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Thrust totranspression and transtension tectonics during the Paleoproterozoic evolution of the Birimian Greenstone Belt of Mako, Kédougou-Kéniéba Inlier, Eastern Senegal

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Abstract

The structural cartography of the Birimian formations of the Mako area shows a polyphase deformation marked by variable structures such as imbricated shear zones, thrusts and reverse-shears, poly-folding, boudinage, normal faults. The multiscale analysis of the various mapped structures combined with the satellite images allowed us to distinguish three major phases of Eoeburnean and Eburnean deformation. The Eoeburnean D_1 deformation phase is preserved through ductile structures in some lithologies (metabasalts, quartzites). It is composed of early thrusting and late sinistral reverse-shearing due to a NW-SE principal shortening direction, which involved large overturned folds verging northwestward and associated with thrust faults. It is also associated with the emplacement of early granitoids (c. 2200 Ma) followed by andesitic to felsic volcanic rocks around c. 2160 Ma. The Eburnean event is divided into two phases of deformation namely D_2 and D_3. The D_2phase is the early Eburnean event which involves a sinistral transpressive deformation. It is characterized by a NNE-SSW shortening direction which creates major NNW-SSE (N160°-170°) and NNE-SSW (N20°-30) sinistral reverse-shear zones associated with ENE-WSW (N60°-70°) dextral reverse-shear zones. Interference between both major NNE-SSW and NNW-SSE reverse-shear zones involves an anatomizing pattern of deformation. The D_3 phase is a transtensional deformation associated with a dextral movement which creates dextral shear zones and conjugate normal faults leading to graben depression. The D_3 principal maximum stress is ENE-WSW oriented. The granitoids were emplaced during these Eoeburnean and Eburnean orogenic events.

Keywords: Eburnean, Birimian, thrust, transpression, transtension, Kédougou-Kéniéba inlier

1. Introduction

The Man-Leo shield represents the southern part of the West African Craton (WAC). It is composed of two generations of Precambrian rocks, the Paleoproterozoic "Birimian" rocks in the east, and the Archean cratonic nucleus in the west which are tectonically separated by the Sassandra fault (Bessoles, 1977; Feybesse et al., 1989; Egal et al., 2002) (Fig. 1a). Birimian terranes of the Kédougou-Kéniéba and Kayes inliers which straddle the border between Senegal and Mali, are the westernmost exposed of the Man-Leo shield (Fig. 1).

The Paleoproterozoic "Birimian" terranes of the WAC are formed by sedimentary basins and linear to arcuate volcanic belts intruded by several generations of granitoid plutons. The accretion of these Paleoproterozoic rocks and associated granitoid plutons corresponds to the 'Eburnean orogeny' which represent a major juvenile crust-forming event. The term 'Eburnean' refers to all tectonic, metamorphic and plutonic events affecting the Birimian rocks during the Paleoproterozoic. The Paleoproterozoic rocks are dated between 2.27 Ga and 2.04 Ga (Bonhomme, 1962 ;Abouchami et al., 1990; Liégeois et al., 1991; Boher et al., 1992; Dia et al., 1992; Davis et al., 1994; Hirdes et al., 1992, 1996; Kouamelan et al., 1997; Doumbia et al., 1998; Gueye et al., 2008; Masurel et al., 2016 ; Parra-Avila et al., 2016 ; Eglinger et al., 2017).

A pre-Eburnean cycle in the WAC is suggested by pre-Birimian ages in the time interval of 2266 Ma and 2150 Ma which were obtained on zircon grains from different rocks (sediments, tonalites, granites) of the Man shield (Dia et al., 1992; Davis et al., 1994; Doumbia et al., 1998; Kouamelan et al., 1998; Gueye et al., 2007; Perrouty et al., 2012; Parra-Avila et al., 2016). During this period of time, two orogenic events are distinguished throughout the Birimian with different ages and terminology. In Ghana, the earlier event is referred as the Eoeburnean (2195-2150 Ma) or the Eburnean I (2266-2150 Ma) and the latter as the Eburnean (2148-2090 Ma) or the Eburnean II (2216-2088 Ma) (Allibone et al., 2002; de Kock et al., 2011). In Burkina Faso the earlier event is the Tangaean (2170-2130 Ma) and is followed by the Eburnean (2130-1980 Ma) (Tshibubudze et al., 2009; Hein, 2010).

The Eoeburnean to Eburnean orogenies are characterized by a complex tectono-magmatic evolution (Ledru et al., 1989, 1991; Milési et al., 1992; Feybesse et al., 1994; Pons et al. 1994; Vidal et al., 2009; Lompo, 2010; Dabo and Aïfa, 2010; Diatta et al., 2017; Masurel et al., 2017). At the scale of the WAC, they are now considered as polycyclic with two models of evolution: (i) the dome and basin geometry model which results of vertical movements due to gravitation instabilities followed by regional-scale transcurrent tectonics (Vidal et al., 2009; Lompo, 2010; Pitra et al., 2010; Delor et al., 2010); (ii) the tangential to transcurrent model with nappes stacking along orogen parallel thrust faults (Ledru et al., 1989; Milési et al., 1992; Feybesse et al., 2006).

This paper contributes to the details characterization of the Eoeburnean to Eburnean orogenies in the Mako Greenstone Belt southwestern part of the Kédougou-Kéniéba Inlier (KKI). The goal is to propose a tectonic evolution model based on the analyses of the field structural features.The methodology consists of cartography, detailed structural analysis of field data and satellite images, in order to better constrain the evolution of the Mako Greenstone Belt.

2. Geological setting

The volcanic, volcano-sedimentary and sedimentary rocks of Paleoproterozoic Birimian of the KKI are arranged into two Supergroups (Bassot, 1987), which are tectonically separated by the SW-NE to NS trends crustal-scale shear zone, the Main Transcurrent Zone (MTZ)(Fig. 1b). The MakoSupergroup to the west is dominantly composed of submarine volcanics, pillowed basalts, andesitic to rhyolitic flows associated with pyroclastites and ultramafic bodies. The volcano-plutonic rocks are bimodal and consist of basal tholeiitic sequence and upper calc-alkaline sequence. The tholeiitic sequence consists of pillowed and massive basalt and ultramafic bodies (Bassot, 1966; Ngom, 1995; Dia et al., 1997; Delor et al., 2010). The mafic and ultramafic assemblages are petrogenetically co-magmatic (Ngom, 1995). They show a tholeiitic affinity relative to mantle plume basalts environment (Abouchami et al 1990; Boher et al., 1992; Pawlig et al., 2006 ; Ngom, et al., 2010; Delor et al., 2010). The emplacement age of the mafic rocks estimated by Sm/Nd method on the whole rock (WR) is 2197±13 Ma (Dia etal., 1992). The ultramafic rocks are not dated yet, however, they are found in inclusions within the mafic rocks and can be regarded as the base of an ophiolitic sequence characteristic of the Birimian formations of the Mako sector (Dabo et al., 2017). It should be noted that previous geochemical, geochronological and lithostratigraphicworks (Dia, 1988; Bertrand etal., 1989; Dia et al., 1992) consider the amphibolite-gneisses of Sandikounda-Laminia dated at 2206±6Ma (Pb/Pb on zircon, Dia et al., 1992) as the base of the Mako Supergroup.

The calc-alkaline rocks are composed of andesitic to rhyolitic flows associated with volcano-sediments (tuffs, pyroclastites, epiclastites) (Ngom, 1995; Dia et al., 1997). They show a geochemical affinity of subduction zones (Delor et al., 2010), and of an Island-arc (Dia, 1988; Pawlig et al., 2006 ; Lambert-Smith et al., 2016). These intermediate and felsic rocks are dated between 2160±16 Ma and 2070 Ma (Calvez et al., 1990; Boher et al.,1992; Hirdes and Davis, 2002). The sedimentary rocks are represented by lenses of quartzites, ribbons of limestones and of conglomerates interstratified within the mafic, intermediate and felsic rocks (Diallo, 1994; Ngom, 1995). The volcano-sediments and sediments represent the top of the lithological sequence of the Mako Supergroup (Dabo et al., 2017).

The Dialé-Daléma Supergroup is dominantly sedimentary (Table 1) and consists of interlayered pelites, sandstones, greywackes, marbles, quartzites and breccias (Milési et al.,1989; Dabo, 2011). It is represented by the upper part of the stratigraphic KKI Birimian formations (Ngom et al., 2010; Delor et al., 2010). Geochronological data from zircons of Dialé-Daléma detrital sedimentary rocks indicate an age between 2093±7 Ma and 2165±1Ma (Boher et al., 1992; Hirdes and Davis, 2002).

The sedimentary sequence is cross-cut by a calc-alkaline volcanic complex (andesite, rhyodacite, rhyolite) which has orogenic volcanic arc affinities (Milési et al.,1989; Delor et al., 2010;Lambert-Smith et al., 2016). Rhyolitic flow of Daléma has been dated at 2099±4 Ma (Hirdes and Davis, 2002).

Several generations of Eburnean granitoids occurred into the Birimian rocks of the KKI. They form three batholiths: Badon-Kakadian, Saraya and Boboti (Bassot, 1966). Recent works of Théveniaut et al. (2010) regard these batholiths as a suite of granitoids. They distinguish thus three suites of granitoids:

Soukouta (former Badon-Kakadian batholith of Bassot (1966)), Saraya and Boboti. The Badon-Kakadian batholith is an assemblage of plutons mainly composed of felsic rocks, dated in the range of 2140 Ma to 2213 Ma (Bassot, 1966; Dia, 1988; Dia et al., 1997; Gueye et al., 2008). The Saraya and Boboti batholiths are composed of various granitoids (diorites, granodiorites, granites) with ages ranging between 2100-2060 Ma (Saraya) and 2080-2060 Ma (Boboti) (Bassot, 1966; Hirdes and Davis, 2002; Théveniaut et al., 2010; Lambert-Smith et al., 2016). Recent U-Pb ages data from Boboti and Balangouma plutons in the Boboti batholith, indicate crystallization at 2088.5±8.6 Ma and 2112±13 Ma, respectively and inherited zircons in the the Boboti pluton indicatea magmatic activity in the Falémé Belt (Daléma) at 2218±83 Ma(Lambert-Smith et al., 2016; Masurel et al., 2017).

TheKKIBirimian formations are affected by a regional metamorphism of greenschist facies (Bassot, 1966). The amphibolite facies is found in the contact aureole around some granitoid massifs (Bassot, 1966; Dia, 1988) and associated with the ultramafic rocks particularly at Lamé sector in the SE of Mako (Dabo et al., 2017). At the scale of the WAC, the greenschist facies metamorphism affected most of the Birimian formations (Debat et al., 2003; Block et al., 2015). It resulted from a large retrograde metamorphism of amphibolite facies which are reworked to greenschist facies (John et al., 1999; Klemd et al., 2002; Block et al., 2015).The greenschist to amphibolite-facies metamorphic assemblages that developed during the Eburnean orogeny are superimposed on an early thermal regime that produced high-pressure greenschist- to blueschist-facies metamorphic assemblages (Ganne et al., 2014).

The Eburnean metamorphism is accompanied by deformation whose phases and styles are variously interpreted (Table 2). Some authors (e.g. Leube et al., 1990; Eisenlohr and Hirdes, 1992; Hirdes et al., 1996; Gasquet et al., 2003) argued for a single orogenic cycle. Other authors considered a polycyclic model with two (Ledru et al., 1989), three (Ouedraogo and Prost, 1986; Ouedraogo, 1987; Feybesse et al., 1989, 2006; Milési et al., 1992) or more than three (Block et al., 2015; Baratoux et al., 2015) major phases of Eburnean deformation with variable styles of deformation.

1- The first D_1 thrusting phase (Feybesse et al., 1989; Ledru et al., 1989, 1991; Milési et al., 1992) or a peri-plutonic deformation (Pons et al., 1995; Vidal et al., 1996; Debat et al., 2003; Pitra et al., 2010; Delor et al.,2010).

2- The second D_2 transcurrent to transpressive phase is responsible for large NS- to NE-trending Eburnean tectonic shear zones and the emplacement of several intrusions within Proterozoic terranes (Ledru et al., 1989, 1991; Liégeois et al., 1991; Pons et al., 1992).

3- The third D_3 phase is currently recognized in all the Birimian provinces of the WAC with variable tectonic styles: transcurrent or transtension and/or brittle ductile deformation (Feybesse et al., 1989, 2006; Ouedraogo and Prost, 1986; Ouedraogo, 1987; Dabo and Aïfa, 2011; Lawrence et al., 2013; Delor et al., 2010).

4- The other deformation phases are differently described throughout the WAC according to the Birimian provinces and the authors (Baratoux et al., 2015; Block et al., 2016).

3. Lithologyof the Mako area

The Mako sector, in the southern part of the Mako Supergroup (Fig. 1b), is primarily made up of ultramafic, mafic, intermediate and felsic rocks associated with some sedimentary quartzite slices (Fig. 2a). Mafic rocks are most significant and constitute the main part of the greenstone hills between Sékhoto Peul to the north and Wassadou in the south. Associated with the greenstone mafic hills appear the Lamé and Massanritana black hills that consist of ultramafic rocks, located at the east and west of Mako village, respectively. Kilometric lenses of quartzites, NNW-SSE and NE-SW oriented, are intercalated within the mafic rocks. Breccias and lavas of intermediate and felsic rocks occupy the tectonic corridors cross-cutting the previous units. Several generations of plutons (granitoids and gabbros) constitute the main part of the outcrops in Niéméniké village (Fig. 2).The NW-SE cross-section between Lamé and Sékhoto Peul (Fig. 2b), shows lateral succession of ultramafic rocks, layered metagabbros, pegmatitic metagabbros and isotropic metagabbros separated by diffuse and irregular subvertical contacts. In the mylonitic corridor of Bafoundou, the metagabbros are cross-cut by altered andesitic breccias and pass laterally to quartzites then to metabasalts in pillow lavas. The metabasalts, often pillowed, are frequent towards Sékhoto Peul. In addition, several generations of plutonic intrusions (granitoids and gabbros) with variable tectonic fabrics, are emplaced in volcanic and volcano-sedimentary units between Niéméniké and Sékhoto Peul (Fig. 2).

Based on the field geometrical relationship between the different facies, Dabo et al. (2017) distinguished two lithological units in the Mako area: the tholeiitic ophiolitic complex at the base and the calc-alkaline mixed volcanic complex at the top, separated by lenses of quartzites (Fig.3).

4. Structural features

The ophiolitic sequence and the mixed volcano-sedimentary complex of the Birimian Greenstone Belt rocks of Mako (Ngom, 1995; Ngom et al., 2011; Dabo et al., 2017) were subject to polyphase deformations. These deformations are attributed to Eoeburnean (2195-2150 Ma) and Eburnean (2148-2060 Ma) events (Bonhomme, 1962; Allibone et al., 2002; Tshibubudze et al., 2009; Hein, 2010; de Kock et al., 2011). Three phases of deformation are distinguished, they are composed of a major (D_1) Eoeburnean deformation phase and two (D_2,D_3) major Eburnean deformation phases.

4.1. The Eoeburnean D_1 compressive to thrust phase

The Eoeburnean D_1 phase is a compressive deformation which reveals thrust and sinistral reverse-shearing structures and large overturned folds (Figs. 4;5;6). The thrusts are the early manifestation of the D_1 phase which ends by sinistral reverse-shearing. The structures of this early deformation phase are locally preserved in certain rigid lithologies (metaperidotites, metagabbros, metabasalts and ribboned quartzites) (Figs. 5a-d). The ductile deformation structures are constituted of thrust zones, sinistral reverse-shearing, folds, L_1 stretching lineation and S_1 foliation (Figs. 4;5;6g,h).

The thrust zones and sinistral reverse-shearing are identified and characterized at the scale of the outcrops (Fig. 5). They mainly show a NE-SW direction which locally varies because of post-deformation (Eburnean). In the field, the thrust structures are poorly preserved as a result of subsequent deformation. The thrust planes are marked out by a rough N40°-45°foliation (highlighted by chlorite

and sericite minerals) with a variable dip (20°-30°) towards the SE or the NW (Figs. 5b,c). The stretching lineation (L_1) which accompanies the displacement is hardly identifiable in the metabasalts. However, in the layers of the ribboned quartzites north of Niéméniké, it is slightly underlined by quartz-sericite minerals aggregates stretched in the N125°-25° direction along N20°-20°SE oriented foliation planes (S_1) (Figs. 5c,d).

The criteria of displacement associated with these thrusts are shown by the XZ foliation planes by sigma clasts and microfolds which formed at the same time as the foliation and indicate an overlapping towards the NW (Fig. 5d).

The sinistral reverse-shearing is responsible for the Massanritana metaperidotites hill displacement by more than 1 km towards the SW (Fig. 2a).The L_1 stretching lineation associated with the displacements is marked by metabasalt enclaves stretching along N110°-70 direction in the Soukourtou granodiorite (Fig. 6h).

The folding (P_1) related to this first deformation phase appears at various scales. In the metabasalts, the limbs of the folds (P_1) are highlighted by the inclination and the bending of the pillow axial planes which define a primary bedding (S_o) modeled by a buckled folding of N60°-50SE axial plane (Figs. 5e,b). In Badian, the interpillow material of the metabasalts shows a P_1 folding (Fig. 6a) which involves high-strain characters. In addition, centimetric P_1 overturned folds are also highlighted by felsic injections within metabasalts. In the metaperidotites, remnants of P_1 folds are locally observed with curvilinear axis (Fig. 6c). On the Aster satellite images, kilometric megafolds, buckled towards the NW, appear on digital terrain models (DTM) in two (2D) and three (3D) dimensions (Fig. 4). These large folds are highlighted by alternation of asymmetric hills and depressions. In the pillow-lava hills, from backlimb to forelimb, the altitude of the main axis dip of pillow bodies indicate asymmetric folding (Figs. 6c,d). Their axes, on average NE-SW oriented, are sometimes upturned by the second post-folding P_2 (Fig.6b). The principal stress responsible for this Eoeburnean deformation phase would logically be oriented SE-NW taking into consideration conjugate shear joint cross-cutting the pillowed metabasalts body (Figs. 6e,f), the asymmetry of P_1 folding (Fig. 5e) as well as criteria of shearing observed in the S_1 foliation planes (Fig. 5d).

In addition, the granodiorite of Soukourtou (southern part of the Badon granodiorite) shows ptygmatitic overturned folds with N75-70SE oriented axial plane, relative to synmagmatic deformation of the D_1 phase (Fig. 6g). These folds appear also in the gneiss enclosing the granodiorite and are cross-cut by N25° oriented S_2 foliation. This granodiorite contains locally deformed metabasalt enclaves which are often stretched along the N110-40 L_1 stretching lineation (Fig. 6h). The boundaries between enclaves and granodiorite are sinuous and irregular (contact often in flower structure shape) that attests the contemporaneous emplacements between the two magmatic materials (Fig. 6h). The Badon granitoid is dated around c. 2213 Ma (Bassot and Caen-Vachette, 1984; Gueye et al., 2007), i.e. during the Eoeburnian period.

Thus, the D_1 deformation is constrained by the age of emplacement of the early granitoids and metabasalts estimated by Pb/Pb methods on WR and single Zrat 2213±3 Ma and 2195±11 Ma, respectively (Dia, 1988; Gueye et al., 2007).

This D_1 deformation would therefore be late to the emplacement of the metabasalts (≤ c. 2195 Ma) and corresponds to the Eoeburnean period. The emplacement of intermediate and felsic volcanic rocks dated at 2160±16 Ma by Sm/Nd on WR (Boher et al., 1992) marks the end of the D_1 Eoeburnean phase.

4.2. The Eburnean D_2 transpressive deformation phase

The D_2deformation phase is well expressed in the Birimian formation of the Mako area by reverse-shear zones of variable dimensions in which foliation (S_2), lineation (L_2), and folding (P_2) are concentrated and revealed clearly. The semi-ductile and brittle structures (tension gashes, shear joints, rolls, fractures, faults) have a random distribution and are not always located in the shear zones.

The reverse-shear zones are oriented according to three conjugate principal directions, NNE-SSW (N20°-35°), NNW-SSE (N160°-170°) and ENE-WNW (N60°-70°)(Figs. 2a,c). A fourth direction, NS oriented, is interpreted to result from local flexure of the path of the NNE-SSW oriented shear zones (Figs. 2a;6e;7a). These shear zones are associated with three major directions of foliation S_{2a} (N20°-35°), S_{2b} (N150°-180°) and S_{2c} (N60°-70°) (Figs. 7b-d). The stretching lineations associated with these various shear zones show a rather moderate to steep plunge (> 35°) and a NE-SW to NW-SE and NNW-SSE direction (Fig. 7e).

The gentle ENE-WSW (N60°-70°) reverse-shear zones, with main S_{2c} N70°-65 SSW and minor S_{2a} N30°-55 SE foliations, are observed in the andesitic tuffs and ultramafic rocks of the Lamé sector. These shear zones reveal the kinematics criteria of a dextral movement (Fig.7d) associated with the N140°-25 oriented mineral stretching lineation. In the Lamé sector the abundance of weathering surface and alluvial deposits often mask these shear zones paths and their contact with the other shear zones (NNE-SSE, NNW-SSE) which were not observed in the field. The most illustrative example of these ENE-WSW dextral reverse-shear zones is the Lamé Shear Zone (LSZ) located in the southeast of Lamé village (Fig.2a).

The reverse-shear zones oriented NNE-SSW are more represented in the north at the Niéméniké sector (Fig. 2a). The NNE-SSW major foliation is associated with a stretching lineation of clasts along with the N100°-120° direction and dip of 25°-60° (Fig. 7e). The criteria of rotation in the XY and XZ foliation planes are clasts which indicate a sinistral reverse-shear (Figs. 7e,f).

The most important NNW-SSE (N170°) shear zone in the study area is that of Bafoundou Corridor (BC) (Fig. 2a). It is a mylonitic corridor which lengthens in the form of depression from the south of the village of Bafoundou until the north of Niéméniké on several kilometers in the NNW-SSE direction (Fig. 2a). Its lateral extension is variable and can reach 3 km locally. The principal foliation N165°-50°SW oriented (S_{2b}), crenulates a former foliation (S_{2a}) of N25° to N30°direction with a dip around 70°SE (Figs. 7b;8c). The criteria of shearing in the XZ and XY foliation planes (delta clasts, S/C, synfolial folds, etc.) indicate a sinistral reverse-shear (Figs. 7b,c;8c). The stretching lineation in the N160° foliation planes is roughly oriented N175°-40°.

Throughout this NNW-SSE BC mylonitic corridor most rigid facies (quartzites, metaperidotites) underwent a stretching and a boudinage accompanied by a sinistral shear on their edges (Fig. 2a). They would behave like rigid cores packed in a soft coat represented by the mylonitic facies (breccias, tuffs). Thus, the metaperidotites hill of Massanritana would have undergone at the same time as the ribboned quartzite beds of western Mako, a stretching and a boudinage accompanied by a sinistral shear in the N170° direction. On the vertical plane the conjugate NE-SW and NNW-SSE reverse faults with opposed dips, reveal locally graben structures (Figs. 8c;9a).

The P_2 folds related to the Eburnean D_2 compressive phase are mostly of modest size (metric to centimetric). They are often concentrated in the shear zones and sometimes superimposed on the P_1 folds. Thus, the gabbros and the rhyolitic tuffs of the BC shear zone show isoclinal folds (P_2) with tilted curved axis oriented N40°-18°and N310°-46°, respectively (Figs. 7e;9b).

In addition, on the Aster satellite images, P_2 folding appears by the bending of the P_1 folds axes (Fig. 4). Stereoplot projection of measurements relative to the geometry of the semi-ductile to brittle structures (conjugated joints, slickenside in slip plane) indicate the NNW-SSE direction of the principal maximum stress of this phase (Figs. 6e,f;8b,c). The whole of the structures relevant to D_2 assumes a sinistral transpressive phase with a partitioning of the deformation between the mylonitic zones and the rigid cores which they pack.

4.3. The transtensive D_3 deformation phase

It is a dextral transtensional phase whose deformations are less intense than those of the former phases, primarily marked by semi-ductile and brittle structures. It appears locally by mostly dextral narrow shear zones some of which are related to a reactivation of former sinistral shear zones (Figs. 8d;9e,f). The D_3 shear zones are generally oriented NNE-SSW and NNW-SSE with a variable foliation of N20° and N150° direction cross-cutting those of the D_2Eburnean deformation. The stretching lineation associated with this phase is seldom expressed. In the NNE-SSW shear zone affecting the mottled gabbros of Niéméniké, the lineation is underlined by the stretching of the pyroxene needles ouralitized along the N25° direction (Fig. 2a). The criteria of the movement observed in these shear zones (extrusion, folds synchronous with foliation development and clasts) reveal a dextral shear (Fig. 9f). However, the relics of a sinistral shear are still perceptible in certain NNE-SSW shear zones (Fig. 9e).

In the tuffs of Laméthe NNE-SSW foliation is affected by N160°-60°SE dextral crenulated foliation (Fig. 10a) related to D_2 phase. Also, a crenulated foliation, N160°-60°NW oriented, in a dextral shear appears locally in the pink granite of Niéméniké (Fig. 10b).

The semi-ductile deformation is demonstrated by very frequent tension gashes cross-cutting the S_2 foliation. In the quartz diorites of Niéméniké and the metabasalts in pillow lavas of western Mako appear tension gashes cross-cutting S_2 indicating a dextral shear. In the light diorite of northern Niéméniké, “en echelon” tension gashes relative to the N70°-60°SE normal fault plane appear locally (Fig. 10c).

The brittle deformation appears in the metaperidotites and the tuffs of Mako, marked by a system of conjugate normal faults oriented N140° with opposite dips (NE and SW). They involve the tilt of S_1 foliation in the form of drag fold with downthrown side indicating a collapse (Figs. 10d,e). These

conjugate normal faults with opposite dips created a graben structure along the Mako village (Figs. 8d; 10f). In the north of Niéméniké, the graben structure observed in the silicified metabasalts looks like a negative flower structure (Fig. 10f).

5. Discussion and Conclusions

The architecture of the Birimian formations of the KKI is primarily related to the Eoeburnean and Eburnean orogenesis which presents a polyphase evolution at the scale of the WAC (Ledru et al., 1991; Feybesse et al., 2006; Delor et al., 2010; Lompo, 2010; Dabo et al., 2010; Baratoux et al., 2011; Jessell et al., 2012).

Our investigations in the Mako area allowed us to distinguish three major phases of Eoeburnean (D_1) and Eburnean (D_2, D_3) deformations evolving in different tectonic styles (Fig. 8). The D_1 phase is a compressive event which leads to thrust and sinistral reverse-shear zones. It is marked by large overturned folds towards the NW (Figs. 6c,d;8a), relics of thrust and sinistral reverse-shearing associated with stretching lineation generally oriented NW-SE with a variable dip (Fig. 2a). The principal shortening direction associated with this phase of deformation is NW-SE oriented (Figs. 6e,f;8a). These early deformation structures are filled and/or cross-cut by intermediate to acid rocks which are dated around c. 2160 Ma (Boher et al., 1992). The high-strain folding of pillowed metabasalt and ptygmatic folding in granodiorite (Fig. 6a,g) suppose a high temperature deformation at the end of the basaltic magma cooling between 2197±13 Ma and 2195±11 Ma using Nd/Sm and Pb/Pb methods on WR, respectively (Bassot et Caen-Vachette, 1984; Dia, 1988; Gueye et al., 2007). Therefore, the D_1 deformation phase is believed to have began around c. 2195Ma, after the emplacement of the pillow-lavas basalts. This period of time corresponds to the early Paleoproterozoic event which age and terminology differs throughout the Birimian. In Ghana, the earlier event is referred as Eburnean I (2266-2150 Ma) (Allibone et al., 2002) or as Eoeburnean (2195-2150 Ma) (de Kock et al., 2011). In Burkina Faso, the early Paleoproterozoic event is the Tangaean which corresponds to the period between2170 Ma and 2130 Ma (Tshibubudze et al., 2009; Hein, 2010). In the Birimian of the KKI, Delor et al. (2010) revealed an early Eburnean phase of gravity deformation (Dg) related to Eoeburnean diapirism associated with the plutonism of the Sandikounda-Soukouta Suites.

Our interpretation is that in the Mako area of KKI, the early Eoeburnean deformation (D_1), characterized by thrust to sinistral reverse-shear deformation is associated with large overturned folds and a regional NNW-SSE shortening that occurred at approximately 2.19-2.17Ga.

An early Eburnean compressive to thrust deformation, i.e. D_1 deformation phase, was announced in the sedimentary Birimian formations of the Dialé-Daléma Supergroup (Ledru et al., 1989; Milési et al., 1992; Dabo and Aïfa, 2010). The age of this early Eburnean deformation is not specified in this Supergroup.

In the Birimian formations of Ghana, a D_1-thrust deformation with SW vergence (Feybesse et al., 2006) associated with reverse shear zone and large scale folds (Block et al., 2016), similar to those of Mako, is reported in the D_1 Eburnean phase.

The Eoeburnean event has variably characteristics through the WAC. In Ghana, it reveals the development of regional scale folds and bedding parallel foliation, associated with the development of east-west trending structures during a regional north-south shortening (Perrouty et al., 2012). In Burkina Faso, the Tangaean event (2170-2130 Ma) is characterized by northwest to north-northwest trending dextral-reverse shear zones, and fold-thrust belts that developed during a period of northeast-southwest crustal shortening (Tshibubudze et al., 2009 ; Hein, 2010).

The late stage of the D_1 deformation phase is marked by the emplacement of intermediate and felsic volcanic rocks which are dated around c. 2160 Ma (Boher et al., 1992).

In NW of Ghana, the N-S extensional deformation followed the D_1 Eburnean phase (Block et al., 2016). According to Feybesse et al. (2006), this period of extensional tectonic precedes or was partly contemporaneous with the first Eburnean deformation phase in Ghana.

The structures of the Eoeburnean phase are generally disturbed and overturned by the Eburnean deformations (Fig. 8b). The Eburnean D_2 phase of deformation is a transpressive tectonics which revealed sinistral NNE-SSW and NNW-SSE,and dextral ENE-WSW conjugate reverse-shear zones (Fig. 8c'). These NNW-SSE and NNW-SSE shears may have played the part of R and P structures in a NS oriented Riedel system where ENE-SSW shears represent the R' structures (Fig. 8c').

The principal shortening is NNW-SSE oriented according to brittle structures geometries (Figs. 9c,d; 8d'). In the course of the deformation the NNW-SSE oriented sinistral reverse-shear zones which cross-cut the preceding ones (NNE-SSW), involve a flexure of their ends according to a N-S direction (Fig. 7a).

The anastomosed interconnection of very deformed shear zones (NNE-SSW and NNW-SSE) which frame the cores of little-deformed rocks results in the deformation partitioning.

This Eburnean D_2 phase is similar to those described in the Dialé-Daléma Supergroup (Ledru et al., 1989; Dabo et al., 2010) as well as in the Birimian of Burkina Faso (Baratoux et al., 2015; Tshibubudze et al., 2015) and Ghana (Feybesse et al., 2006).

Throughout the WAC the age of the early Eburnean deformation phase (denoted here D_2) is estimated between 2140 Ma and 2100 Ma contemporaneously with the emplacement of the syntectonic Eburnean granitoids dated between c. 2142 Ma and c. 2102 Ma (Bassot and Caen-Vachette, 1984; Liégeois et al., 1991; Dia et al., 1997; Hirdesand Davis, 2002; Gueye et al., 2007; Delor et al., 2010; Goujou et al., 2010; Block et al., 2015; Lambert-Smith et al., 2016).

The Eburnean D_3 phase is a dextral transtension mainly with semi-ductile and brittle structures. It is characterized by narrow shear zones NNE-SSW and NNW-SSE oriented with dextral movement. Some of these shear zones could result from a reactivation of D_2 sinistral reverse-shear zones (Figs. 9e,f). The other structures of this phase are the graben structures which result from a set of conjugate normal faults (Figs. 10d-f). The principal shortening responsible for these deformations is inferred to be oriented NNE-SSW (Figs. 9c,d). All these Eburnean structures of the D_3 deformation phase indicate a less intense deformation than those of the Eburnean D_1 and D_2 deformation phases and characterize a dextral transtension.

The Eburnean D_3 deformation probably occurred between 2100 Ma and 2060 Ma associated with the emplacement of the syntectonic granitoids of Saraya and Boboti Suite which are dated between 2100 Ma and 2060 Ma (Abouchami et al., 1990; Hirdes and Davis, 2002;Gueye et al., 2007; Delor et al., 2010).

In the Dialé-Daléma Supergroup, the D_3 Eburnean deformation characterized by different structures with local reactivation of old D_2 sinistralshear zones (Delor et al., 2010; Dabo and Aïfa, 2011; Lawrence et al., 2013). At the scale of the KKI, Delor et al. (2010) distinguished an Eburnean D_3 transcurrent phase (Dt_3) characterized by conjugate zones of NE-SW dextral and NW-SE sinistral shears.

In the other Birimian provinces of the WAC, the Eburnean D_3 phase is also less intense than the former Eburnean phases (Feybesse et al., 2006; Lompo, 2010; Baratoux et al., 2011). In Ghana, it involves major ENE-SSW to minor WNW- ESE dextral shear zones with a local reactivation into dextral of the old NE-SW sinistral shear zones (Feybesse et al., 2006). In Burkina Faso, it is marked either by thrusts with northern or southern dip and an E-W crenulation foliation associated with kink folds (Baratoux et al., 2011) or by a transtension with dominant NE-SW dextral shear faults (Lompo, 2010).

Thus, the Mako sector in line with many Birimian provinces of the WAC is marked by a polyphase Eoeburnean to Eburnean deformations. The Eoeburnean began with compression which leads to thrusts towards the southwest associated with a sinistral reverse shearing (D_1) and subsequently the emplacement of intermediate to felsic volcanic rocks at around c. 2.16 Ga. The Eburnean event is marked by a sinistral transpression with NNE-SSW shortening direction (D_2) followed by dextral transtension with ENE-WSW shortening direction (D_3).

Plutonic intrusions emplaced before and during the Eburnean deformation phases, i.e. between 2213 Ma and 2060 Ma (Abouchami et al., 1990; Dia et al. 1992; Hirdes and Davis, 2002; Gueye et al., 2007; Delor et al., 2010). The metamorphism evolves from greenschist to amphibolite facies (Bassot, 1966, Dia et al., 1992; Delor et al., 2010; Dabo et al., 2017).

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Tables Captions

Table 1: Lithostratigraphy of the Birimian formations of KKI from bottom to top

Table 2: Eoeburnean and Eburnean deformation phases in some Birimian provinces of the WAC

Figures captions

Figure 1: Kédougou-Kéniéba Inlier (KKI) in the Man shield, southern part of the West African Craton (WAC). (**a**) Schematic map of the major Precambrian greenstone belts of the southern part of the WAC (simplified from Pouclet et al., 2006). (**b**) Simplified geological map of the Birimian of KKI (modified after Pons et al., 1992). Rectangle delimits the study area. Bo: Boboti; Gm: Gamaye; MTZ: Main Transcurrent Zone; SMF: Senegalo-Malian Fault.

Figure 2:(**a**) Geological map of the Mako Paleoproterozoic Greenstone Belt (modified after Dabo et al., 2017): BC: BafoundouCorridor; LSZ: Lamé Shear Zone; MSZ: Mako Shear Zone. (**b**) Geological

sections (AA') showing the geometrical relations between different lithologies (the vertical scale is approximative). (**c**) Equal area projection, lower hemisphere, showing foliation and shear planes orientations in the study area. RN7: trunk road n°7.

Figure 3: Schematic lithostratigraphic column of the Paleoprotezoic formations of the Mako sector (Dabo et al., 2017). The thickness of the facies is estimated approximatively. From bottom to top it appears a mafic ophiolitic complex mainly of tholeiitic nature, topped by mixed volcanic complex with calc-alkali trend. The unit is intruded by three generations of granitoid (early, syn- and post-tectonic).

Figure 4: Aster radar image of Mako sector showing (**a**) in two (2D) dimensions orientation of the features and the rose diagram of the different directional features; (**b**) in three (3D) dimensions the morphological aspect with large overturned folds (P_1) whose hinges are re-folded (P_2). (**c**) and (**d**) correspond to the location of images of Figs. 6c,d. TH:Trace of syncline hinges.

Figure 5:(**a**) Pillowed metabasalts affected by a thrust fault, (**b**) and foliationS_1 affecting the normal limb of the overturned P_1 large fold within the metabasalts in pillows lavas. (**c**) Equal area projection, lower hemisphere, showing the position of the stretching lineation L_1within S_1foliation. (**d**) S_1 foliation, stretching lineation L_1 (underlined by stretched pebbles and recrystallization of fine quartz grains along L_1 in the microphoto) and sigma clasts indicating a SE-NW overlapping in the quartzites. (**e**) Overturned bending P_1 folds affecting the metabasalts in pillow lavas. Cl: clast; TF: Thrust Fault.

Figure 6:(**a**) Metabasalts in pillow lavas showing high strain P_1 folds. (**b**) P_1 foldswith curved axis in the metaperidotites. (**c,d**) Arcuate and flatteningpillow lavas affected by P_1 mega-folds in the forelimb (c) and backlimb (d) of metabasalthills. (**e**) Metabasalts in pillow lavas flattened and affected by shear joints and conjugate tension gashed indicating an NW-SE principal stress. (**f**) Equal area projection, lower hemisphere, showing conjugate shear fractures and their relation to the position of the principal stress. (**g**) Ptygmatic overturned folds highlighted by leucosome facies in the granodiorite of Soukourtou and cross-cut by S_2foliation. (**h**) Metabasalt enclaves in Soukourtou granodiorite showing flower structure border (Cf) and locally stretched along L_1 stretching lineation direction.

Figure 7:(**a**) Bending of the trajectory of a NE-SW shear zone along with the N-S direction.(**b**) NW-SE shear zone affecting the tuffs of Bafoundou and showing two directions of foliation (S_{2a}, S_{2b}) and a stretching lineation L_2 underlined by the micro-pebbles stretching. (**c**) Shear zone showing a foliation S_1-S_2 and a sinistral movement underlined by the bending of the pillow lavas. (**d**) S_{2a}foliation crenulated by S_{2c} foliation in the andesitic tuffs of Lamé. (**e**) Rhyolitic tuffs affectinga thrust-shear highlighted by a synkinematic fold (P_2) of the sinistral shear (XZ plane), stretching lineation (**f**) and delta clasts (XY plane) indicating a NE vergence.

Figure 8: Schematic block diagram of the structural evolution model of the Makosector: (**a**) EoeburneanD$_1$ phase with thrusting followed by(**b**) NW-SE sinistralreverse-shear zones; (**c**) early Eburnean D_2 phase which occured after emplacement of intermediate to felsic rocks and is marked

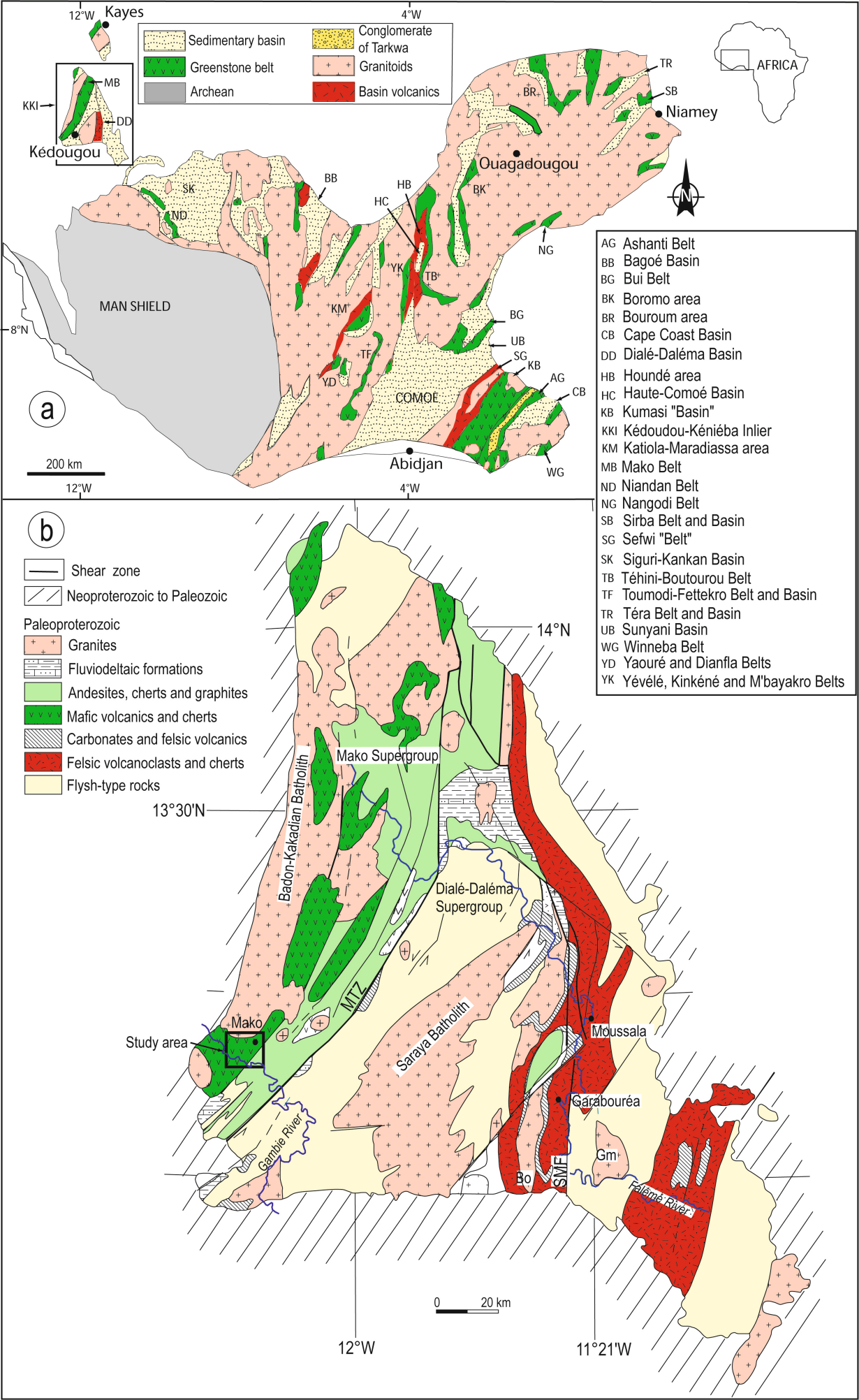
by sinistral transpression responsible for the occurrence of NNW-SSE mylonitic corridor with stretching and boudinage of metaperidotites and quartzites ; (**d**) Eburnean D_3 phase characterized by dextral transtensional deformation which creates dextral shear zones and extensional structures (normal faults, grabens). Relations between (**b'**) NE-SW reverse-shear zones and the principal stress during the D_1 deformation phase, (**c'**) conjugated reverse-shear zones and the principal stress during the D_2 deformation phase, and (**d'**) conjugated shear zones and the principal stress during the D_3 deformation phase. EZ: extensional zone; Gb: graben; TC: "en-echelon" tension crack; CRF: conjugated reverse faults with a positive flower structure. 1: Ultramafic rocks, 2: Metagabbros, 3: Metabasalts, 4: Quartzites; 5-6: granitoids; 7-8: intermediateto felsic rocks; 9: silicified metabasalt with spotted gabbro injection in D_3 shear zones; 10-11: thrust fault and fault.

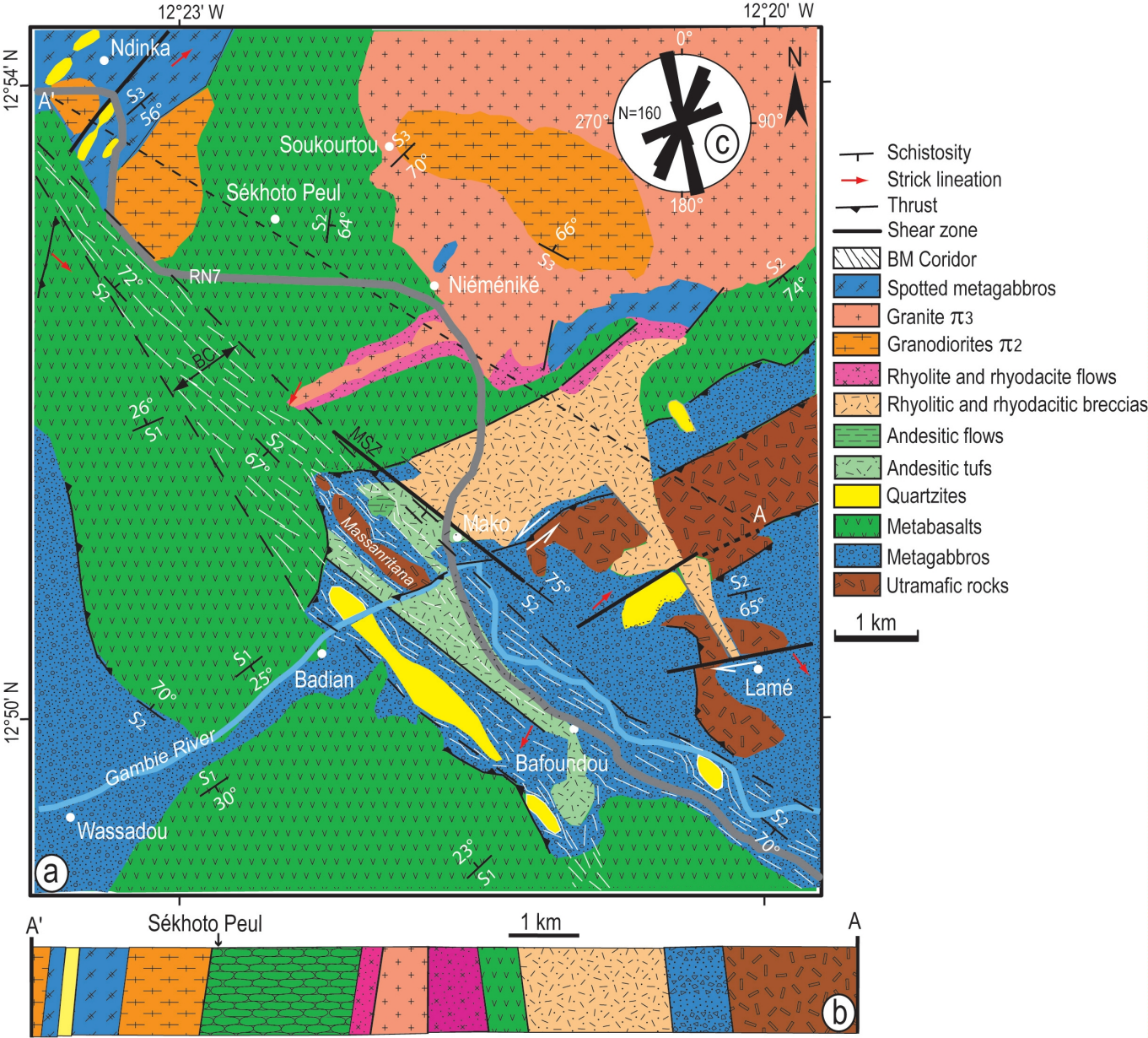
Figure 9:(**a**) Metagabbros affected by conjugate reverse faults (RF) which shifted a quartz vein (Qv) that underlined positive flower structure shape; (**b**) P_2 folds with tilted and short axis affecting the metagabbros;(**c**) Slickenlines in fault surface (slickenside); (**d**) The pitch and the fault surface plotted on a stereonet (equal area, lower hemisphere) showing the orientation of the principal stress; (**e**) Relics of synfolial folding in sinistral NNE-SSW shear zone related to D_2 deformation phase in the silicified metabasalts. (**f**) This same shear zone shows also synfolial folding and boudinage of felsic intrusion along S_3 foliation direction indicating a dextral shearing (D_3).

Figure 10:(**a**) S_3 foliationinvolving the S_{2b}foliationcrenulation in the granite of Niéméniké; (**b**) S_3 foliation involving the S_2 foliation crenulation in the NNW-SSE reverse-shear zone that affect the tuffs of Lamé; (**c**) "En-echelon" arranged extensional fractures related to normal faulting in the quartziticdiorite of Niéméniké; (**d**,**e**) Normal faults with opposite dips related to graben structure in the metaperidotites (Mp) and the tuffs (Tf); (**f**) Conjugate normal faults in the silicified metabasalts.

Highlights

- Paleoproterozoic rocks of KKI were affected by Eoeburnean and Eburnean orogenic events with three deformation Phases.
- The Eoeburnean events are characterized by a compressive D_1 phase.
- Age of D_1 deformation deduced from emplacement of metabasalts in pillow lavas and the Badon granodiorite (c. 2198 Ma)
- The Eburnean event is marked by two deformation phases: transpressional D_2 followed by transtensional D_3.


a
b
Sedimentary basin
Greenstone belt
Archean
Conglomerate of Tarkwa
Granitoids
Basin volcanics
AFRICA
Kayes
Kédougou
Niamey
Ouagadougou
Abidjan
MAN SHIELD
COMOE
12°W
4°W
8°N
14°N
13°30'N
11°21'W
200 km
0 20 km
AG Ashanti Belt
BB Bagoé Basin
BG Bui Belt
BK Boromo area
BR Bouroum area
CB Cape Coast Basin
DD Dialé-Daléma Basin
HB Houndé area
HC Haute-Comoé Basin
KB Kumasi "Basin"
KKI Kédoudou-Kéniéba Inlier
KM Katiola-Maradiassa area
MB Mako Belt
ND Niandan Belt
NG Nangodi Belt
SB Sirba Belt and Basin
SG Sefwi "Belt"
SK Siguri-Kankan Basin
TB Téhini-Boutourou Belt
TF Toumodi-Fettekro Belt and Basin
TR Téra Belt and Basin
UB Sunyani Basin
WG Winneba Belt
YD Yaouré and Dianfla Belts
YK Yévélé, Kinkéné and M'bayakro Belts
Shear zone
Neoproterozoic to Paleozoic
Paleoproterozoic
Granites
Fluviodeltaic formations
Andesites, cherts and graphites
Mafic volcanics and cherts
Carbonates and felsic volcanics
Felsic volcanoclasts and cherts
Flysh-type rocks
Mako Supergroup
Badon-Kakadian Batholith
Dialé-Daléma Supergroup
MTZ
Saraya Batholith
Mako
Study area
Moussala
Garabouréa
Gambie River
Falémé River
SMF
Bo
Gm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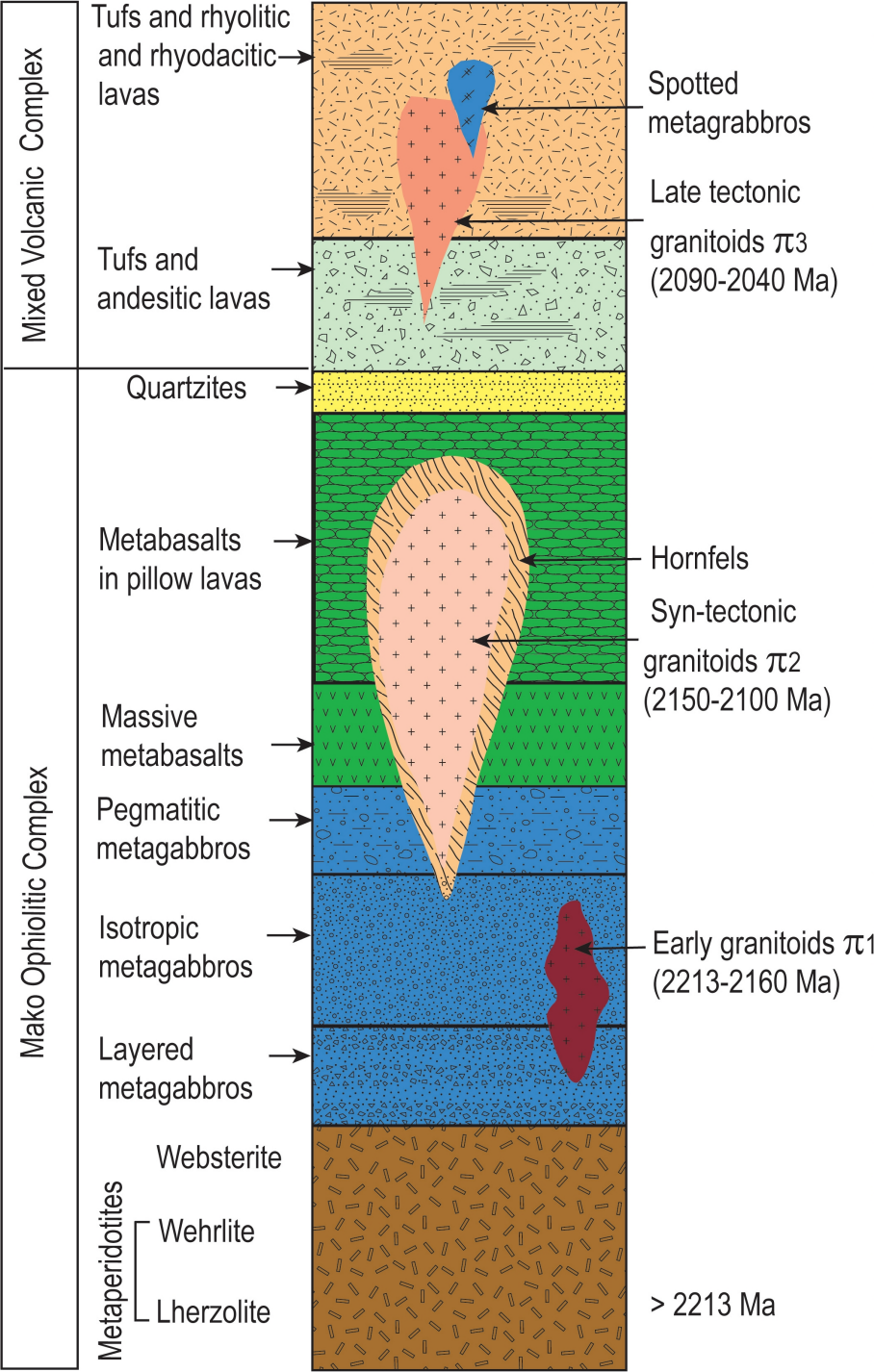
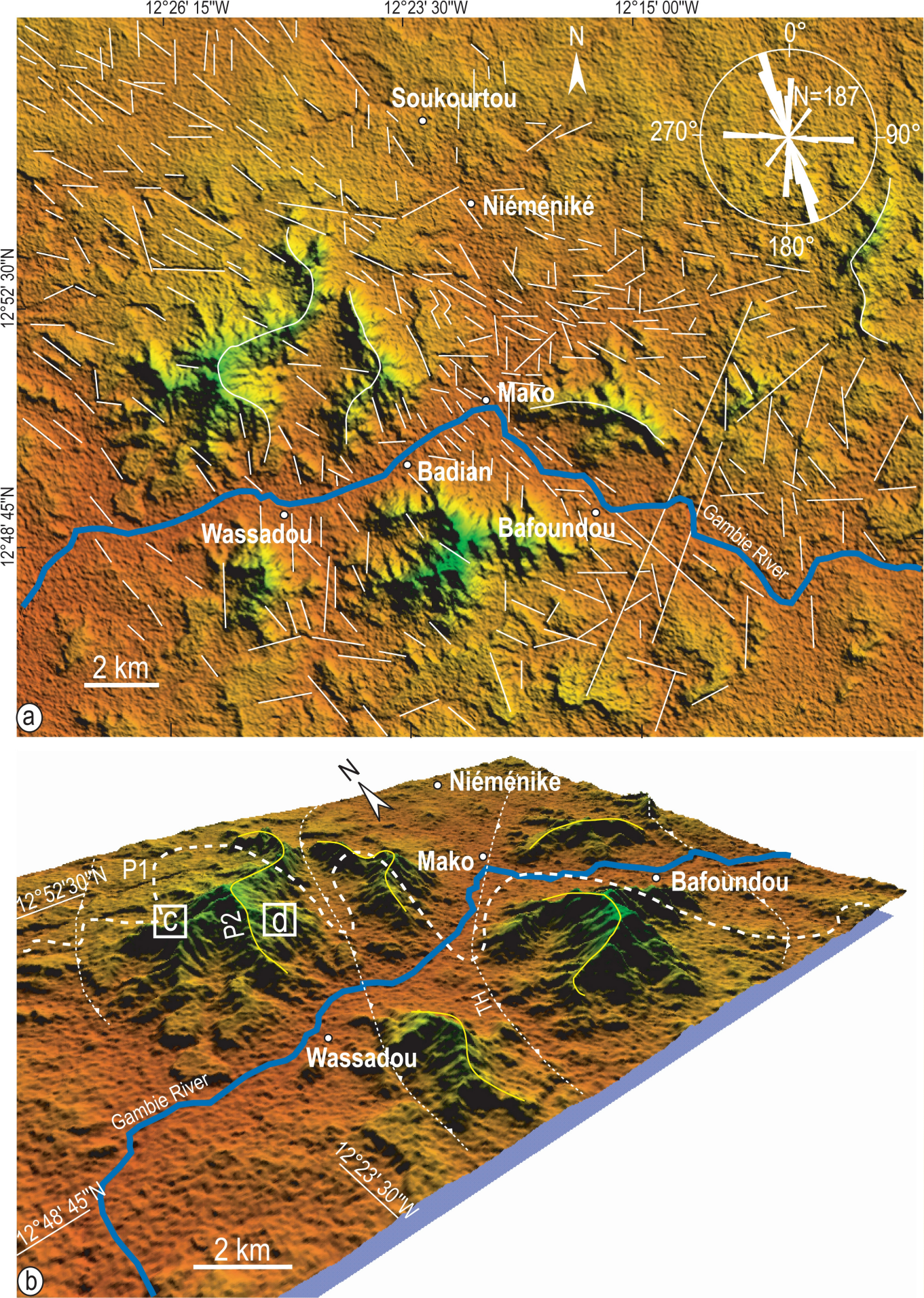
12°20' W
12°54' N
12°50' N
Ndinka
A'
S3
56°
Soukourtou
S3
70°
Sékhoto Peul
S2
64°
72°
S2
RN7
Niémeniké
S3
66°
S2
74°
BC
26°
S1
S1
67°
MS2
Massanritana
Mako
A
75°
S2
65°
Lamé
S1
25°
Badian
70°
S2
Gambie River
S1
30°
Bafoundou
Wassadou
S2
70°
23°
S1
a
0°
90°
180°
270°
N
N=160
c
Schistosity
Strick lineation
Thrust
Shear zone
BM Coridor
Spotted metagabbros
Granite π3
Granodiorites π2
Rhyolite and rhyodacite flows
Rhyolitic and rhyodacitic breccias
Andesitic flows
Andesitic tufs
Quartzites
Metabasalts
Metagabbros
Utramafic rocks
1 km
A'
Sékhoto Peul
1 km
A
b


Mixed Volcanic Complex
Mako Ophiolitic Complex
Tufs and rhyolitic and rhyodacitic lavas
Tufs and andesitic lavas
Quartzites
Metabasalts in pillow lavas
Massive metabasalts
Pegmatitic metagabbros
Isotropic metagabbros
Layered metagabbros
Websterite
Metaperidotites
Wehrlite
Lherzolite
Spotted metagrabbros
Late tectonic granitoids π3 (2090-2040 Ma)
Hornfels
Syn-tectonic granitoids π2 (2150-2100 Ma)
Early granitoids π1 (2213-2160 Ma)
> 2213 Ma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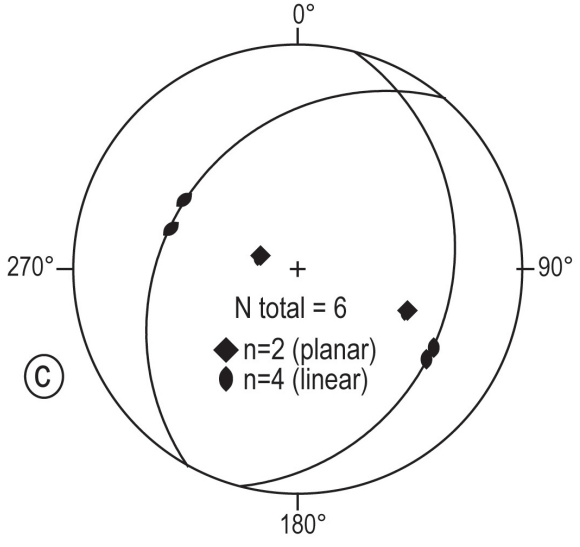
12°23' 30"W
12°15' 00"W
12°52' 30"N
12°48' 45"N
N
0°
90°
180°
270°
N=187
Soukourtou
Niéméniké
Mako
Badian
Wassadou
Bafoundou
Gambie River
2 km
a
N
Niéméniké
Mako
Bafoundou
12°52'30"N
P1
P2
c
d
H
Wassadou
Gambie River
12°48' 45"N
12°23' 30"W
2 km
b


W
E
TF
a


NW
SE
S1
b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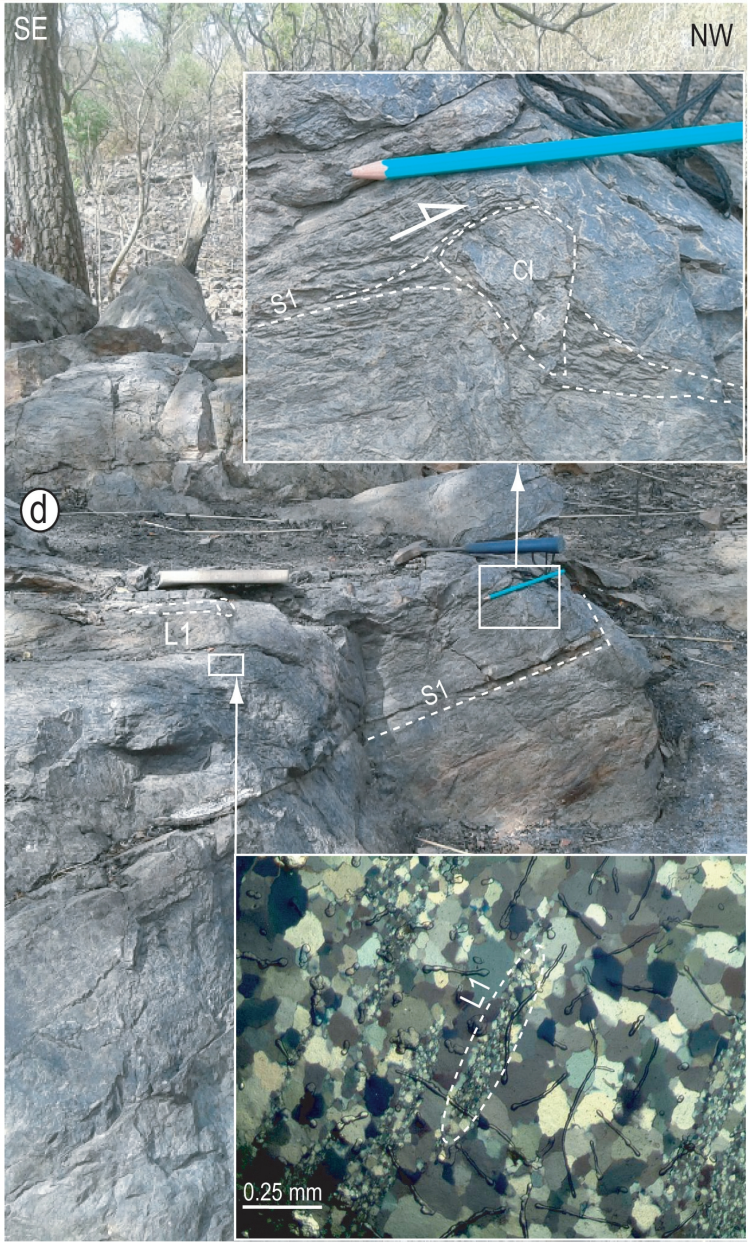
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NW
SE
P1
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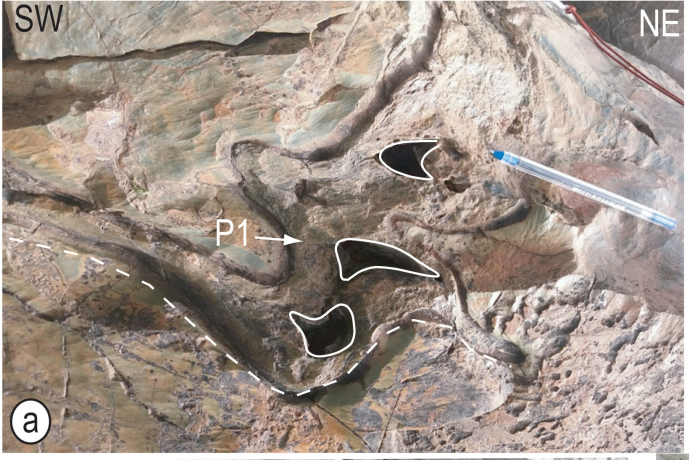
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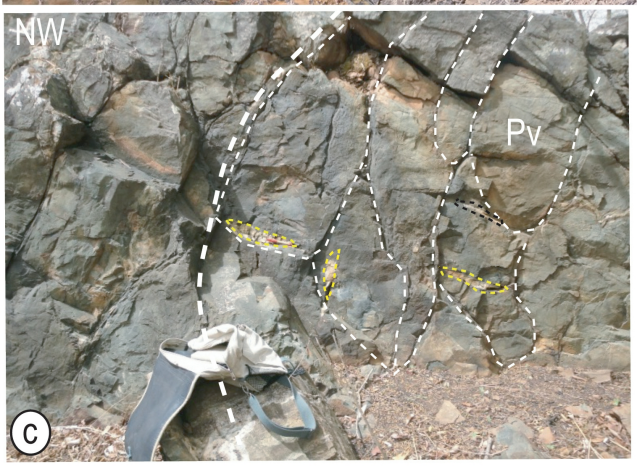
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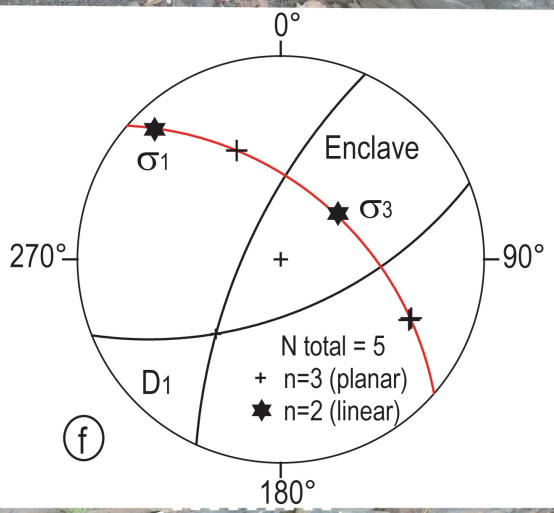
Pv
c


SE
Pv
d


NW
e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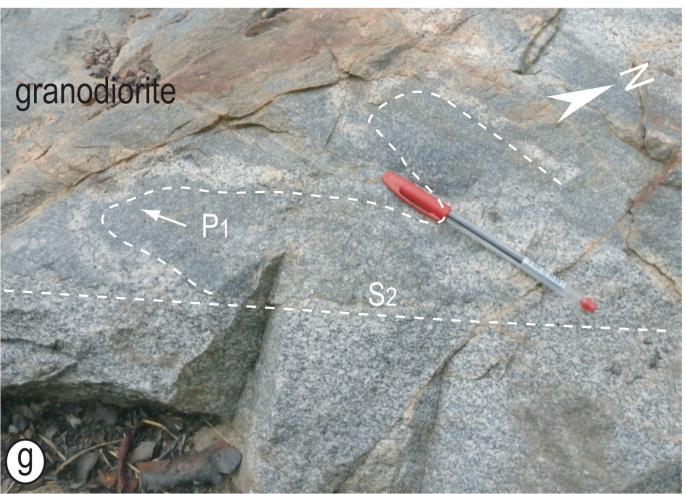
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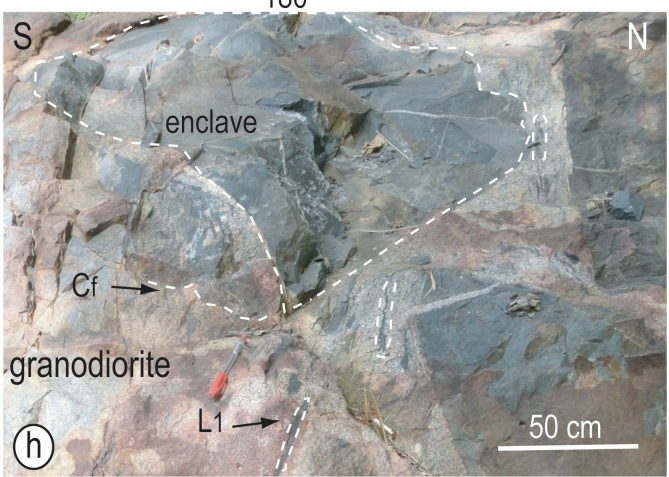
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Cf
granodiorite
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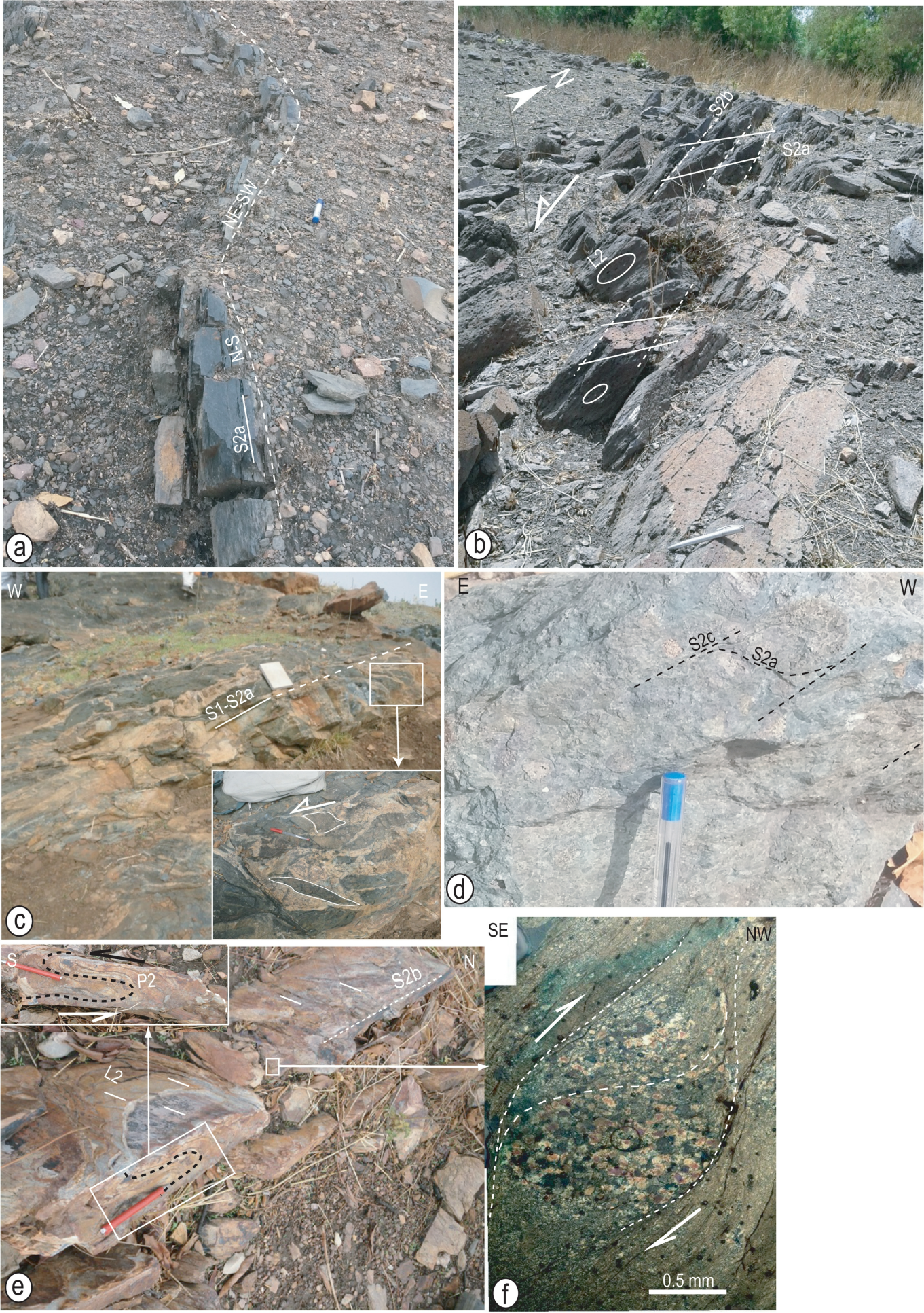
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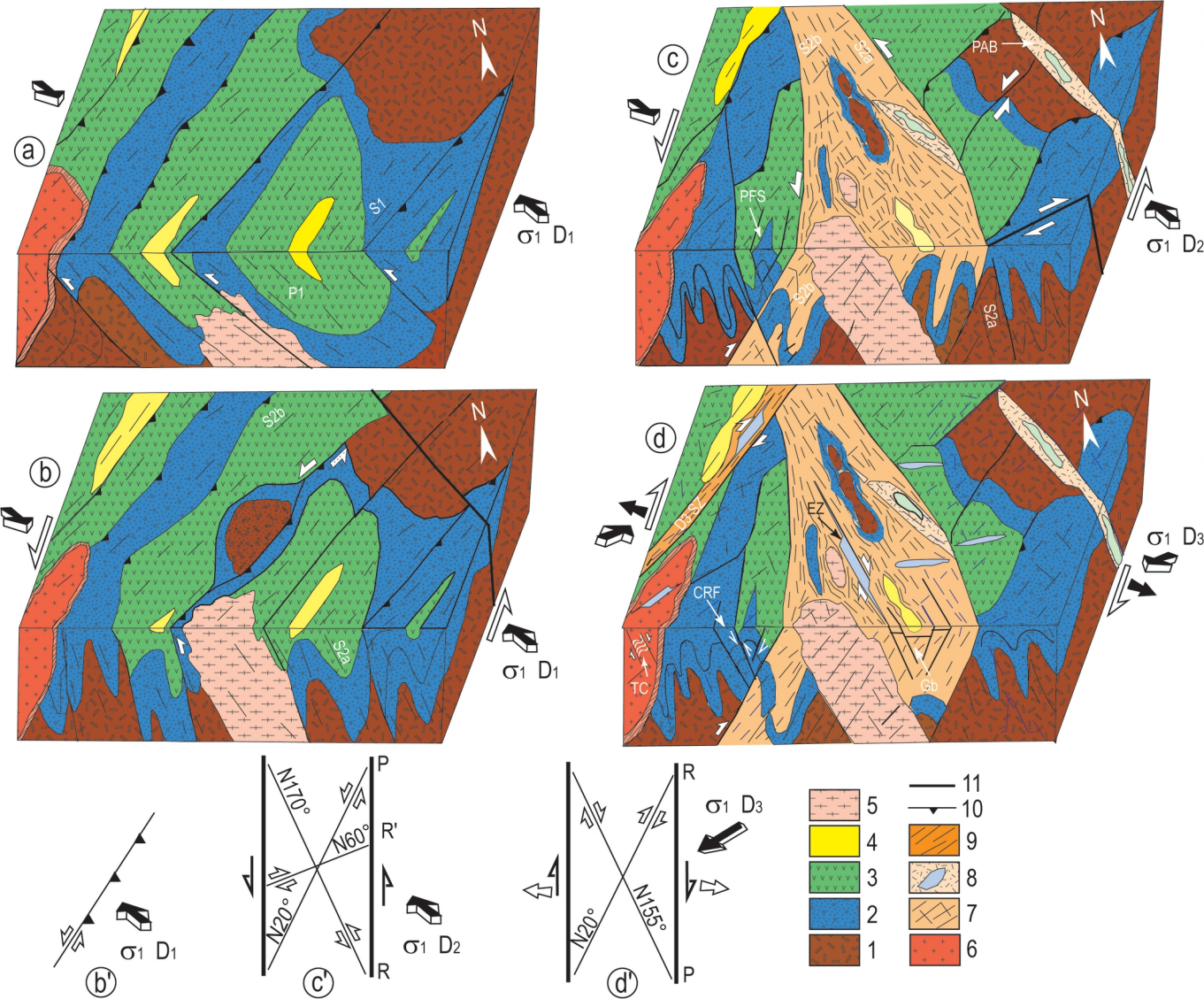
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S2a
σ1 D2
d
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CRF
TC
Gb
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b'
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c'
P
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N60°
R'
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R
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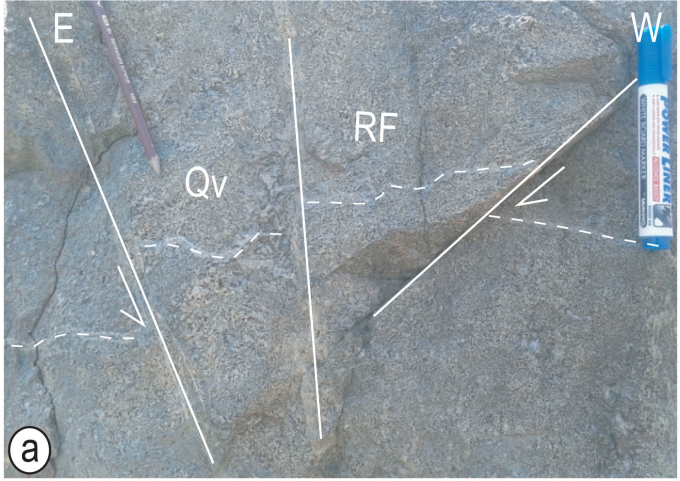
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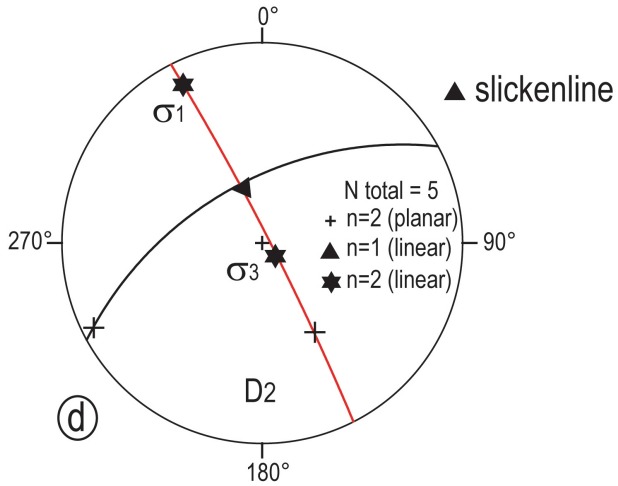
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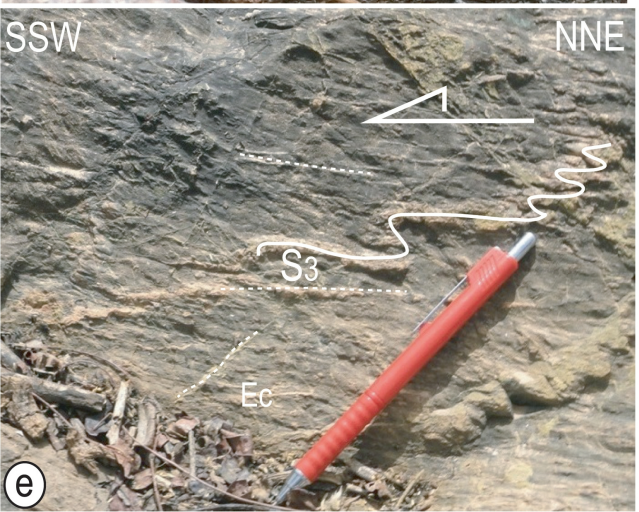
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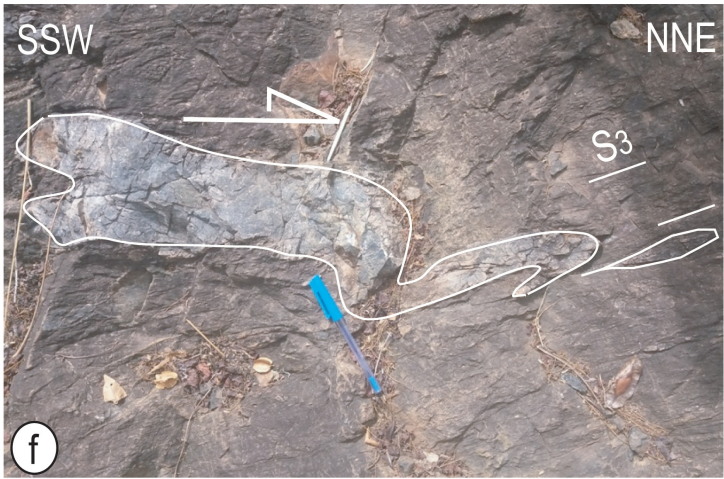
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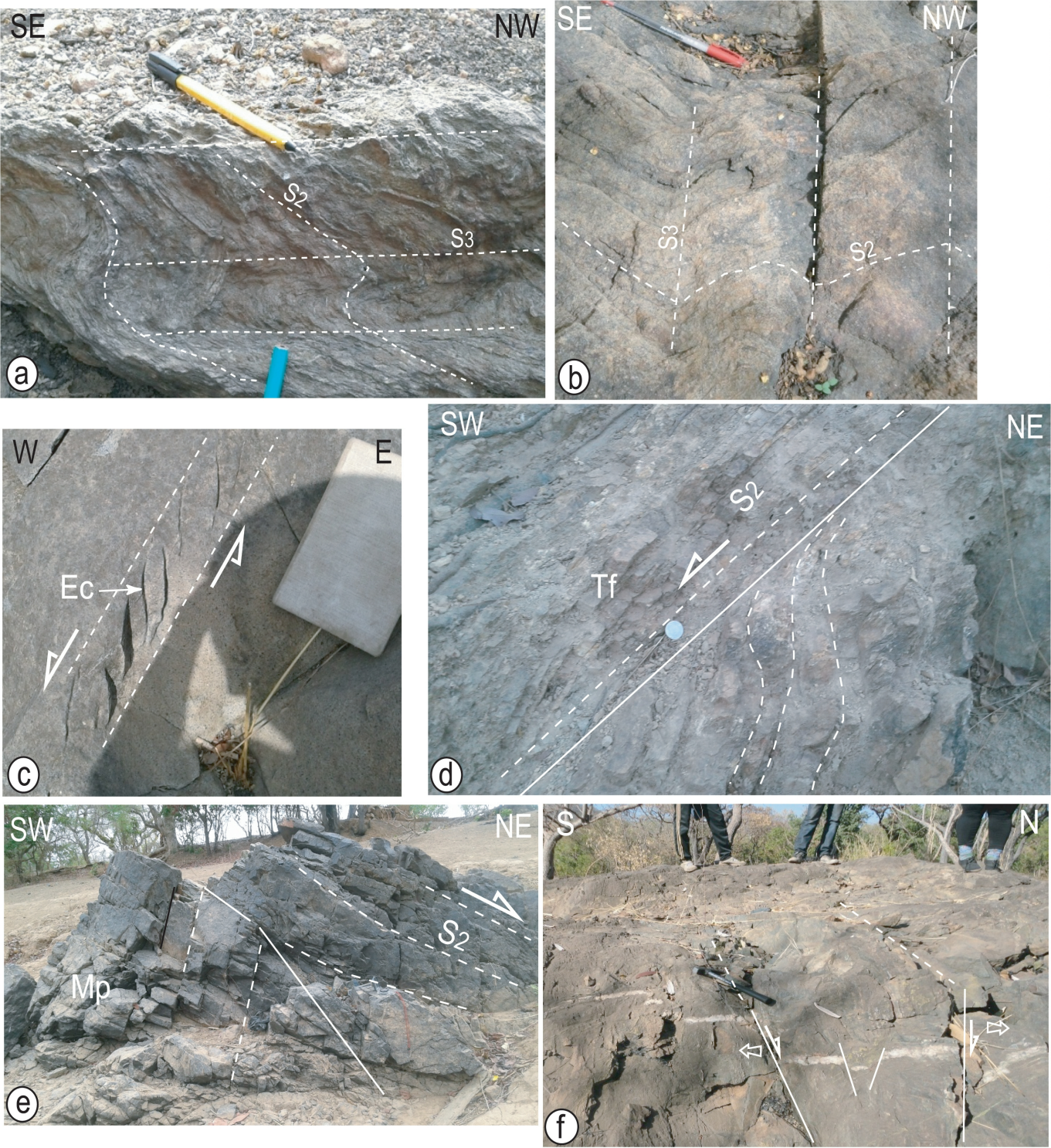
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Ec
c
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NE
S2
Tf
d
SW
NE
S2
Mp
e
S
N
f

Table 1: Lithostratigraphy of the Birimian formations of KKI from bottom to top

	Bassot (1966)	Delor et al. (2010)	Ngom et al. (2011)
Dialé-Daléma Supergroup (top)	- Granitoids - Flysch - Cipolins, graywackes, quartzites, schists	- Andesites, rhyodacites and volcano-sediments - Quartzites, sandstones - Graywackes, pelites, siltites - Carbonates	- Granitoids 4 - Graywackes, sandstones, pelites - Pyroclatics - Andesitic flows - Graywackes, sandstones, pelites - Conglomerates
Mako Supergroup (bottom)	- Late mafic rocks - Granitoids - Flysch and conglomerates - Andesitics dominantly flows - Ophiolitic rocks	- Volcano-sediments, sandstones, pelites and conglomerates - Rhyolite and rhyodacite - Basalts - Ultrabasic rocks	- Granitoids 2 and 3 - Volcano-sediments - Massive felsics - Massive basalts - Sediments - Granitoids 1 - Peridotites - Pillowed basalts and jaspers

Table 2: Eoeburnean and Eburnean deformation phases in some Birimian provinces of the WAC

Authors	Study area	D_1 deformation	D_2 deformation	D_3 deformation	D_{3+n} deformation
Delor et al. (2010)	Kédougou-Kéniéba, SE Senegal	Eoeburnean: peri-plutonic gravity driven deformations (2.17-2.14 Ga)	Eburnean Dt_1 and Dt_2: transcurent tectonism		
Feybesse et al. (2006)	Regional Ghana	Trust tectonism (2.13 - 2.105 Ga)	D_{2-3} strike-slip movement (2.095 - 1.98 Ga)		
Block et al. (2015)	NW Ghana	NS horizontal shortening with reverse shear zones	NS extensional shearing	EW shortening and N to NNE stretching	D_4-D_7 narrow shear zones in dominantly transcurrent regime