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Characterization of the Damagaram Province Pan - African basement Deformation (South - East, Niger)

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Abstract: ***This paper focuses on the characterization of the deformation of the Damagaram basement (Southeastern, Niger), which represents the northeastern part of the Benin - Nigerian Shield. The Pan - African terrains belonging to this mobile zone, which is located to the east of the West African Craton, are mainly represented by gneisses, migmatites, metasediments and granitoids. They are intruded by a complex of granites with annular structures commonly called "Younger Granites", which are Carboniferous to Permian in age. The methodological approach implemented combines microtectonic field analysis with petrostructural study of rocks fine section by using a polarizing microscope. The analysis of the schistosity / foliation fabric (symmetric or asymmetric) and of the rheological behavior of rock materials (ductile, semi - ductile or brittle) during the deformation allowed to determine the chronological succession of the deformation phases. The results of microtectonic and petrostuctural analyses highlight a polyphase tectonics history marked, firstly by a D1 extension stage with ~ N20° trending stretching, probably ante - Panafrican, and secondly by three compressive deformation phases (D2, D3 and D4), Panafrican in age. The D2 phase consists of two episodes noted D2a and D2b: (i) the D2a, which is a pure - shear - dominated episode, is ductile to brittle, and related to NW - SE shortening (~ N130°); (ii) whereas the D2b episode, semi - ductile to brittle, is marked by mylonitic deformation, related to an ENE - WSW shortening (~ N80°). The D3 deformation phase, semi - ductile to brittle, was related to a NE - SW shortening. The last deformation phase D4, really brittle, is marked by N - S shortening. Preliminary results of the structural analysis highlight a progressive counter clockwise sinistral rotation of the shortening direction, from azimuth N130° to N00°. This progressive rotation of the shortening direction reflects a continuum of Pan - African deformation, in connection with the convergence between the West African, São Francisco, Congo cratons and the Saharan Metacraton.***

Keywords: Benin - Nigerian shield, Damagaram, Pan - African mobile zone, mylonitic deformation

1. Introduction

The Damagaram basement is a part of the Pan - African mobile chain, corresponding to the southern extension of the Trans - Saharian belt. It corresponds to the northeastern appendage of the Benino - Nigerian Shield. The Damagaram basement consists of a set of metamorphic rocks of Neoproterozoic age, including: migmatites, gneisses, metamorphic conglomerates, schists and quartzites [1], [2]. These metamorphic formations are intruded: (i) by pan - African calcalkaline granitoids, commonly known as "Older granites" [1] - [3], (ii) then by a set of granites of Carboniferous to Permian ages better known as "Younger Granites", forming an N - S alignment. The latter form complexes with annular or subcircular structures [1], [4], (**Fig.2**).

The pan - African Damagaram province has been little studied [2], [5], [6], unlike its counterpart in northern Nigeria, which has been the subject of several geological [7] - [9], structural [10], [11], geochemical [12], [13] and radiometric [14], [15] studies. The first geological map of Damagaram was made in the context of mining research at the scale of 1: 200, 000 [2]. The investigations carried out in the Damagaram province were aimed at revealing metallogenic potential. To date, very few structural studies have been carried out on this pan - African province. The only works mentioning structural deformations have been carried out in the context of geological and mining research [1], [2], [5] - [7]. The present study, focused on the characterization of the deformations affecting the Pan - African province of Damagaram, aims to overcome this deficiency.

Specifically, it is necessary to:

- Identify the different geological formations of the study area;
- Determine their petrostructural characteristics;
- Classify chronologically the main deformation phases.

2. Regional Geological Context

The basement of the Damagaram province corresponds to the southern segment of the Trans - Saharan chain, extending from the Hoggar in the North to the Gulf of Benin in the South (**Fig.1**).

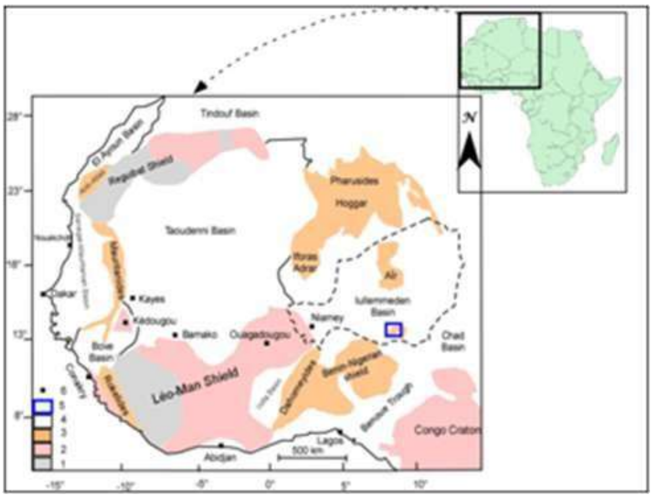

Figure 1: Location of the study area on the simplified

geological map of the West African Craton ([8]; modified).1: Archean; 2: Paleoproterozoic; 3: Pan - African mobile zones; 4: Neoproterozoic to Paleozoic sedimentary basins; 5: Study area; 6: Cities.

The Trans - Saharian chain corresponds to an ancient crust reactivated by the Pan - African orogeny, comprising Archean and Paleoproterozoic panels [8], [9], [15], [16]. The Benin - Nigerian province of the Pan - African chain has been subdivided into three lithostratigraphic units:

1) The gneisses and migmatites, considered to be the oldest formations in this region, are affected by high - grade metamorphism, generally in the amphibolite facies [7].
2) The schist rock belts correspond to supracrustal assemblages [17], exhibiting mineralogical assemblages, indicative of metamorphism in the greenschist facies.
3) All these formations are cut by syn to post - tectonic calcalkaline granitoid intrusions [8].
4) Structurally, the Pan - African formations of the Benino - Nigerian Shield are intersected by two conjugate NE - SW and NW - SE fracture systems, affecting an already cooled Pan - African continental crust [18].

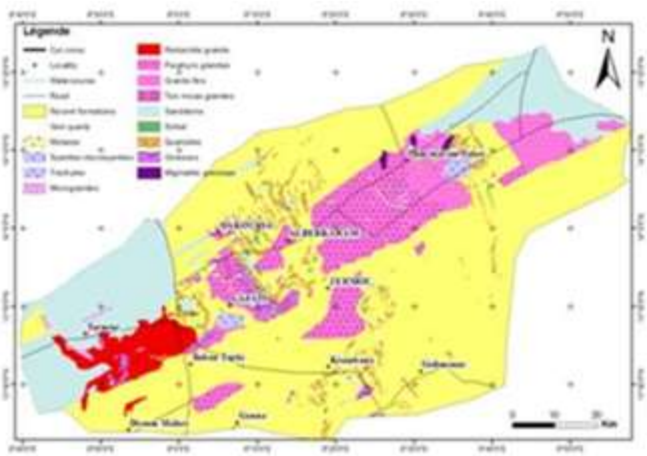

Figure 2: Geological map of the study area (extracted from the map of [2])

3. Methodological Approach

To achieve the objectives, several field campaigns were conducted in the study area. Samples were taken in the field, along with microtectonic analyses of deformation structures. The petrographic description of the outcropping rocks in the field is completed by microscopic analysis in the laboratory. Out of 106 rock samples (metamorphic, plutonic) collected, 32 samples were selected for the preparation of rock thin sections. The thin sections were prepared at the Laboratory of the "Centre de Recherche Géologique et Minière (CRGM) " of Niger. Their study was carried out at the Laboratory of Geology: Groundwater and Georesources of the Abdou Moumouni University of Niamey, using a LEICA DM2700 polarizing microscope. After identifying the different mineral species constituting the rock, the texture and the deformation microstructures were determined. The analysis of the schistosity/foliation fabric (symmetrical or asymmetrical) and of the rheological behavior of the rock materials during deformation (ductile, semi - ductile or brittle), associated with the analysis of geometrical overlapping relationships between the structures (schistosity/foliation, faults, fractures) allowed to establish a relative chronology of the deformation episodes.

For each family of structures (schistosity/foliation, faults), the measured planes were processed with the Win - Tensor program developed by [19]. The processing of these structural data allowed us to determine the main deformation phases or episodes (extensive or compressive) that affected the study area.

4. Results

Petrostructural analysis

The Damagaram Province was affected by the Pan - African orogeny around 600 ±50 Ma [6], [8], [20]. It consists of migmatitic gneisses, calcic gneisses, banded gneisses, schists, quartzites, conglomerates, biotite granites, 2 - mica granites, porphyry granites, and pink granites.

Cross - section of the Damagaram Takaya area

The cross - section was surveyed along a SW - NE direction (**Fig.2**). The petrographic succession, includes from SW to NE: porphyritic granites, banded gneisses, two - mica granites, quartzites, migmatitic gneisses and quartzites (**Fig.3**). The gneisses and quartzites have an average N50° schistosity/foliation orientation, with dips of 30° to 60°. These different formations are intruded by pegmatite veins.

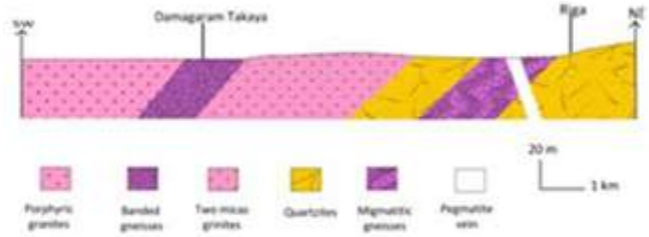

Figure 3: Cross - section of the Damagaram Takaya area.

Migmatitic gneiss of Damagaram Takaya

This formation occurs only in the Damagaram Takaya and Zarnouski areas (**Fig.2**). The migmatitic gneisses are grayish in color and dip NE - SW at 20° to the East. They are cut by a muscovite pegmatite vein.

The migmatitic gneisses consist mainly of quartz, orthoclase, biotite and muscovite. Migmatization has strongly disrupted the S1 foliation directions. However, in some gneissic parts, the N30° to N50° direction of the S1 foliation seems regular and predominant. The latter is underlined by alternating light bands rich in feldspar and dark bands rich in ferromagnesian minerals. This syn - migmatitic S1 foliation is sometimes affected by entrainment folds indicating a dextral N40° shear play (**Fig.4. a**). It is locally affected by subparallel, more or less boudinous granitic veins (**Fig.4. b**). Locally, the migmatites are sometimes cut by post - tectonic muscovite pegmatite veins.

Microscopically, the dominant texture of the migmatitic gneisses is granolepidoblastic. The foliation is underlined by alternating quartzo - feldspathic beds and micaceous beds with biotite and muscovite (**Figs.4. c and 4. d**). The mineralogical association consists of quartz, plagioclase, biotite, muscovite and microcline. Microstructural analysis reveals a mylonitic foliation, marked by the presence of anterokinetic phenocrysts molded by either synkinematic crystals of quartz or plagioclase, or by biotite or muscovite (**Fig.4. d**).

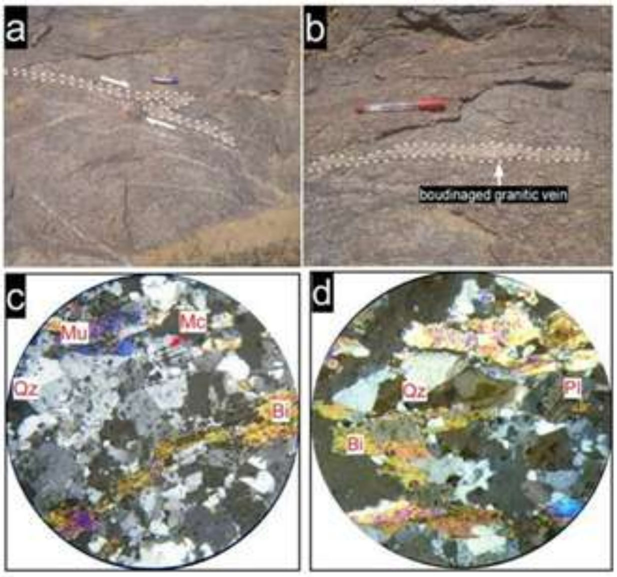

Figure 4: In (a): Outcrop appearance of migmatitic gneiss. Training fold indicating a dexterous displacement. In (b): Boudinage of granitic vein. In (c) and (d): Microphotographs of migmatitic gneiss. Qz: quartz, Bi: biotite, Mu: muscovite, Pl: plagioclase, Mc: microcline

Calcic gneiss of Kissambana

Calcic silicate gneisses outcrop in the Kissambana, Kandari and Dogon Doutchi areas (**Fig.2**). They consist of quartz, orthoclase, amphibole, pyroxene, and plagioclase. The abundance of amphibole gives the rock a greenish appearance (**Fig.5. b**). The S1 foliation of direction N00° to N30° is marked by alternating light and dark bands (**Fig.5. a**).

Microscopically, this S1 foliation is marked by alternating light quartzo - feldspathic bands and dark bands of actinote and diopside. The mineral paragenesis consists of quartz, microcline, actinote and diopside. Two generations of diopside have been identified. The first one consists of diopside crystals arranged according to foliation and the second one forms patches (**Fig.5. d**). The analysis of the crystals factory allows to distinguish actinote crystals with dextral sigmoid geometry (**Fig.5. c**).

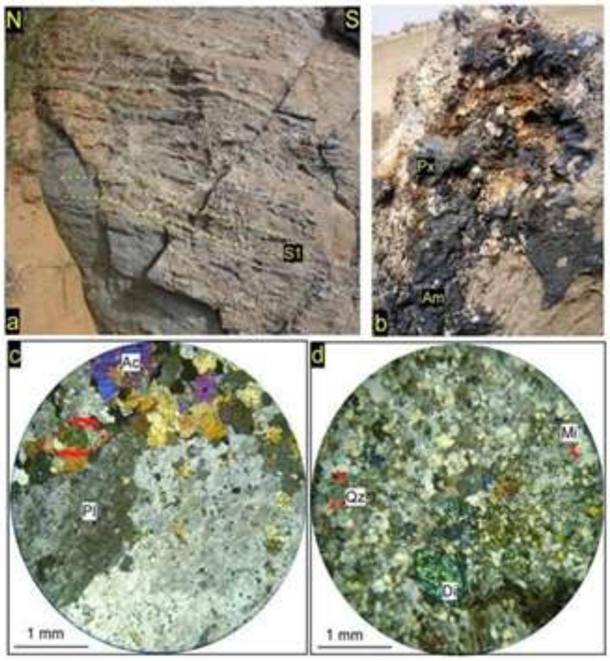

Figure 5: a and b: Outcrop aspects of calcic gneiss. c and d: Microphotographs of calcic gneiss. Foliation S1 N30°, Px: pyroxene, Qz: quartz, Bi: biotite, Ac: actinote, Pl: plagioclase, Mi: microcline, Di: diopside.

Gafati banded gneisses

The banded gneisses, grayish in color, outcrop to the northeast of Damagaram Takaya, to the east of the Bargouma sector, to the northeast of Gafati and to the east of Kandari (**Figs.2 and 6**). They form small buttes about 1 m high, with an average orientation of N95°, dipping to the north at 35°. The direction of the S1 foliation varies from N00° to N30° with a dip of about 20° SE. The sub - symetric character of the S1 foliation and boudinage (**Figs.6. a and 6. b**) indicates that the ductile deformation has a weak rotational component. At some gneiss outcrops in the Damagaram Takaya area (**Figs.5 and 6. d**), the sigmoidal geometry of the quartz and feldspar crystals shows a dextral, with C - planes of N50° direction (**Fig.6. d**).

Microscopic observation shows that the banded gneisses, of granoblastic texture, are essentially composed of quartz, plagioclase, microcline, and amphibole. Two generations of amphibole have been highlighted: (i) the first one, syn - cinematic, is molded around quartz and feldspar crystals, (ii) while those of the second generation, post - cinematic, are marked by the presence of quartzo - feldspathic inclusions (**Figs.6. e and 6. f**).

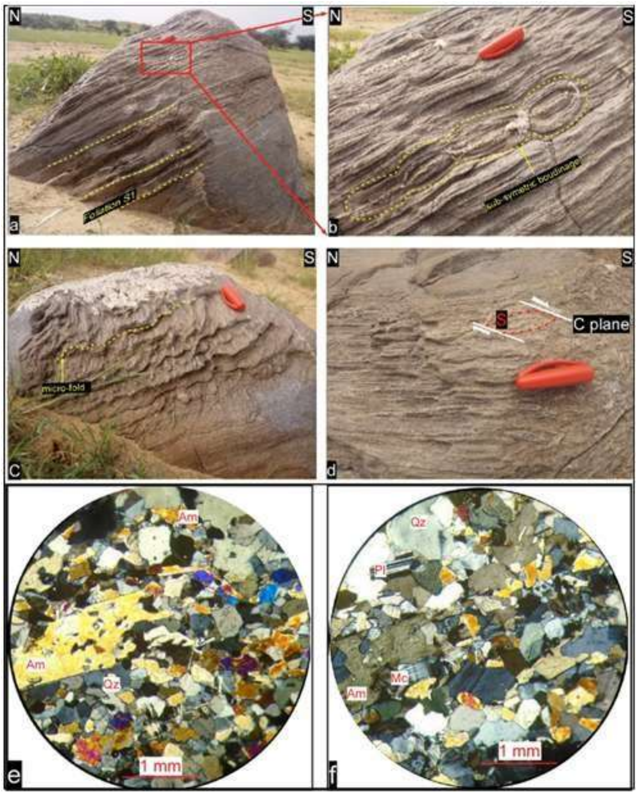

Figure 6: In a, b, c and d: Outcrops of banded gneiss. In a: Regular foliation of direction S1 N20°. In b: Sub - symmetrical boudinage of the S1 foliation. In c: Microfolding of the S1 foliation. In e and f: Microphotographs of banded gneiss. Qz: quartz, Am: amphibole, Pl: plagioclase, Mc: microcline.

Garin Malam Quartzites

The quartzite outcrops form chains of small discontinuous hills 5 to 30 m high, observable over tens of kilometers. The quartzites are generally very massive and of beige, pinkish to grayish color. They are essentially composed of quartz and feldspar. According to the importance of recrystallizations, they are classified in:

1) Reddish - colored, medium - to fine - grained foliated quartzites that exhibit S1 schistosity with N30° to N50° orientation (**Fig.7. a**). This S1 schistosity is affected by centimetric P1 microfolds (**Fig.7. a**), with subvertical axial planes;
2) Quartzites with greater recrystallization, pinkish to grayish in color. These types of quartzites are cut in platelets, reflecting a regular S1 schistosity, of N00° to N30° direction, well marked in the quartzites of the Garin Malam sector. They are affected by undulating mirrors of normal microfaults (syn - lithification) trending N95° - N110°, with a steep dip of 65°SW (**Fig.7. c**). NW - SE sinistral shear corridors and their NE - SW dextral conjugates affect these quartzite types (**Figs.7. e and 7. f**). The second fracture schistosity S2 with a mean direction N130° is intersected by another schistosity S3 with a mean orientation N100°. A fourth schistosity S4, with a mean direction N50°, intersecting all previous structures, was observed in this quartzite type;
3) Muscovite Quartzites. They have a grayish to pinkish color, with yellowish alteration patches. The muscovite quartzites have many fractures filled with iron oxides.

Microscopically, the quartzites show a granolepidoblastic texture (**Figs.7. g and 7. h**), with stretched quartz blasts with rolling extinction. Two mineral parageneses were highlighted: (i) the first, comprising an association of quartz, biotite, muscovite, feldspar and garnet, characteristic of the amphibolite facies, (ii) the second paragenesis, corresponding to the greenschist facies, is marked by an assemblage of quartz, biotite, muscovite and plagioclase. The amphibolite facies and the greenschist facies reflect mesozonal and epizonal metamorphism respectively.

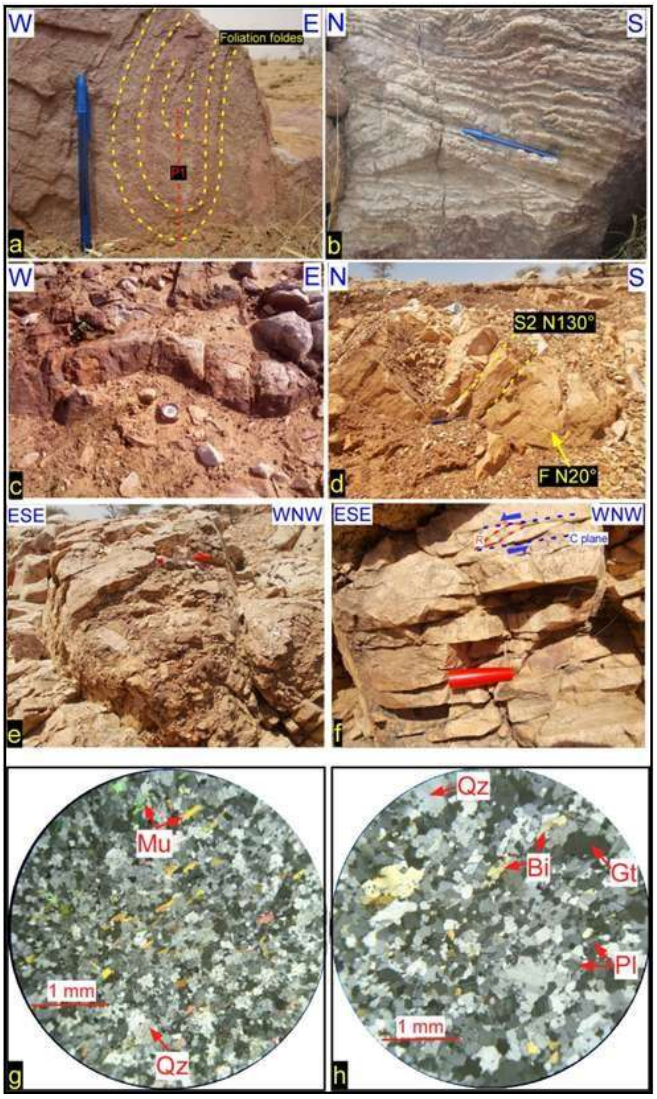

Figure 7: Quartzites showing different deformation structures. In a: isopaque folds with axial planes parallel to the foliation. In c: Curved mirror of normal fault in the Garin Malam sector (Zinder town). In d: S2 N130° schistosity intersected by a normal fault mirror. In e and f: Sinistral shear corridors. In g and h: Microphotographs of quartzite thin sections showing a more or less mylonitic foliation. Qz: quartz, Bi: biotite, Mu: muscovite, Pl: plagioclase.

Phyllades of Bourbourwa

Phyllades are dominant in the Bourbourwa - Doungouram area. They form small massifs, constituting the substratum of the quartzites. The phyllades are of greyish to greenish hue. The outcrops of phyllades consist of chains of small discontinuous mounds 2 to 5 m high. The phyllades correspond to sericite schists, of greyish color. They are composed of quartz, feldspar and a felting of fine sericite flakes (**Figs.8. a and 8. b**). The phyllades are affected by a regular S2 schistosity of average direction N130°, inclined from 50° to 85° towards the NE or SW. These variations in dip reveal the existence of a fold P1 whose axial planes are almost parallel to the S2 schistosity. In places, this schistosity is slightly folded, giving very open folds P2 with vertical axial planes (**Fig.8. a**). A second fracture schistosity S3, with a mean direction N100°, intersects the S2 schistosity (**Fig.8. b**).

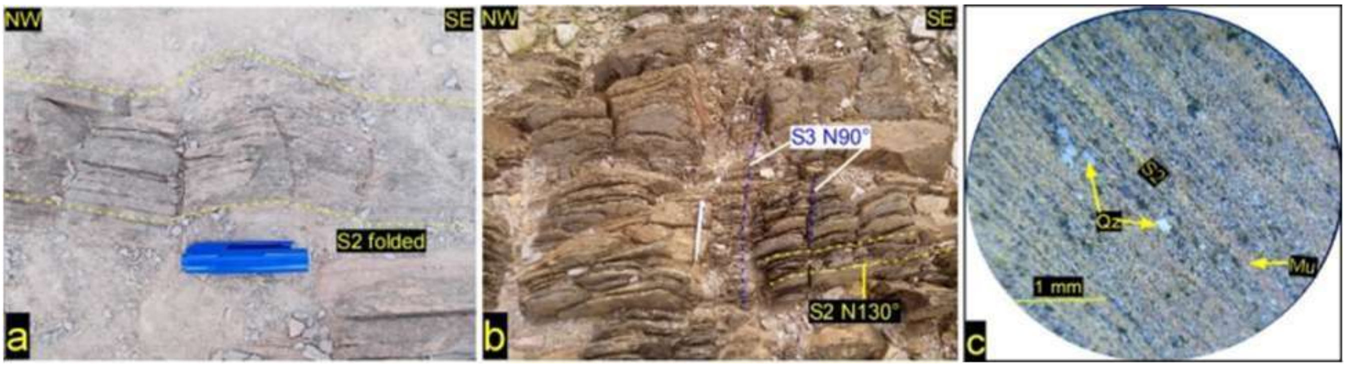

Figure 8: (a and b): Shale outcrops in the Bourbourwa area. In a: The S2 schistosity, of N130° direction, is slightly micro - folded. In b: The S2 N130° schistosity is crossed by a second schistosity S4 N50°. In c: Microscopic aspect of the emerging S1 flow schistosity. Qz: quartz, Mu: muscovite.

Bourbourwa molasse

The rock corresponds to massive conglomeratic deposits, discontinuous of diamictite type, of multi - decimetric to metric thickness. These molasse are made of polygenic, heterometric pebbles (of quartz and quartzite) of variable shape: angular subangular (sometimes faceted), subrounded to rounded. The pebbles are floating and packed in a matrix, silt - sandstone, siliceous to ferruginous, relatively coarse, without granoclassing (**Fig.9**). These molasse deposits are practically devoid of schistosity.

Figure 9: Outcrop of diamictite molasse in the Bourbourwa sector.

Biotite granites of Zinder

The biotite granites outcrop throughout the study area. They are composed of quartz, feldspar and biotite. Locally, these granites are intruded by quartz veins, which are themselves sometimes cut by fractures and faults of average orientation N30° (**Fig.10. a**).

Microscopic observation shows that these granites, of heterogranular grainy texture, are composed of quartz, microcline, plagioclase phenocrysts and biotite (**Fig.10. b**).

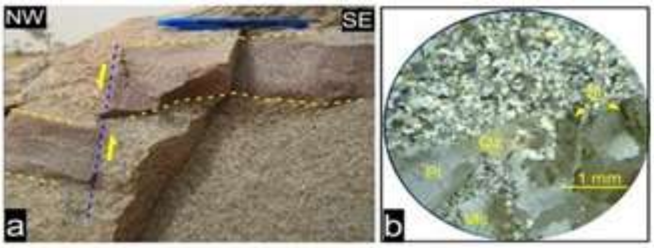

Figure 10: In a: Post - magmatic N30° normal fault, probably pre - Panafrican, offsetting a quartz vein, in a biotite granite: In b: Microphotograph of a thin granite sheet. Qz: quartz, Bi: biotite, Mu: muscovite, Pl: plagioclase, Mc: microcline.

Dakoussa two - mica granites

These are fine to medium grained biotite and muscovite granites that outcrop in the Bourbourwa and Dakousa areas (**Fig.2**). The outcrops of these types of blackish - gray granites consist of rocky chaos (**Fig.11. a**). These undeformed granites are post - Panafrican.

Microscopically, these granites have a heterogranular gritty texture (**Fig.11. b**). They have a mineralogical assemblage composed of quartz, orthoclase, plagioclase, biotite, and muscovite. The orthoclase is subautomorphic and perthitic and contains biotite inclusions. Quartz grains are xenomorphic and show a rolling extinction.

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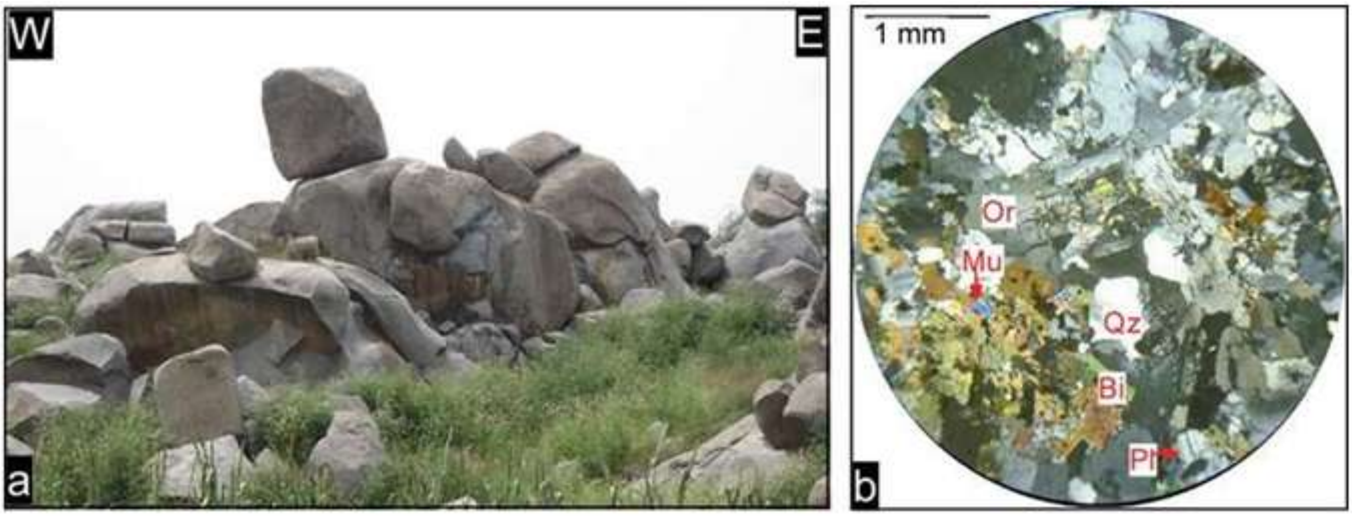

Figure 11: In a: Undeformed, post - Panafrican biotite granites. In b: Microphotograph of biotite granites. Qz: quartz, Bi: biotite, Mu: muscovite, Pl: plagioclase, Or: orthoclase.

Porphyric granites of Garin Tawaké

The porphyritic granites, undeformed, outcrop throughout the study area. They are pinkish in color and have a porphyritic gritty structure (**Fig.12. a**). The porphyritic granites outcrop in the form of balls and are sometimes cut by pegmatite or quartz veins.

Microscopic observation shows that these granites, with a gritty porphyroid texture, are composed of quartz, plagioclase, potassium feldspar and biotite (**Fig.12. b**). Secondary minerals are represented by sphene and zircon.

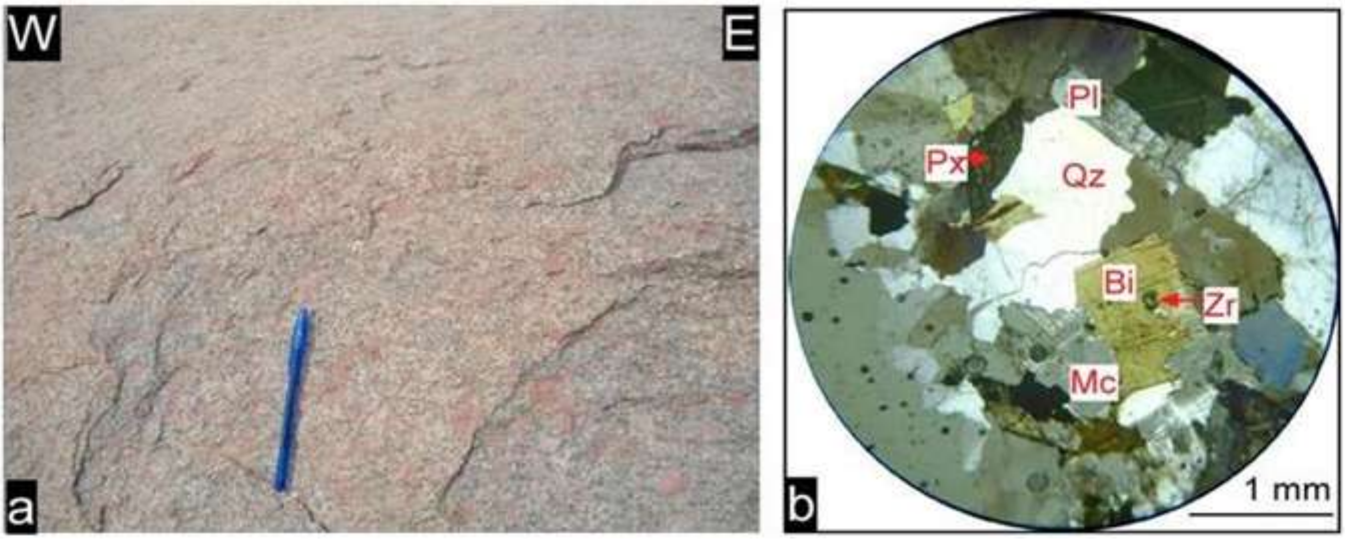

Figure 12: In a: Porphyritic granite. In b: Microphotography of porphyritic granites. Qz: quartz, Bi: biotite, Mu: muscovite, Pl: plagioclase, Mc: microcline, Px, pyroxene, Zr: zircon

4.2.10 Pink granites of Zinder

These are undeformed granites that outcrop throughout the study area, in the form of dome - shaped multi - metric intrusions (Gafati sector). They are distinguished by their pinkish color. From the microscopic point of view, these granites are constituted of quartz, orthose and rare crystals of plagioclase.

4.3 Microtectonic analysis

The chronological calibration of the ductile, semi - ductile and brittle deformation markers highlights four deformation phases:

The first phase of extensive, probably pre - Panafrican, D1 deformation has been demonstrated in the quartzites of the Garin Malam and Agama sectors (**Figs 7. c and 7. d**) and in the granites of the Dan Ladi sector (**Fig.10. a**). In these quartzites, this phase of extensive semi - ductile deformation is characterized by normal fault mirrors, presumably synlithification. The observed fault mirrors are of variable size, multi - decimetric to multi - decametric, with a strike of N95° to N110°, and dips of 62° to 80°. These fault mirrors or microfaults, with curved geometry, frequently show striations and grooves (**Figs.7. c and 7. d**).

The granites of the Dan Ladi area were affected by normal faults after their emplacement (**Fig.10. a**). On the other hand, the presence of curved and grooved striations on the mirrors of normal faults, affecting the Garin Malam quartzites, rather reveals their synsedimentary characteristics. Based on this observation, the granites of the Dan Ladi sector are older than the Garin Malam quartzites. Projections on the stereodiagram of the normal microfaults measured at each station (Dan Ladi and Garin Malam) show that a D1 extensional phase with a mean direction of N10° (**Figs.13. A and 13. B**) affected the study area.

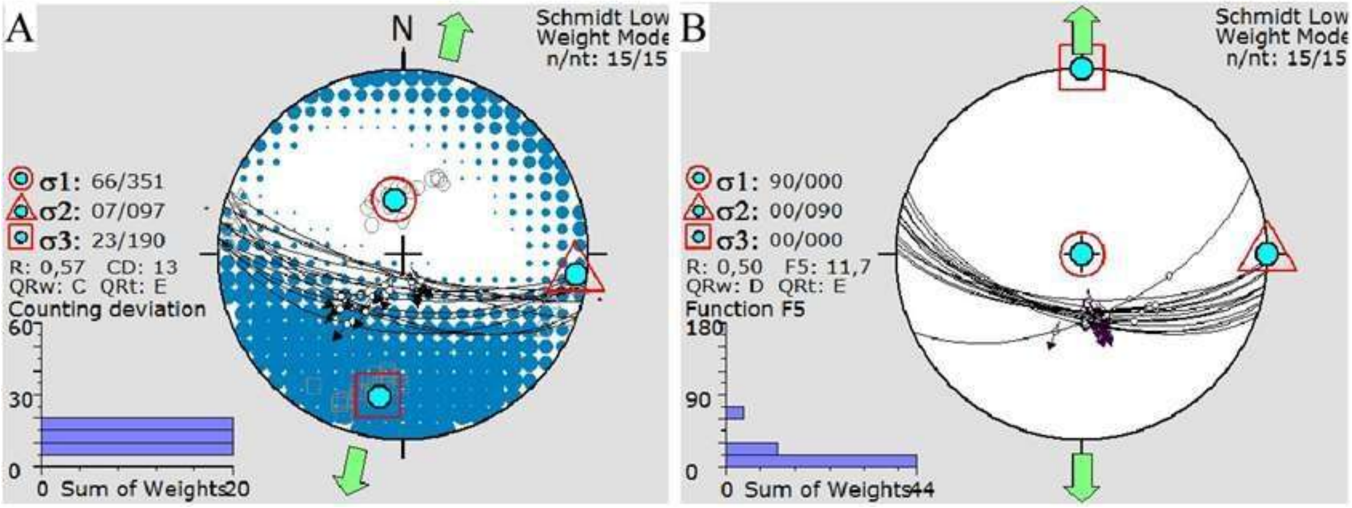

Figure 13: (A) Projection of the S3 microfaults planes of the Garin Malam sector on the Win - Tensor stereodiagram [25], defining an N20° extension. (B) Projection of the S3 microfacial planes of the Agama sector on the Win - Tensor stereodiagram [25], defining a N00° extension

The second phase of deformation D2, ductile, semi - ductile to brittle, comprises two episodes noted D2a and D2b:

(1) The first episode D2a, ductile to semi - ductile, is marked by the development of a symmetrical S1 schistosity/foliation, with an average orientation N50°, generally sloping 35° towards the North. This S1 schistosity is affected by isoclinal P2 folds, whose subvertical axial planes have an average direction N50°. Locally, the presence of subsymmetric boudinages in the migmatitic gneisses indicates that the ductile deformation has a coaxial component. These deformation markers are associated with the first D2a episode. It should be noted, however, that in the quartzites the S1 schistosity corresponds to a fracture schistosity. This S1 schistosity/foliation direction, in both the gneisses and quartzites, is consistent with NW - SE shortening (N140° on average) (**Fig.14. a**).

(2) The second semi - ductile to brittle D2b episode is characterized by mylonitic deformation by simple shearing: (i) marked in the gneisses by the formation of anisopic folds and a resumption of the S1 schistosity in semi - ductile shear channels, (ii) in the quartzites, it is characterized by brittle shear channels. In the gneisses, this D2a episode is marked by a ductile S - C type fabrication. Whereas in the quartzites, the factory is rather brittle of type R - C. These N50° and N105° conjugate shear zones are compatible with an ENE - WSW shortening direction (N80°). This observation is in agreement with the N80° shortening direction inferred from the projection of the schistosity planes in the stereodiagram of the Win - Tensor program developed by [19] (**Fig.14. b**).

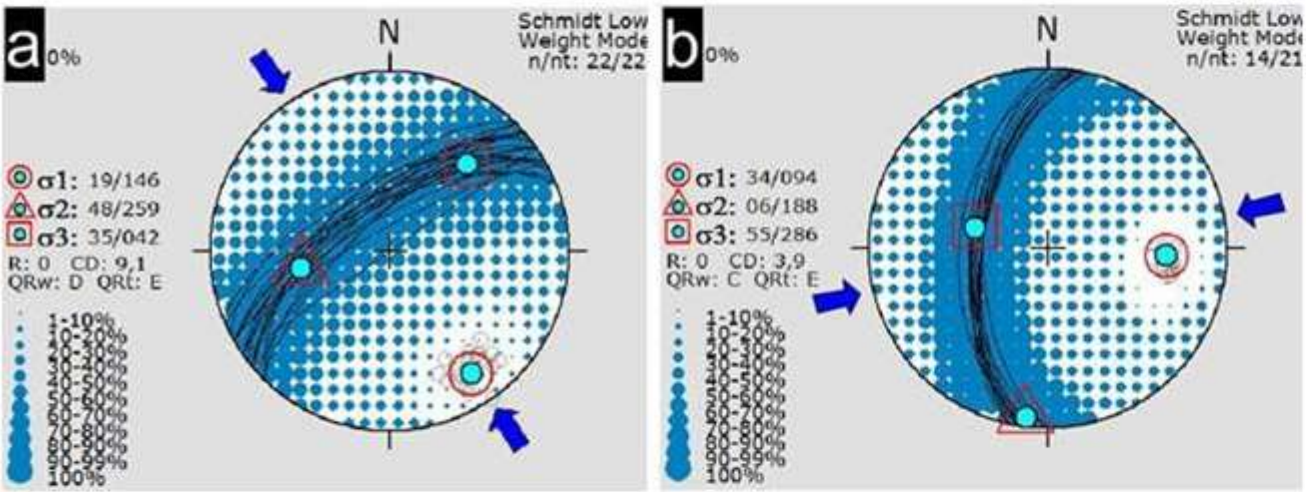

Figure 14: In a: Projection on the stereodiagram of the S1 schistosity planes, defining a NW - SE compression. In b: Projection on the stereodiagram of the schistosity planes S2, defining a globally E - W compression.

The semi - ductile to brittle deformation phase D3

The deformation phase D3 is characterized by the development of a flow or fracture schistosity S2 of average orientation N130°, which intersects the schistosity/foliation S1. In places, the folding of this second schistosity S2 leads to the formation of subvertical folds P2, with axial planes parallel to S2. This S2 schistosity is well represented in the Bourbourwa shales and in the Agama quartzites. The result of the treatment of the schistosity planes with the Win - Tensor program of [19] indicates an average NE - SW shortening direction (**Fig.15**).

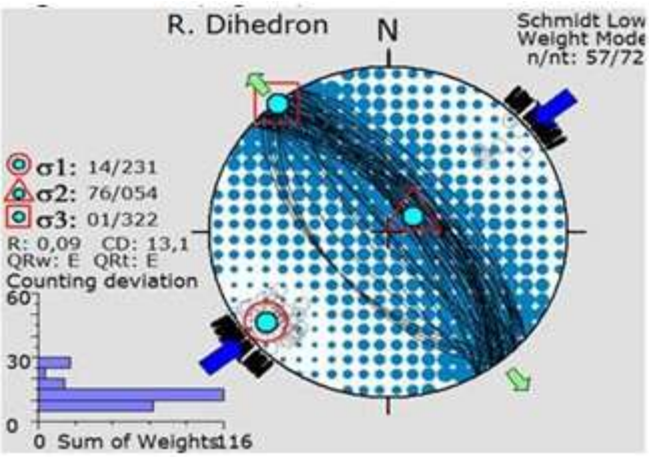

Figure 15: Stereodiagram projection of S2 schistosity planes, defining NE - SW compression

Subsequent to these phases of ductile, semi - ductile to brittle deformation, a **phase of D4 deformation**, frankly brittle of the "fracture cleavage" type (fracture schistosity), affected the terrains of the Pan - African Damagaram Province. This S3 fracture schistosity of N90° to N110° orientation, related to the D4 phase, is cut by a system of conjugate N135° to N170° (dextral) and N0° to N20° (sinistral) decays. The projection of the S3 schistosity planes on the stereodiagram of the Win - Tensor program (**Fig.16**) shows a globally N - S shortening.

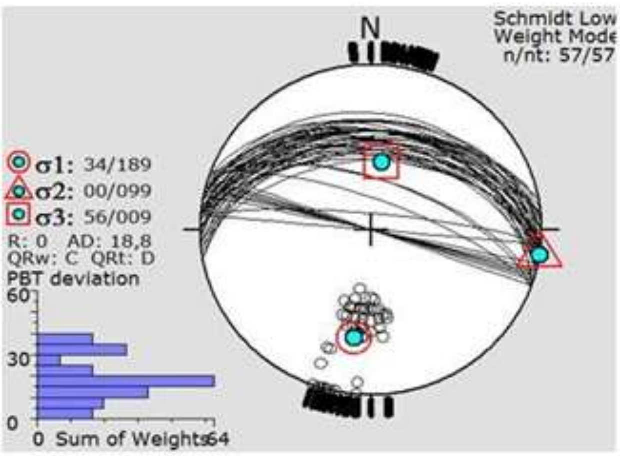

Figure 16: Projection on the stereodiagram of the S3 schistosity planes, defining a globally N - S compression.

5. Discussion

The geological units mapped in the Pan - African Damagaram Province have been modified and completed, and then correlated with the major geological units of the Southern Maradi [18] and the Benin - Nigerian Shield [12], [21], [22]. In these two provinces, the Pan - African terrains are represented by gneisses, migmatites, as well as by a set of metasediments, and granitoids.

In the Damagaram province, the oldest tectonic event is associated with the emplacement of migmatitic gneisses and small panels of concordant granites. The migmatitic gneisses are visible in the Kellé panel (East of Zinder) [24], where they are associated with granodiorites, amphibolites and schists. A Paleoproterozoic age has been assigned to the migmatitic gneisses in southern Maradi [25]. On the basis of radiometric dating (U - Pb method), a Neoproterozoic age was obtained [18]. However, basement panels of gneisses and migmatites, found in Nigeria [10], [16], [26], [27] and Chad [28], have given a Paleoproterozoic age. Thus, it appears from these comparisons that the age of the migmatites in these different Pan - African provinces is still a matter of controversy.

Despite the fact that this preliminary work has not made it possible to specify the age of emplacement of the formations and/or the main deformation phases that have affected this Pan - African province, the observation of intersections between structures (schistosity, faults or fractures) has made it possible to establish a relative chronology of deformation phases.

From this microtectonic analysis, four main phases of deformation emerge: (i) a first extensive phase (D1), which is likely to be pre - Pan - African, and (ii) three phases of compressive deformation (D2, D3 and D4) marking the Pan - African remobilization [20], [29], [30] - [32] and responsible for the emplacement of most of the deformation structures observed in the Damagaram province, and in the Pan - African Nikki complex in Benin [47]. Thus, on the scale of the Trans - Saharian chain, the Pan - African compressive deformations have been attributed to 2 (D1 and D2, [18], [29]), 3 (D1, D2 and D3, [30]), 4 (D1, D2, D3 and D4, [20]), or even 5 phases (Dn, Dn+1, Dn+2, Dn+3 and Dn+4, [31], [32]).

Pre - Pan - African extensive deformation phase D1

The D1 extensive deformation phase, which was demonstrated in the Garin Malam and Agama quartzites, is characterized by an average N20° elongation direction (**Fig.17**). This direction of elongation is sem to the NNW - SSE to NNE - SSW direction obtained in the Tondibia - Soudouré sandstones [33] and similar to the NNW - SSE direction of extension obtained in the Karey Gorou sandstones [20].

The extensive D1 N20° (NNE - SSW) phase revealed in the Damagaram province is different from the D1 N140° (NW - SE) phase described in the Firgoun sector of Niger [34]. The geodynamic context as well as the age of this extensive phase are the subject of debate [34]. Thus, the reactivation of ancient Mesoproterozoic fractures, which would have favored the genesis of basins during the Neoproterozoic, would be at the origin of this extensive phase D1 [36].

Compressive deformation phase D2

The first episode D2a, highlighted by the present study, corresponds to an NW - SE direction compression (130° on average). In Nigeria, this D2a episode, corresponding to the migmatization period [9], [11], [16], is related to the emplacement of oriented, concordant granites. The kinematic indicators (S1 foliation, isoclinal folds, symmetrical boudinage, lineation) highlighted in the Gafati banded gneisses and the Kissambana calcic gneisses show the characteristics of a coaxial deformation.

The NW - SE shortening (**Fig.17**) is close to the N95° to N125° Pan - African compressive phase D1, revealed in the adjoining basement of the Kandi Basin [35] and to the N110° to N140° compressive episode D1a obtained in the Pan - African basement of South Maradi [18]. Thus, at the edge of the West African Craton, in the Niamey area [33], the D2a episode, recorded by the Neoproterozoic sandstones, is represented by a comparable compressive episode of generally NNW - SSE direction (N155° to N160°).

The second semi - ductile D2b episode, with ENE - WSW shortening (N80°), is identical to the N70° to N90° direction attributed to this second episode (**Fig.17**), associated with mylonitization in southern Maradi [18], [25]. This episode is at the origin of the straightening of the S1 schistosity, and of the formation of anisopic folds as well as shear corridors, which are semi - ductile in the gneisses and rather brittle in some quartzite levels. In the Neoproterozoic sandstones of the Niamey area, an identical N70° to N80° shortening direction has been demonstrated [33]. While this semi - ductile to brittle D2b episode has been linked to the Pan - African D2 and D3 deformation phases [36] - [38]. In the southern part of the Ouaddaï (Chad), this deformation phase is marked in the parallelepiped rocks by interference figures, P1/P2 folds observable from the outcrop to the sample scale [38].

Compressive deformation phase D3

For most authors [8], [10], [32], [36], [39], the NE - SW D3 compressive phase (**Fig.17**), corresponds to transcurrent tectonics. The brittle character of this deformation suggests that the Pan - African continental crust was cooling. The rare allusions to this NE - SW shortening D3 deformation phase are those made in the Neoproterozoic formations that recorded the Pan - African deformation by [34] in the Firgoun Sandstone (Niger) and in the Beli Basin (Burkina Faso) [40].

Brittle deformation phase D4

The D4 deformation phase is thought to be late to post - Panafrican [18], [36]. It is marked by the development of a fracture - like S3 schistosity, orientation N90° to N110°. This deformation phase is marked by the formation of conjugate fractures, with orientations N135° to N170° and N00° to N20°. These have been linked to the Pan - African D3 and D4 deformation phases described in the Pharusides [41] and Dahomeyides [36]. As mentioned above, these conjugate fracture systems would result from N - S shortening (**Fig.17**). The direction of shortening attributed to the D4 deformation phase in the Damagaram is identical to that demonstrated in the Neoproterozoic sandstones of Karey Gorou (Niamey area) [20]. The D4 deformation phase, which would have affected the study area, towards the end or after the Pan - African event (530 Ma), is considered to be later [41].

From this structural analysis, it is apparent that the shortening direction that was initially NW - SE during D2a gradually shifted to NNE - SSW during the D4 phase. This highlights a sinistral counterclockwise rotation of the shortening direction (**Fig.17**). This sinistral counterclockwise rotation reflects a continuum of deformation during the Pan - African event, related to the convergence of the West African, São Francisco, Congo cratons and the Saharan Metacraton.

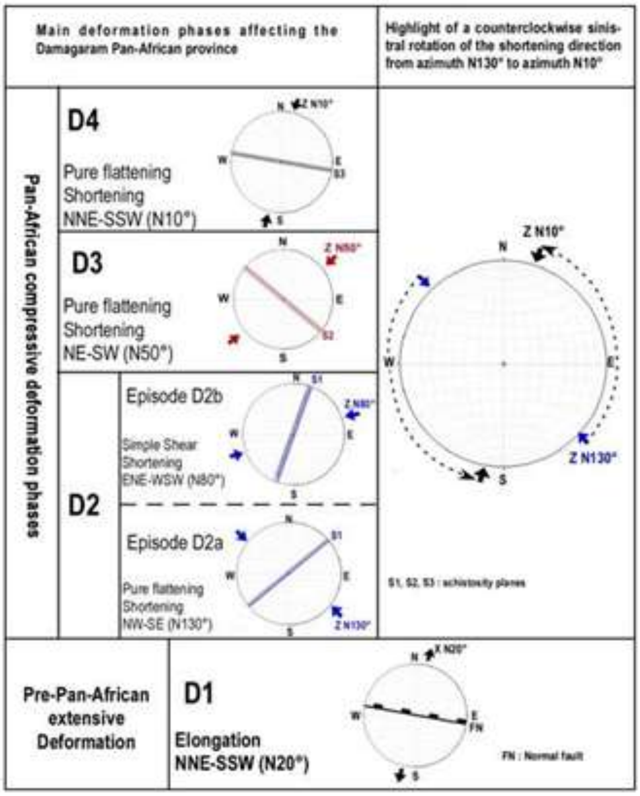

Figure 17: Summary of the main deformation phases that affected the Pan - African Damagaram Province.

6. Conclusion

The Damagaram Pan - African province is affected by two types of deformation:

- An extensive pre - Pan - African deformation with a NNE - SSW elongation (~ N20);
- And, three shortning Pan - African phases (D2, D3 et D4).

The first Pan - African shortning phase D2 comprises 2 episodes: a first D2a ductile, with a NW - SE (~ N130°) shortning, followed by a second compressional episode ENE - WSW (~ N80°), D2b semi - ductile.

The second Pan - Africain phase of shortning D3 semi - ductile to brittle trending NE - SW (~ N50°). The last phase D4, brittle to be late to post - Pan - African is associated with a global compression NNE - SSW (~ N10°).

Moreover, the change of shortning direction initially from ~N130° during the D2a episode to the NNE - SSW during the D4 phase, define an counterclockwise progressive sinistrial rotation showing a continuum of Pan - African deformation event. This counterclockwise rotation was associated to a convergence between the West African Craton, the São Francisco one, the Congo one, and the Saharian Metacraton.

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