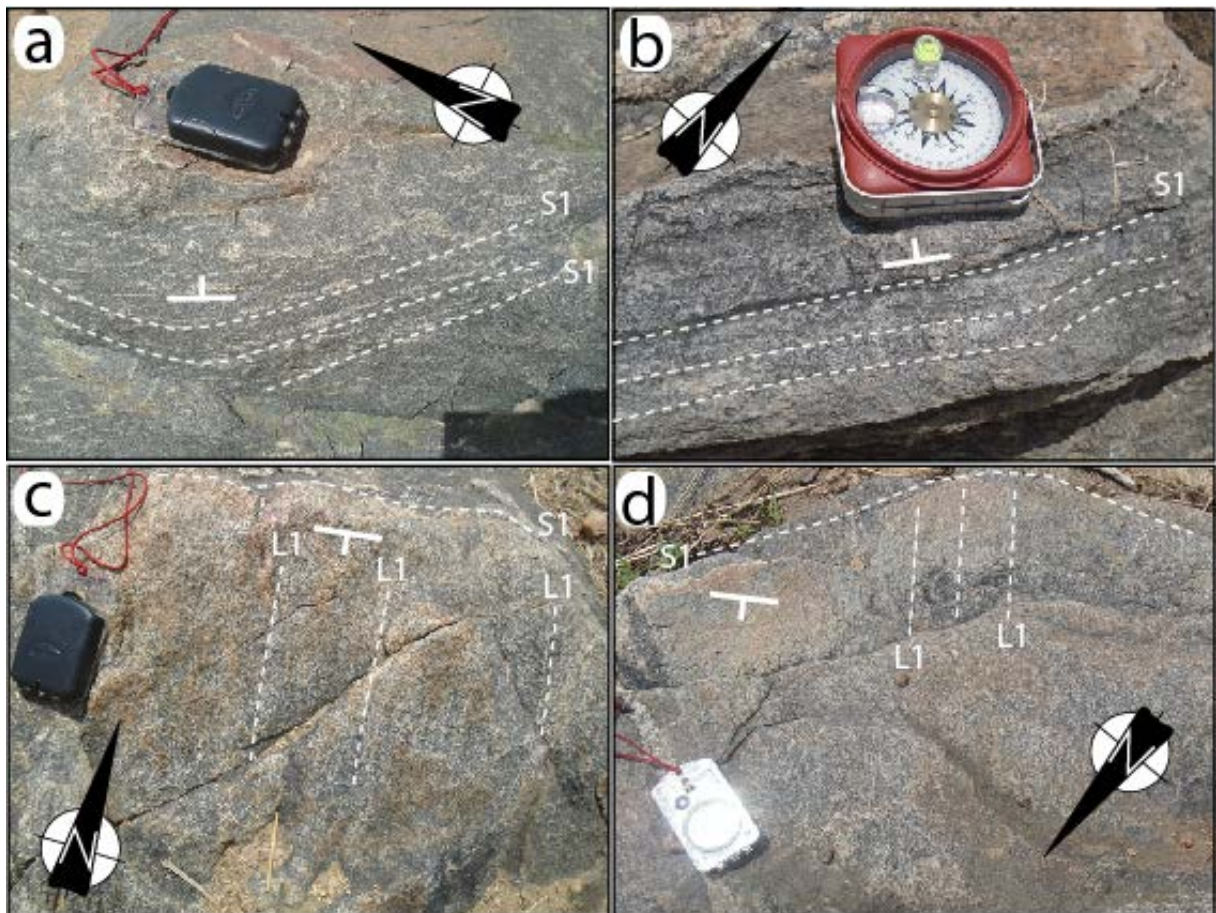


Figure 6. S1 foliation and L1 lineation in the Kaélé region: a) S1 foliation marked by an alternation of fine discontinuous quartzo-feldspathic light beds and dark beds rich in ferromagnesian minerals in the Doumrou amphibolite; b) S1 foliation marked by the horizontal alignment of amphibole and feldspar in the Boboyo amphibolite; c and d) Plane of S1 foliation bearing mineral and L1 stretching lineation in the Boboyo and Midjivin amphibolite respectively

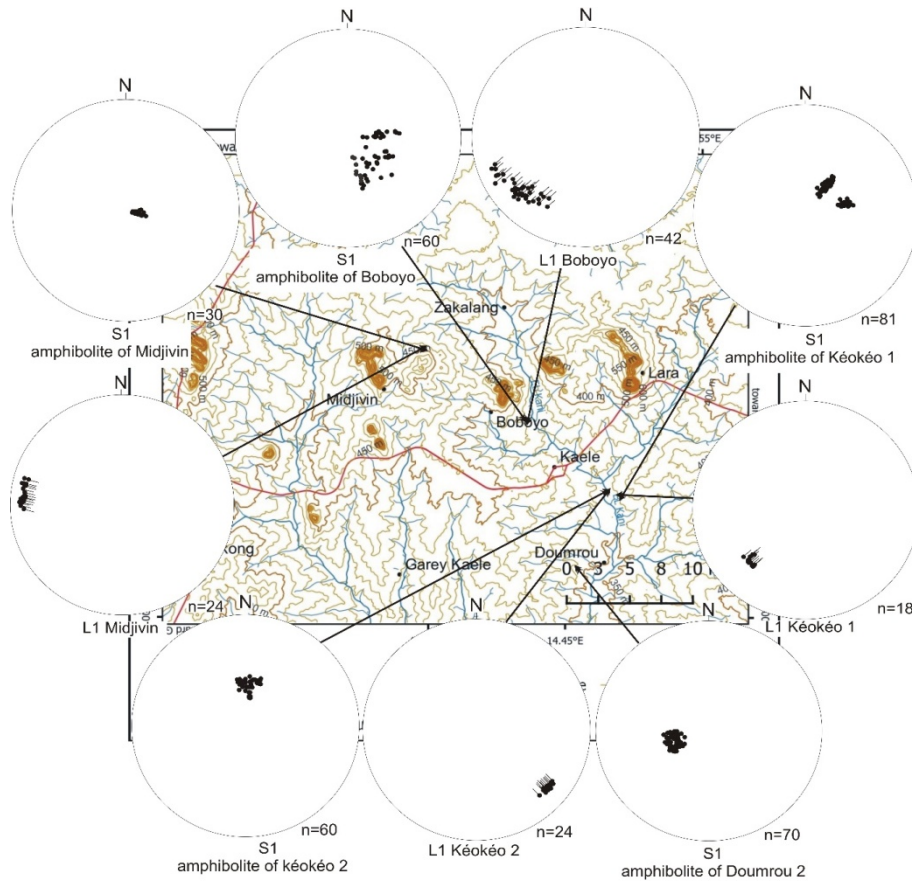


Figure 7. Map of the Kaélé region showing the stereograms of S1 foliation and L1 lineation

4.2. Field Data

The study area was affected by polyphase deformation. Four phases of deformations are highlighted in this zone and designated D1, D2, D3 and D4 in the chronological order of their manifestation. The first phase of deformation is reported in amphibolites and is responsible of S1 foliation and L1 lineation. S1 foliation is observed in amphibolites at Doumrou, Boboyo, Kéokéo 1, Kéokéo 2, and Midjivin. In Doumrou (Figure 6a), S1 is marked by an alternation of fine discontinuous quartzo-feldspathic light beds and dark beds rich in ferromagnesian minerals in the amphibolites, while at Boboyo (Figure 6b), Kéokéo 1, Kéokéo 2 and Midjivin, S1 is materialized by horizontal alignment of amphibole, biotite and feldspar minerals in the amphibolites. The poles of the S1 are close to the center of the stereogram, consequence of their low to medium dip angles (5° to 40°). The S1 poles are located in the SE, E-ENE, W and N-NNW quadrant of the stereograms of Boboyo, Kéokéo 1, Kéokéo 2 and Midjivin respectively, results of the NW, W-WSW, E and S to SSE dip direction of the S1 foliation (Figure 7). The L1 lineation is a composite, mineral and stretching, lineation; the mineral lineation is underlined by an alignment of amphibole and biotite, while the stretching lineation is marked by quartzo-feldspathic strips and stretched feldspar aggregates (Figure 6c and Figure 6d). In the stereogram, the poles of L1 lineation are close to the fundamental circle and concentrated around SW quadrant for the Kéokéo 1 and Boboyo stereogram, SE quadrant for the Kéokéo 2 stereogram and W to WNW quadrant for the Midjivin stereogram (Figure 7) consequence of the low

dipping L1 lineation towards the SW, SE and W to WNW. This phase of deformation (D1) is strongly transposed by the second phase of deformation (D2).

The second phase of deformation (D2) is more intense and is marked by S2 foliation, L2 lineation, B2 boudin, F2 folds and C2 shear. The S2 is the result of the tectonic transposition of S1. S2 foliation is seen in metamorphic rocks: gneisses, amphibolites, banded amphibolites, quartzites, micaschists, chloritoschists, talschists. In gneisses (Figure 8a) and banded amphibolites (Figure 8b), it is a compositional bedding with alternating millimetric quartzo-feldspathic light beds and centimetric sometimes discontinuous dark beds rich in ferromagnesian minerals. S2 foliation is marked by planar arrangement of quartzo-feldspathic minerals, amphibole and/or biotite in amphibolites (Figure 8c), and quartz in quartzites. In shales (micaschist, chlorotoschist, talschist), it is marked by sheet layering (Figure 8d and Figure 8e). S2 foliation is subvertical. Its poles are located between E and S of the stereogram, reflecting W to N dipping planes at Bissélé, Gadas, Kassile, Garey, Midjivin 1, Midjivin 2 and Goubara (Figure 9a). The poles of the S2 foliation are located between N and E of the stereogram, as consequence of the S to W dip direction at Zaklang 1, Zaklang 2, Moundjouing, Aviation, Zanoumi 1, Zanoumi 2, Doumrou (Figure 9a). The poles of the S2 foliation are located between the NW and the N of the stereogram, as consequence of the SE to S dip direction at Midjivin 3 and Mazang (Figure 9a). L2 lineation is observed in amphibolites and gneisses. It is a mineral lineation marked by the alignment of amphibole and biotite in amphibolite (Figure 8f) and a stretching lineation underlined by

quartzo-feldspathic straps and aggregates of stretched feldspars in gneisses (Figure 8g). L2 lineations are also observed in quartzites (Figure 8h). L2 lineation plunges towards W to NW in the localities of Aviation 1, Aviation 2, Aviation 3, Moundjouing, Zaklang 2, Zanoumi 1, Zanoumi (Figure 9b), towards SW to W in the localities of Mazang, Midjivin and Zaklang 1 (Figure 9b) and towards NE to E in the locality of Zanoumi 2. The angles of plunge are low to medium, where the positions close to the fundamental circle. Boudinage is observed in amphibolites and gneisses. It manifests as stretched syn-S2 quartzo-feldspathic materials in amphibolites (Figure 8i). Boudinage also affects amphibolites interbedded in biotite gneisses; amphibolites relatively

more competent than gneiss are often cut by dextral shear into boudins (Figure 8j). These sigmoid shaped boudins are oriented N-S and NNW-SSE. They have variable dimensions 24 cm to 45 cm long axis and 12 cm to 20 cm short axis. F2 folds encountered in the studied area are isopach (Figure 8k) to anisopach (Figure 8l) folds, asymmetrical with NNE to N vergence (Figure 8m). F2 fold axes have low to medium plunging angles and variable plunging directions: W to N (Boboyo 2, Boboyo 3, Zanoumi) (Figure 9b), S to WSW (Boboyo 1, Kéokéo 1, Kéokéo 2) (Figure 9b). C2 shear affecting S1 shows dextral mouvement (Figure 8n), inducing the formation of folded microlithon. C2 shear planes are filled with the same quartzo-feldspathic materials as the S2 foliation.

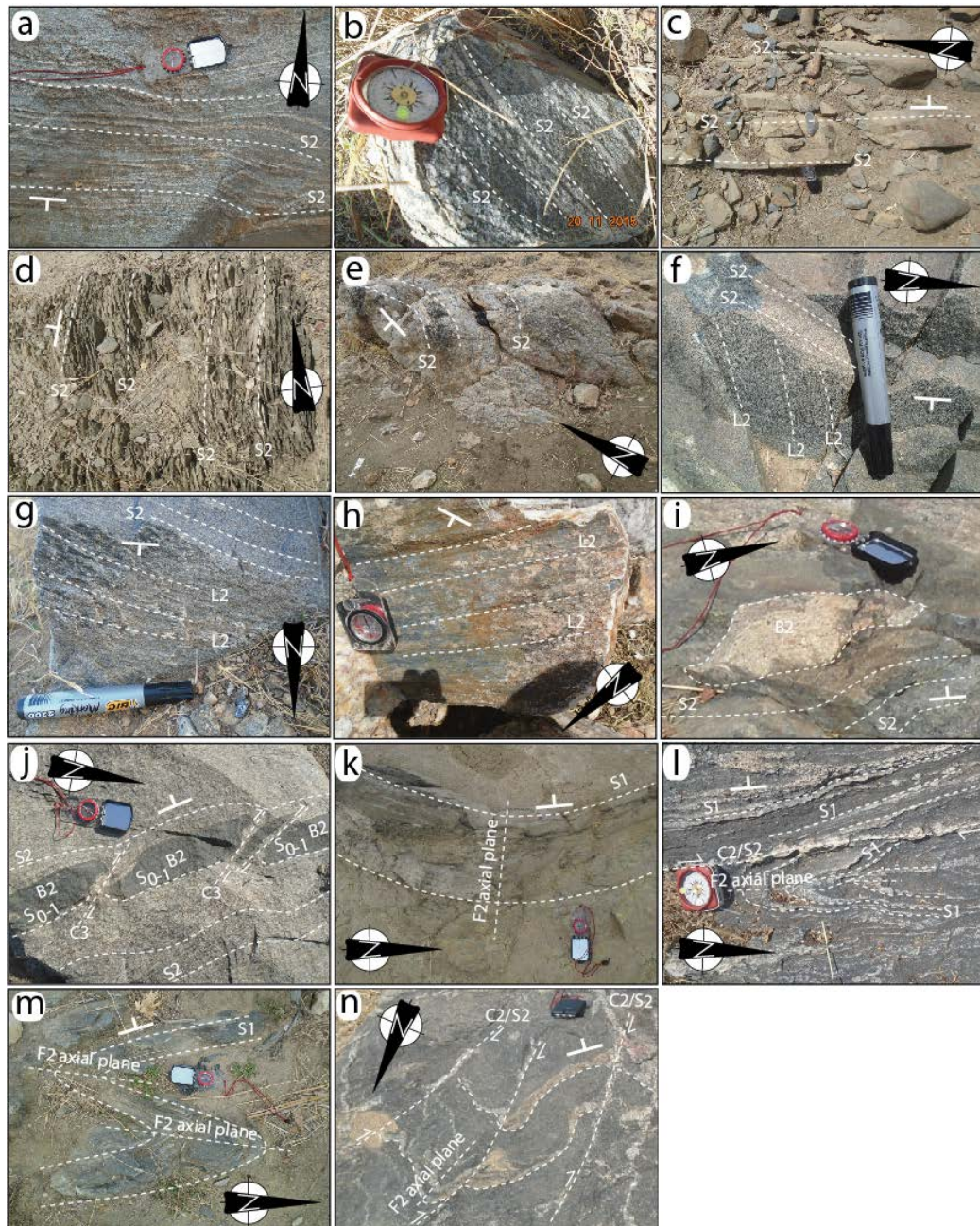


Figure 8. Structural elements of the second phase of deformation: a) S2 foliation in the amphibole and biotite gneisses of Mazang; b) S2 banding in the banded amphibolite of Boboyo ; c) S2 foliation in the amphibolites of Doumrou; d) S2 foliation in midjivin micaschist; e) S2 foliation in the Morsalé talcschist; f) L2 Mineral and stretching lineation in the Zanoumi amphibolites; g) L2 Mineral and stretching lineation in the biotite gneisses of Zanoumi; h) L2 striae in Guéréme quartzites; i) B2 Boudin of sigmoid quartzo-feldspathic materials in the Zanoumi amphibolites; j) Amphibolite sheared into boudins in Aviation biotite gneiss; k) F2 isopach folds at Kéokéo; l) F2 Anisopach folds at Boboyo; m) F2 Anisopach and dissymmetrical folds at Kéokéo; n) C2 Dextral shear in the banded amphibolites of Boboyo

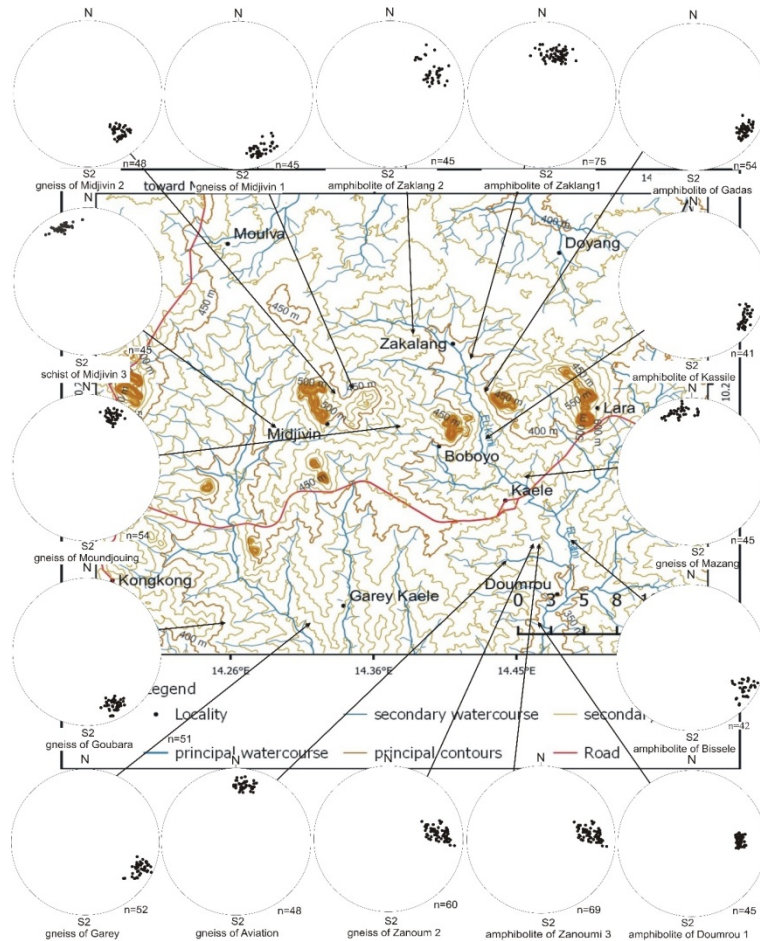


Figure 9a. Map of the Kaélé region showing the stereograms of the poles of the S2 foliation

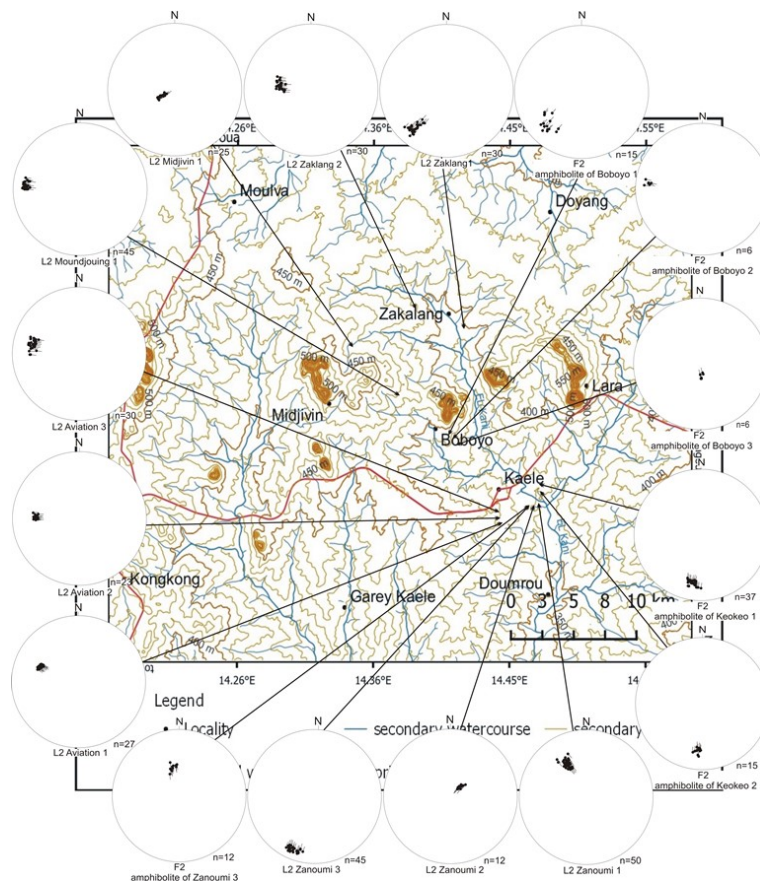


Figure 9b. Map of the Kaélé region showing the stereograms of the poles of the L2 lineation and the F2 folds axis

D3 phase of deformation is characterized by S3 foliation, C3 shear and F3 fold. S3 foliation is evidenced in the amphibole and biotite gneisses of Mazang, where it is marked by fine compositional bedding. It is an S3/C3 syn-shear foliation, perpendicular to the S2 foliation (Figure 10a and Figure 10b). In the syn-tectonic granite, S3 foliation is materialized by planar the alignment of amphibole, biotite and feldspars (Figure 10c) and it intersects the S2 foliation in the Mazang amphibolite with approximately an angle of 30° (Figure 10d). The poles of S3 foliation are located between E and SE of the stereogram, as consequence of W to NW dip direction at Zaklang 1, Zaklang 2, Mazang and between the N of the stereogram, a consequence of the S dips at Aviation (Figure 11). F3 folds are asymmetrical folds with NE vergence (Figure 10e and Figure 10f), isopach (Figure 10e and Figure 10g) or anisopach (Figure 10 f, g

and h). F3 folds are also found as intrafolial folds (Figure 10i) and sheath fold (Figure 10j). F3 folds are often induced by C3 conjugate shear planes (Figure 10k). F3 fold axes (Figure 11) have a low to medium angle plunge toward NNW to N and SE to SSE (Bissélé 1), WNW to NW (Zaklang 1), NW to WNW (Zaklang 2), SW (Mazang), SW to W (Midjivin). C3 shear affects the S2 foliation. It is represented by a shear zone at Zanoumi. C3 shear is highlighted by the relative movements of the compartments that they separate and causes the folding of the S2 foliation. The movement is induced the shrinking and thickening of the S2 foliation in the shear corridor and it causes the boudinage by stretching of the quartzo-feldspathic materials of the S2 foliation. The cusp and shift highlight the dextral character of the C3 shear (Figure 10a, b, k and l).

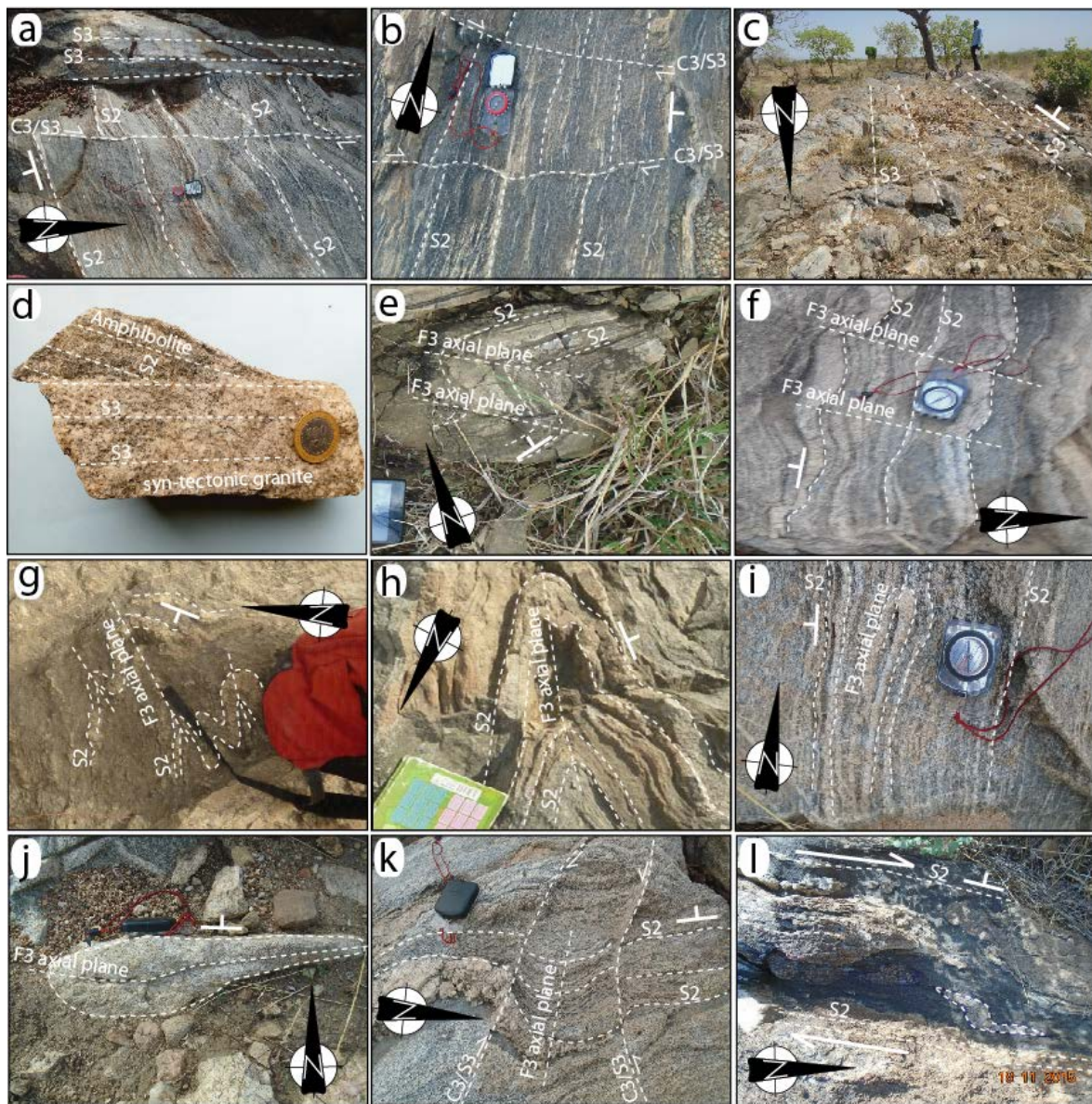


Figure 10. Structural elements of the third phase of deformation: a) S3 foliation in the C3 shear plane in the amphibole and biotite gneisses of Mazang; b) S3 foliation in the C3 shear plane in Aviation amphibolites; c) Granite with amphibole, biotite and deformed epidote bearing an S3 foliation at Garey; d) S3 foliation in a sample of amphibole, biotite and epidote granite in contact with an amphibolite bearing an S2 foliation; e) Anisopach F3 fold in the Midjivin shales; f) Isopach and anisopach F3 fold in the amphibole and biotite gneiss of Mazang; g) Isopach and asymmetrical F3 fold in muscovite gneisses of Gadas; h) Anisopach F3 fold in the Bissélé amphibolites; i) Intrafolial F3 fold, anisopach in amphibole gneiss and biotite from Mazang; j) F3 Fold in sheaths in the amphibole and biotite gneisses of Mazang; k) F3 fold induced by C3/S3 conjugate shear in the amphibole and biotite gneisses of Mazang; l) Dextral C3 shear corridor in the Zanoumi biotite gneiss

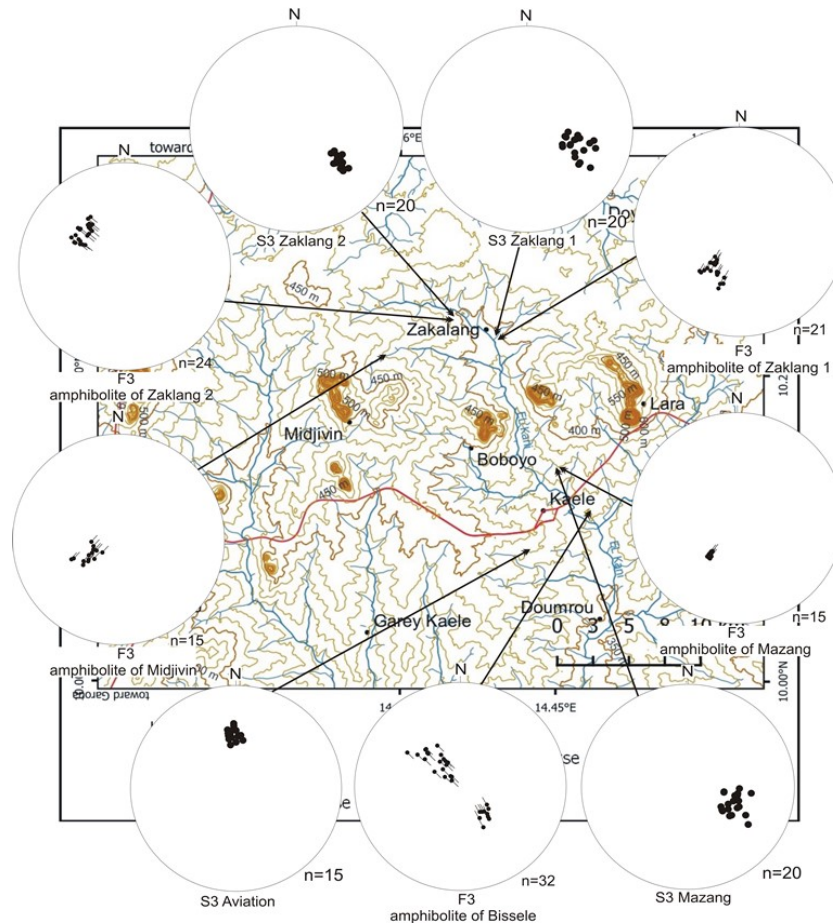


Figure 11. Map of the Kaélé region showing the stereograms of the poles of the S3 foliation and F3 fold axis.

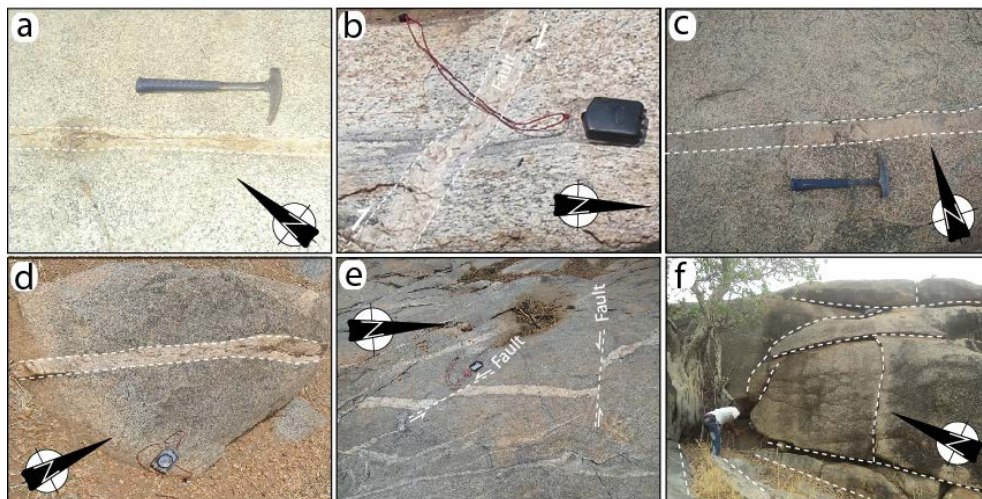


Figure 12. Structural elements of the fourth phase of deformation: a) vein of biotite granite cutting the amphibole, biotite and epidote granite at Boboyo; b) Pegmatite vein occupying the dextral fault plane in the amphibole and biotite gneiss of Midjivin; c) aplite vein in biotite granite at Gadas; d) quartz vein in amphibole-biotite gneiss at Moursalé; e) Aplite dyke shifted by sinistral fault planes in the banded amphibolites of Zaklang; f) fracture networks on biotite granites at Lara

The fourth phase of deformation (D4) is brittle. It results in an intense fracturing of the rocks of our study area. Some of these fractures are filled by magmatic material (vein joints) and others are not (dry joints). The veins observed in the Kaélé region are biotite granites (Figure 12a), pegmatites (Figure 12b), aplites (Figure 12c) and quartz (Figure 12d) with variable thickness (2 to 180 cm). Rose diagrams of vein (Figure 13) can be grouped into three types according to the major directions: the first type, with a major direction N120E to N130E, consists of

the Lara and Mazang rose diagram with NNE-SSW (N30E to N40E) and ENE-WSW (N60E to N70E) secondary directions. The second type with E-W (N90E-N110E) major direction is made up of Kaélé and Kassilé on rose diagram. They have as secondary directions N20E to N40E, N160E (Kaélé) and N140E (Kassilé). The third type of rose diagram is that of Boboyo with the major direction of N50E and the secondary directions N70E and N160E. Unfilled joints are represented by faults and joints. Faults in the study area are sinistral, offsetting veins

(Figure 12e) or dextral, some of which are occupied by magmatic material (Figure 12b). Joints in the study area allow to realize rose diagram of Figure 13. Three types of rose diagram can be considered, according to their major and or secondary direction: (1) rose diagram with N-S major direction and variable secondary direction (Figure 13: Boboyo, Zanoumi 1, Bissélé, Kaélé, Tibiri, Mazang); (2) rose diagram with NNW-SSE secondary direction and variable major direction (Figure 13: Lara 1 and Kassilé); and (3) rose diagram with NNE-SSW major direction and variable secondary direction (Figure 13).

5. Interpretation and Discussion

5.1. Deformation Regime

D1 deformational phase is characterized by S1 foliation and L1 lineation which are both subhorizontal. The

synthetic stereogram of the first phase of deformation (Figure 14) shows that the poles of S1 are located between NNW and S and the W and WSW of the stereogram, a result of SSW to N and E to ENE of S1. The L2 lineation poles are located to SE of the stereogram, and between WNW and SSW, reflecting their plunge direction. The tangential character of these structures suggest, despite their relictual appearance on field that they have been probably affected by an horizontal general flattening. Such tangential structures (S1, L1) have been recorded in the Poli region at about 150Km south west and is the study area [33,34,35]. Subhorizontal structures in Yaoundé area been interpreted as related to nappe stacking phase during prograde metamorphism [36], under simple shear regime [37]. Nevertheless in the study area, no nappe formation has been yet evidenced. It is not easy to characterize the geometry of the strain during the D1 phase, because of the overprinting of D2 deformation. Nevertheless, it is not unlikely, that the simple shear was dominated.

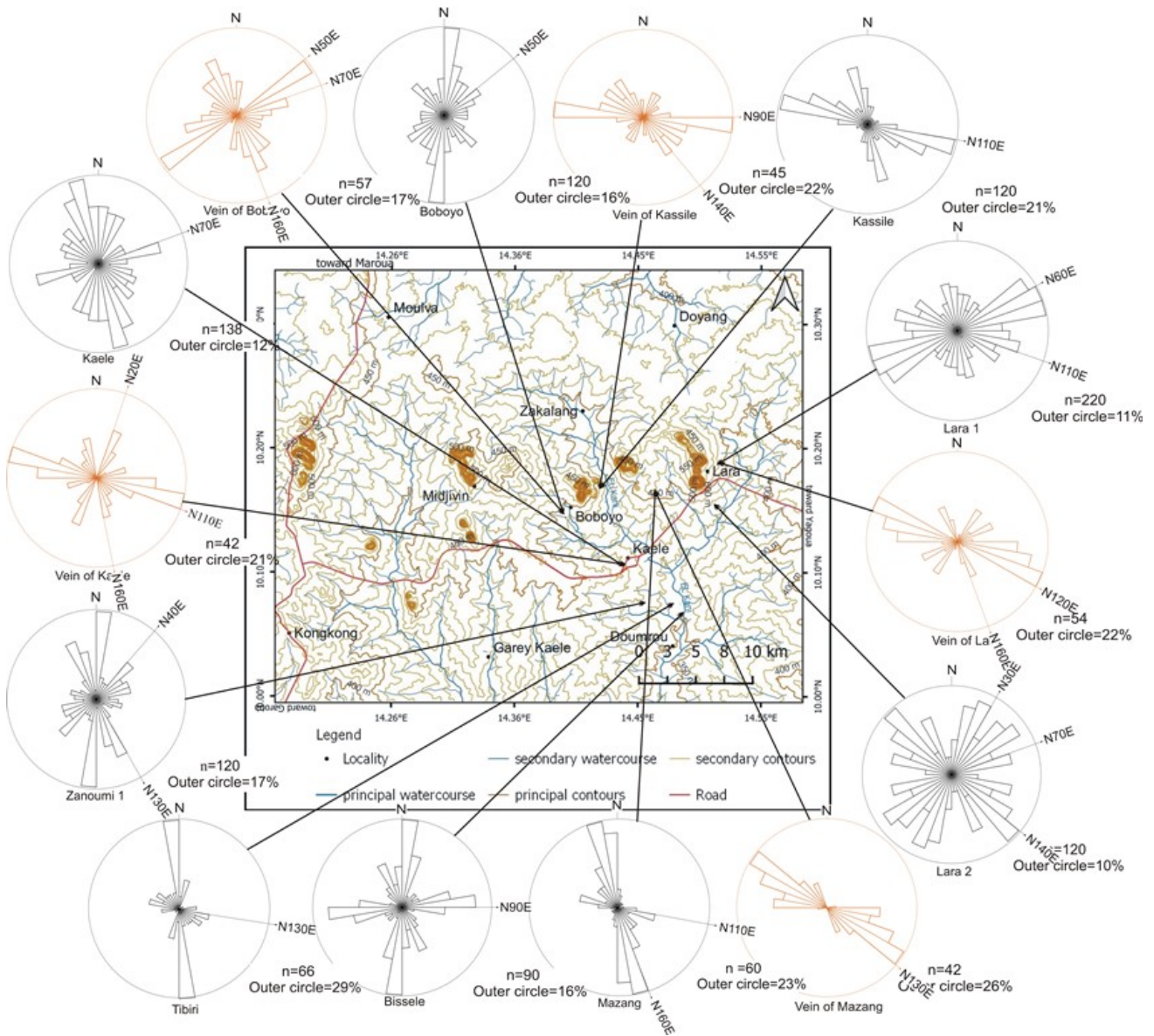


Figure 13. Map showing rose diagram of structural elements of the brittle phase in the Kaélé region (veins (orange); joints (light))

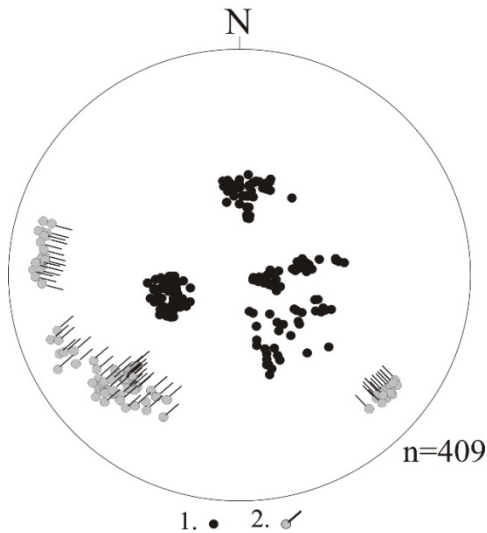


Figure 14. Synthesis stereograms of the structural elements of the first phase of deformation D1 (1. poles of S1 foliation, 2. poles of L1 lineation)

The second phase of deformation set up the subvertical S2 foliation carrying the L2 composite lineation (mineral and stretching), sigmoide shaped B2 boudin, dextral C2 shear which intersects the S1 foliation and the isopach to anisopach F2 folds. The fact that the L2 lineation is subhorizontal on most outcrops shows that the subvertical S2 foliation behaves like shear planes with a strong horizontal component. The asymmetry nature of F2 fold and vertical dip of S2 foliation also shows the shearing character of the second deformation phase D2. This phase of deformation is similar to D2 deformation phase in the regions of Meiganga and Doua-Kalaldi-Badzer respectively [38,39]; Nga Mbappé and Yoro north of the Yaoundé group [40]; the Tcholliré region [41]; Baïbokoum-Touboro-Ngaoundaye region [42] and also interpreted as having a shearing character. S2 foliation, L2 lineation and C2 shear are syn-migmatitic. In the stereonet (Figure 15a), we note the opposite plunge direction of P2 fold axis, globally toward north and south. This imply a folding of

F2 fold axis related to a N-S shortening. It means that the intermediate stress σ_2 is also a compressional stress. The distribution of S1 pole density on a stereonet (Figure 15a) highlight a regional cylindrical F2 fold due to a main stress σ_1 (N53E10SW) induce by a NE-SW compression; the intermediate stress σ_2 is horizontal oriented W-E (N142E02SE) and the minor stress σ_3 (N40E80NE) is subvertical. Some L2 lineation are subparallel to F2 fold axis when they should normally be perpendicular. A rotational movement should have affected the two structures and bringing them closer one to each other. The deformation regime is a constriction, because $\sigma_1 > \sigma_2 > \sigma_3$, but σ_2 also correspond to a shortening direction. The resulting stress ellipsoid is shown in Figure 15b, characterized by an elongated triaxial ellipsoid.

The third phase of deformation (D3) is responsible of subvertical S3/C3 foliation, asymetrical and sheath folds. Those structure highlight the shearing character of the D3 phase. C3 and S3 are filled by the some leucosome. The distribution of S2 pole in a stereogram defines a regional scale F3 fold (Figure 16a). This fold is due to a NNW-SSE compression induced by major stress σ_1 oriented N176E14N. The attitude of regional fold axis is N67E52WSW and close similar to the mesoscale fold axis identified on the field. It is also possible that F3 regional fold being a sheath fold; in fact S2 pole tend to be distribute on a circular curve in the stereogram (Figure 16a). Mesoscale fold axis show opposite plunge direction (Figure 16a) at Bissélé, synonymous of the shortening in their direction (σ_2); thus, the regime of D3 deformation phase is a constriction. Such observation has been made in the region of Baïbokoum-Touboro-Ngaoundaye [42] and in the Bafia region [40,43,44]. The result stress ellipsoid of D3 deformation phase is show in Figure 16b. Two group of F3 fold axis can be distinguished in the stereonet (Figure 16a). One group illustrating a NNW-SSE shortening (grey domain) on the other illustrating N-S shortening (yellow domain). It is possible that the direction of compression was not fixed during D3, moving from NNW-SSE to NW-SE.

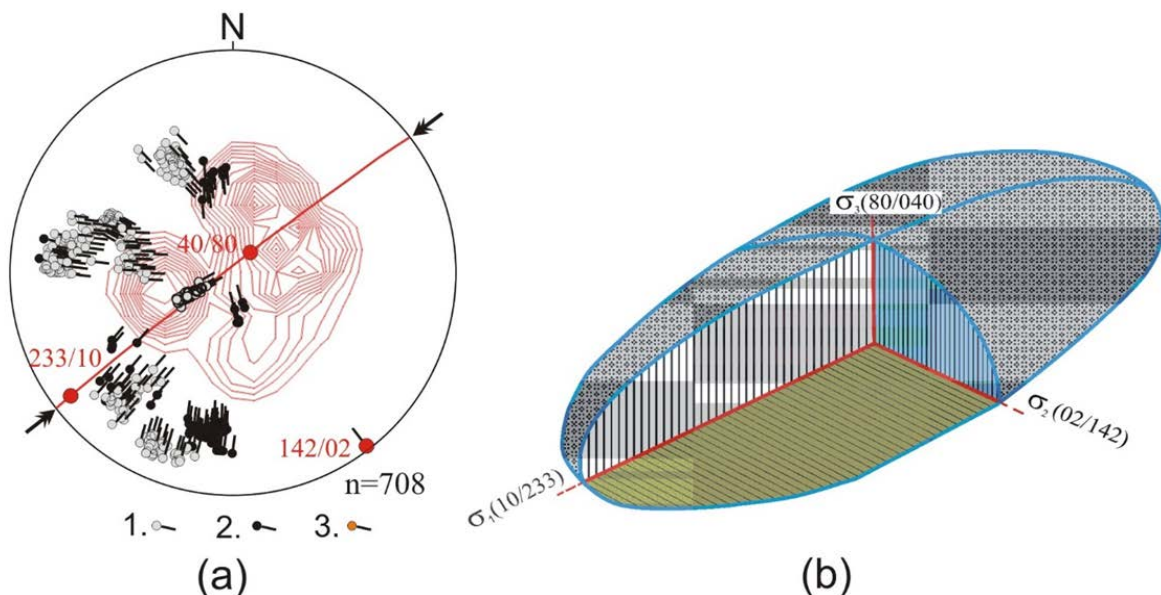


Figure 15. a) Highlighting the F2 regional fold from the S1 compared to the poles of L2 lineation and F3 fold axis (1. poles of L2 lineation; 2. poles of F2 fold axes, 3. Pole of regional F2 fold); b) deformation ellipsoid resulting to second phase of deformation

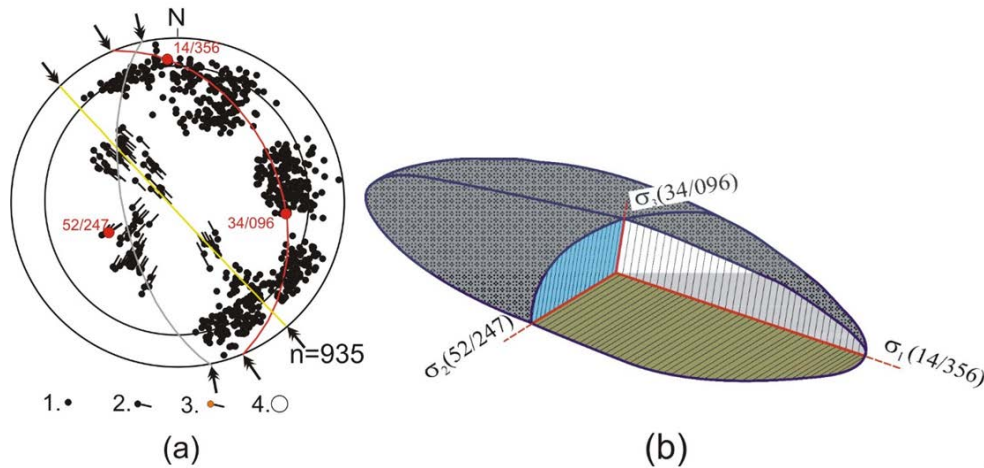


Figure 16. a) Highlighting the F3 regional fold from the S2 compared to the P3 fold axes (1. poles of S2 foliation; 2. poles of P2 fold axes; 3. Pole of regional F3 fold; 4. regional sheath fold); b) deformation ellipsoid resulting to third phase of deformation

Major directions of fracturation during D4 (Figure 13) phase are similar to those known in Central Africa: Adamaoua shear zone ENE-WSW (N70E to N80E) [45]; NNE-SSW Cameroon Hot Line (N20-30E) [46,47,48,49]; NNE-SSW the structuration of the North domain of the CPAFBC [50]; mean direction of the Tcholliré fault (N50E) [1,51]. In Chad, the direction NNE-SSW (N30E) corresponds to the Tibesti fault [52]. The major direction N130E corresponds to the directions of the faults which border the Cretaceous series of Lamé to the south of Pala [19] and those which limit the massif of Yadé to the NW with the sediments of the Doba basin [15]. This direction also approaches the direction of the Cretaceous through of Bénoué (N135E).

5.2. Structural Significance of Lineaments

The NS, NNE-SSW, NE-SW, SSE-NNW directions of the lineaments are similar to the directions of the S2

foliations measured on the field (Figure 4; Figure 5 and Figure 13). Similar foliation directions were obtained in the Pan-African domain of Mayo- Kebbi in southwestern Chad [11,14,15,33]. These results are also consistent with data from [11,17,33,34,53] and could be due to the North-South orientation of the NW Cameroon domain. The similarities of the directions of the lineaments and of the foliations show that it is not certain lineaments could be the trajectories foliation. Such observations have been made by [54] in the region of Ngoura East Cameroon colomines and interpreted as foliation trajectories. It highlights penetrating lineaments (foliation) and non-penetrating lineaments (fractures). The NS and EW directions of the lineaments are similar to the directions of the veins and joints in our study area (Figure 13). Such observations were made by the analysis of spatial images which highlighted dextral E-W strike-slips in the Mayo-Kébbi domain, in southwestern Chad [17].

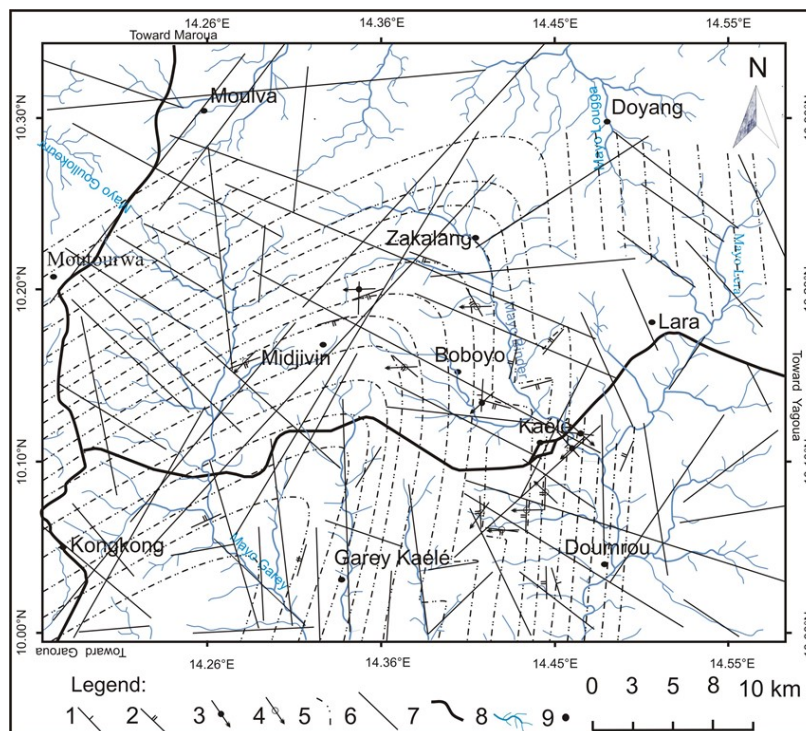


Figure 17. Structural map of the region by Kaélé: 1. Foliation S1; 2. Leaflet S2; 3. Lineation L1; 4. L2 lineation; 5. Trajectory of S2 foliation; 6. Fracturing; 7. Road; 8. Watercourse; 9. Locality

5.3. Structural Map

Structural map of Kaélé region is shown in Figure 17. Extrapolation of trajectories of S2 foliation highlight a regional F3 fold. Axial plane trace of this fold is oriented NE-SW and is subparallel to some regional fractures. This regional F3 fold confirm the NNW-SSE compression during the D3 phase. This result is in conformity with mesoscale fold observed on the field (Figure 16a).

6. Conclusion

The objective of this work was to make a structural study of the Kaélé region from landsat 8 OLI/TIRS images and field data. Image processing allows to identify lineaments in the studied area, some of which appear, in a structural map, as axial plan of regional fold. Field study permit to describe ductile and brittle structures which analyses led to decipher and group them into three successive ductile deformational phases (D1, D2, D3) and one brittle deformational phase (D4). D1 deformational phase is tangential and the regime of deformation is a horizontal general flattening. D2 and D3 are synmigmatitic phases, dominated by stretching and shearing characters, with subvertical foliations, sheat folds and subhorizontal lineations. Stress orientation change during these two phases from NNE-SSW, for the principal main stress, during D2 to NW-SE during D3. D2 and D3 deformational phases took place under constrictive regimes. D4 deformational phase shows fractures which main directions are known in the Central Africa Fold Belt. Kaélé area underwent complex structural history during which one note change of the regime of deformation and variation of the stress orientation. Future works will consist in evaluating the metallogenic potential of the study area in relation to tectonic.

Acknowledgements

The first author is great full to the hospitality of the population of the Kaélé and surrounding. Thanks go to Editor and anonymous reviewers for their critical comments on the manuscript.

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