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New lithostructural map of the Doropo region, northeast Côte d'Ivoire: Insight from structural and aeromagnetic data

Ziandjêdé Hervé Siagné^{1,2}, Tahar Aïfa^{2,*}, Alain Nicaise Kouamelan¹, N'Guessan Nestor Houssou¹, Wilfried Digbeu¹, Bi Koffi Fidèle Kakou³, Pierrick Couderc³

¹UFR STRM, Université Félix Houphouët-Boigny, Abidjan-Cocody, 22 B.P. 582 Abidjan 22, Côte d'Ivoire

²Univ Rennes, Géosciences Rennes - CNRS UMR6118, Bat.15, Campus de Beaulieu, 35042 Rennes cedex, France

³Ampella-Centamin Mining Co., 20 BP 945 Abidjan 20, Côte d'Ivoire

*corresponding author: Tahar.aifa@univ-rennes1.fr

Abstract

This study, performed in the Doropo region (northeastern Côte d'Ivoire) in the Paleoproterozoic domain (southern part of the WAC), aims to produce a detailed lithostructural map of this area. The geology of this region is less known due to the thick lateritic overburden and the scarcity of outcrops. Recent airborne geophysical data (aeromagnetic) integrated with field structural and lithological observations allowed to distinguish several lithologies including biotite granite, gneissic and migmatitic granite, granodiorite, tonalite, gabbro, amphibolite, rhyolite and dolerite. Filtering techniques of derivatives, upward continuation, tilt, analytical signal, spectral analysis and 3D Euler deconvolution showed the presence of faults, shear zones and intrusions. The structural analysis revealed four deformation events (D₁-D₄): (i) D₁ is a N-S compression marked by E-W foliation (S₁), conjugate NE-SW and NW-SE sinistral and dextral shears, respectively, as well as F₁ folds with E-W axial planes; (ii) D₂ is a major transpressive phase characterized by an intense NE-SW foliation (S₂), E-W dextral shear zones, a weakly dipping stretching L₂ lineation plunging N-E, and NE-SW faults; (iii) D₃ is a NE-SW compressional phase generated NW-SE foliation (S₃) with ~E-W shears, and NW-SE axial plane F₃ folds; (iv) D₄ is a late, rather brittle phase characterized by brittle structures (faults, fractures, etc.) and the emplacement of NE-SW and NW-SE dolerite dykes. This tectonic evolution demonstrates that the Doropo region was subject to ductile and then brittle deformations. Furthermore, we suggest that the geodynamic model which could have prevailed in the Doropo region occurred in an oceanic arc collisional tectonic context.

Keywords: granitoids, dolerite dyke, fault, aeromagnetic, geodynamic model, structural analysis

1. Introduction

The Paleoproterozoic terrains of the West African Craton (WAC), particularly those of the Man-Leo Shield, are composed of granitoid and greenstone belts (Metelka et al., 2011; Aïfa, 2021). They represent an interesting target for mineral exploration because they contain numerous mineral deposits (Allibone et al., 2002; Feybesse et al., 2006; Béziat et al., 2008; Amponsah et al., 2015, 2016; Markwitz et al., 2016; Goldfarb et al., 2017). Unfortunately, these regions are very often characterized by surface weathering (lateritization) and limited outcrops that can hinder cartographic surveying, mineral exploration and structural studies. The recourse to use high resolution aeromagnetic data processing appears then as an essential tool to study these terrains. Magnetism has shown its effectiveness in the study of similar terrains, especially within the WAC by producing new geological data (Betts et al., 2003; Peschler et al., 2004; Direen et al., 2005; Peschler et al., 2006; Agyei Duodu et al., 2009; Aitken and Betts, 2009; Stewart and Betts, 2010; Metelka et al., 2011; Perrouy et al., 2012; Baratoux et al., 2015; Eldosouky et al., 2017).

Thus, the recently acquired (2015) aeromagnetic data in the Doropo region (northeast Côte d'Ivoire) present a unique opportunity to investigate this region where no significant geological studies have been done. This region appears promising for mineral prospects, with the current presence of several exploration companies (e.g., Ampella-Centamin Co). Based on this mining interest, detailed geological studies have become a necessity, as most mineral deposits (e.g., gold) are structurally controlled (Mériaud et al., 2019; Murray et al., 2019; Tourigny et al., 2019). Processing (horizontal derivatives, upward continuations and 3D Euler deconvolution, etc.) and interpretation of aeromagnetic data combined with field observations were undertaken in order to gain a better understanding of the lithostructural organization of the Doropo region. This study will contribute to existing geological information on the WAC by: (1) establishing both subsurface and outcrop scale structures, and various deformational episodes of such structures; (2) relating Doropo deformational episode to other documented events of terrains within the WAC, especially Burkina Faso and northwest Ghana, and (3) helping produce an improved lithostructural map at a scale of 1: 50,000 for the Doropo region.

2. Geological setting

The WAC (Fig. 1) occupies most of West Africa with areas of generally low relief (Bessoles, 1977). It is a huge craton of approximately 4,500,000 km², formed by a set of largely granitized peneplanar chains of Precambrian age (Bessoles, 1977). Two major composite orogenic episodes have marked the ancient history of the WAC (Bessoles, 1977): the Liberian (2.9-2.5

Ga) and the Eburnean (2.5-1.6 Ga) at the end of which all the craton stabilized around 1.9 Ga (Liégeois et al., 2005; Begg et al., 2009; de Waele et al., 2015; Aïfa and Merabet, 2021). The WAC, which is covered in its central part by the Neoproterozoic to Devonian Taoudeni Basin, consists of:

(i) the Reguibat Shield to the north occurring in two large areas (Archean and Birimian) separated by the Zednès Fault;

(ii) the Kédougou-Kéniéba and Kayes Inliers to the southwest, formed exclusively of Paleoproterozoic formations occurring in narrow volcanic belts and sedimentary basins which are intruded by Eburnean granitoids (Ledru et al., 1991; Liégeois et al., 2005; Lambert-Smith et al., 2016; Masurel et al., 2017; Dabo et al., 2018). To the west of these inliers, the WAC is bordered by the Caledonian-Hercynian chain of the Mauritanides of Precambrian to the Devonian age end;

(iii) the Man-Leo Shield to the south, covers a large region of the craton. This Shield, like that of the Reguibat, is divided into two parts: (a) in the west, the Kénéma-Man domain of an Archean age and (b) in the east, the Baoulé-Mossi domain of Paleoproterozoic age which would be the extension of the Birimian formations of Kédougou-Kéniéba beneath the Neoproterozoic formations of the Taoudeni Basin (Bassot and Vachette, 1984). These two areas are separated by the N-S Sassandra fault (Kouamelan, 1996). The similarities existing in the geological evolution of the WAC, the Guyana Shield and the small cratonic block of São Luis indicate that these entities formed the same block before its “recent” dislocation (Ledru et al., 1994; Vanderhaeghe et al., 1998; Nomade et al., 2003; Klein and Moura, 2008; Chardon et al., 2020). The Kénéma-Man domain of the Man Shield is made up of Archean rocks (3.4-2.6 Ga) recognized in the west of Côte d'Ivoire, Guinea, Sierra Leone and Liberia (Camil et al., 1983; Kouamelan et al., 1997a,b; Thiéblemont, 2005; Koffi et al., 2020). It comprises granulitic gneisses (3.05 Ga), charnockites (2.8 Ga), Tonalite-Trondhjemite-Granodiorite (TTGs, between 3.6 and 3.0 Ga) and Banded Iron Formations (BIFs) (Kouamelan et al., 2015; Koffi et al., 2020). The Paleoproterozoic domain, which spans between the Archean domain (Kénéma-Man) in the west and the Volta Basin in the east is characterized by rocks with ages between 2.2 and 2.0 Ga (Caen-Vachette, 1986; Gasquet et al., 2003; Feybesse et al., 2006; Vidal et al., 2009; Castaing et al., 2004; de Kock et al., 2011). The Paleoproterozoic (Birimian) terrains are composed of metavolcanic and metasedimentary rocks bordered by large batholiths of TTGs; all intruded by plutons of calc-alkaline and alkaline granites (Milési et al., 1989; Pouclet et al., 2006; Hein, 2010; Baratoux et al., 2011; Perrouy et al., 2012; Block et al., 2016; Lebrun et al., 2016; Masurel et al., 2017). These rocks can be linked to a multistage orogenic event: the

Eburnean (2.5-1.8 Ga; [Bonhomme, 1962](#); [Boher et al., 1992](#)). The beginning of the Eburnean orogeny varies according to the regions: (i) in the northeast Baoulé-Mossi, it occurred around 2.16-2.15 Ga ([Baratoux et al., 2011](#); [Block et al., 2016](#)), (ii) in the southeast ([Feybesse et al., 2006](#); [Perrouty et al., 2012](#)) and (iii) in the northwest ([Liégeois et al., 1991](#); [Egal et al., 2002](#); [Lebrun et al., 2016](#); [Eglinger et al., 2017](#); [Masurel et al., 2017](#)), it is around 2.12 Ga. However [de Kock et al. \(2011, 2012\)](#) have shown that the Eburnean comprises two stages: the Eoeburnean orogenic cycle which captured the geological history between 2.5 Ga and ~2.140 Ga. This was followed with deposition of the sedimentary and volcanoclastic deposition and syndepositional plutonism in the numerous basins separating the Eoeburnean crust due to crustal extension. The Eburnean orogenic cycle commenced with the closure of these basins and syntectonic granite emplacements from 2126 Ma onwards. Studies on the structural evolution of the Birimian of the Man-Leo Shield have led to the recognition of a history characterized by a complex polycyclic deformation linked to the Eburnean orogeny ([Milési et al., 1986](#); [Ledru et al., 1989](#); [Feybesse et al., 2006](#); [Lompo, 2010](#); [Baratoux et al., 2011](#); [Tshibubudze et al., 2013](#); [Block et al., 2016](#)). Thus, three major deformation phases (D₁, D₂ and D₃) have been identified ([Milési et al., 1986](#); [Ledru et al., 1989](#); [Feybesse et al., 1989, 2006](#); [Lompo, 2010](#); [Baratoux et al., 2011](#)). However, other deformation phases (D₄, D₅, D₆ and D₇) are often observed but they are generally more local ([Vidal et al., 1996](#); [Block et al., 2016](#); [McFarlane et al., 2019](#)). Some of these various deformation events are summarized in Table 1. The study area belongs to the Paleoproterozoic domain of the Man-Leo Shield ([Fig. 2](#)). It is located in the northeast of Côte d'Ivoire. Ampella-Centamin Co's cartographic exploration work has highlighted Birimian units. These formations consist mainly of granitoids adjacent to the southwestern limit of the Boromo Greenstone Belt and to the east by the Lawra Belt. [Block et al. \(2015, 2016\)](#) suggest that these granitoid domains of northwest Ghana, precisely the granitoid domain of "Bole Boulenga", can be linked to those of Côte d'Ivoire (Nassian granitoid domain) and that both of these domains belong to the same geological province based on geochemical and geochronology data. This confirms the already published research works in the northeast of Côte d'Ivoire ([Arnould, 1961](#); [Delor et al., 1995](#); [Hirdes et al., 1996](#); [Lüdtke et al., 1998](#); [Vidal et al., 2009](#); [Baratoux et al., 2015](#); [Block et al., 2015, 2016](#); [Siagné et al., 2021](#); [Digbeu et al., 2022](#)). They represent a granito-gneissic basement intruded by various granites and granodiorites intersected by pegmatitic and doleritic dykes. Furthermore, the structures in the northeast of Côte d'Ivoire are similar to those in southwestern Burkina Faso rich in gold indices (e.g., Napelepera, Batié; [Siagné et al., 2021](#)).

3. Methodology

Two major approaches (field and geophysical data analysis) were necessary to produce a detailed map of the region. A field phase was used to collect lithological, structural and magnetic susceptibility data followed by the processing of aeromagnetic data. All data acquired (geophysical, lithological and structural) were integrated within a GIS software for interpretation.

Field work resulted in:

- Identifying the different lithologies encountered, describing them macroscopically as well as measuring their magnetic susceptibility using an SM30 field susceptibility-meter. The macroscopic description focused on textural and mineralogical features.
- The structural framework was described by highlighting the structures that are manifestation of deformations that have affected these different lithologies while specifying their direction and dip if possible. Above all, by establishing their spatial, crosscutting relationships and relative chronology between different deformation events. The various measurements obtained were subsequently processed with the SpheriStat software in order to identify the main directions.

The aeromagnetic data were acquired within the framework of the Doropo Project by the UTS Geophysics company on behalf of Ampella-Centamin Mining in northeast Côte d'Ivoire. The acquisition was made using a *Cessna Grand Caravan C208* type aircraft registered under ZS-ABN and the aircraft was piloted by *Geotch Aviation Ltd.* A total of 21,589 km of lines were flown. The flight lines were spaced at intervals of 200 m and 100 m (filling) in the direction 160°-340° while the control lines were spaced 2000 m and 1000 m (filling) in the direction 070°-250° at an average flight altitude of 100 m. The aeromagnetic data obtained underwent a first processing by making specific corrections to be used and reliable for the further processing (Allard and Bois, 1999). Diurnal, altitude, topography and latitude corrections were applied. After that, the data from these corrections were gridded on a 25 m x 25 m cell size using Geosoft Oasis Montaj software (Finn and Anderson, 2015). This allowed to obtain the total magnetic intensity map on which several filters were applied in order to highlight the geological properties (Metelka et al., 2011; Perrouty et al., 2012; Santos et al., 2017; Osinowo et al., 2020; Aïfa and Lo, 2021). In this study, we used the data sets from the reduction to the pole, the upward continuation, the vertical gradient along X, Y and Z, the analytic signal, the tilt derivative, the spectral analysis and 3D Euler deconvolution. Shaded-relief technique has been applied to all these different data set compilations to highlight anomalies.

The Fast Fourier Transform (FFT) algorithm has been applied to magnetic data for reduction to the pole (MacLeod et al., 1993; Li, 2008). Due to the low magnetic inclinations (e.g., $I = -5.9^\circ$, $D = -3.6^\circ$) and a field intensity of 32,704 nT in the centre of the study area, it was difficult to successfully reduce the magnetic data to the magnetic pole (RTP). Therefore, we used the pseudo-RTP technique (Luo et al., 2010). It consisted in reducing the magnetic field data to the equator. Thereafter, the data were subsequently reversed (i.e., multiplied by -1) to potentially mimic the RTP and position the peaks of the magnetic anomalies above their sources (Baranov and Naudy, 1964; Bhattacharya, 1966; Hildenbrand, 1983; Luo et al., 2010).

The upward continuation is a technique that highlights deep structures. It makes it possible to attenuate the anomalies as a function of wavelengths, the shorter the wavelength, the larger the attenuation (Blakely, 1996). For this study, upwards to 100 m, 200 m, 500 m and 1000 m were applied in order to highlight the deep structures on the RTP map.

The first derivatives filter applied to the RTP map was useful for the interpretation of structural discontinuities as it increases the contrasts between positive and negative anomalies, thus providing details on the limits of magnetic units. This helped to determine the contacts between the various structures or lithologies (Elkins, 1951; Hood, 1965; Cordell and Grauch, 1985; Blakely and Simpson, 1986; Grauch and Cordell, 1987).

The analytic signal (AS) and the tilt derivative are filters based on a three-dimensional combination of the residual magnetic field derivatives in three dimensions. The mathematical expression of the AS for a magnetic anomaly (M) in 3D is defined as being a complex vector which can be expressed as follows (Roest et al., 1992):

$$|AS(x, y)| = \left[\left(\frac{\partial M}{\partial x} \right)^2 + \left(\frac{\partial M}{\partial y} \right)^2 + \left(\frac{\partial M}{\partial z} \right)^2 \right]^{1/2}$$

It is independent of the direction of magnetization and the direction of the Earth's magnetic field (Nabighian, 1974; Roest et al., 1992). This means that bodies with the same geometry have the same AS (Milligan and Gunn, 1997). In addition, the geological structures with strong magnetization can be better assessed in shape and dimension.

The tilt derivative used in this study, based on the tilt angle θ of a magnetic anomaly which is considered as local phase, can be expressed as a horizontal gradient $\frac{d\theta}{dh} = \frac{z}{x^2+z^2}$. At $x = 0$

one can get $z = \left(\frac{d\theta}{dh} \right)^{-1}$ which is useful to map the edges and depths of causative sources (e.g., Salem et al., 2007, 2010). The application of such filters was made on the RTP map.

The power spectral analysis of the magnetic anomaly can also be used to estimate the depths average of the various magnetic sources based on the space transformation of the magnetic data into various frequency fields (Battacharyan, 1966; Spector and Grant, 1970). Spector and Grant (1970) introduced a procedure to compute the depth at the top of the causative magnetic source using the radial power spectrum. It has been further improved to calculate additionally the depth of its centroid and its base (Bhattacharyya and Leu, 1975a,b, 1977; Okubo et al., 1985; Tanaka et al., 1999).

Meanwhile Euler's deconvolution is a processing which allows estimating the position and the depth of the magnetic sources from mesh data covering the survey area. This processing requires the calculation of horizontal and vertical gradients.

The choice of the source model or the structural index, window size (Table 2), the exactitude of the flight altitude and topographic surfaces, and the spacing of flight lines are important to have reasonable and accurate results. The expression of Euler's equation is given by (Thompson, 1982):

$$(x - x_0) \frac{\partial \Delta T}{\partial x} + (y - y_0) \frac{\partial \Delta T}{\partial y} - (z - z_0) \frac{\partial \Delta T}{\partial z} = -N \Delta T(x, y)$$

where x , y , z denote local coordinates, x_0 , y_0 , z_0 the coordinates of the postulated source location, ΔT the difference between the anomaly and the regional field, and N the structural index (SI).

The remanent magnetization is negligible here and therefore does not affect the result of the calculations (Allard and Bois, 1999; Reid et al., 1990). In this study, the parameters used for the calculation of Euler solutions depths are: (i) a specific structural index $SI = 1$ for the detection of dykes; (ii) a tolerance of the solution estimated at 15%. As the profiles are spaced 100 m apart, and the maps have been calculated with a 25 m x 25 m grid, the amount of data has increased significantly. An evaluation of the Euler solutions depths on thin surfaces (0-50 m, 50-75 m, etc.) has been carried out. This has highlighted the obscured near to subsurface structures.

4. Results

4.1. Facies and magnetic susceptibility

Field observations complemented by drill core samples allowed to distinguish several lithologies in the Doropo region. The different mineralogical proportions mentioned below are based on a visual estimation. The main lithologies in order of abundance are:

(i) **Biotite granite** is the dominant lithology in the region and it is encountered all across the study area. It may occur in massive or circular or dome or slab of extremely variable size (meter to kilometer). It can also be observed as a cluster of large blocks exposed by erosion. The rock is leucocratic to mesocratic and ranging from fine- to coarse-grained (Fig. 3a). Based on visual estimation, the rock is mainly composed of quartz (~60%), feldspar (~30%), biotite (~10%) and sometimes small euhedral crystal of sulphides. Histograms from magnetic susceptibility (MS) measurements in the field and laboratory show a multimodal distribution, with MS values in the ranges of $0.025 \times 10^{-3} - 17.1 \times 10^{-3} SI$ and $0.01 \times 10^{-3} - 12.1 \times 10^{-3} SI$ in the field and in the laboratory, respectively (Figs. 4a, 5a, Table 3).

(ii) **Gneissic and migmatitic granites** are found in the south, east and north of the study area. They appear as circular or large slabs and are cross-cut by several quartzo-feldspathic veins (Fig. 3b) and contain mafic enclaves (Fig. 3c). They are light- to grey coloured, medium- to coarse-grained, and show a gneissic texture defined by alternating light colour (quartz, feldspar) and dark colour mineral (mica, amphibole) rich beds, which sometimes are migmatitic. Furthermore, the rocks contain quartz (~55%), feldspar (~35%), biotite (~5%), and some rare amphibole (~3%) and magnetite. Their histogram relatively displays high values and substantially close to those of biotite granite. Magnetic susceptibility values range from 0.093×10^{-3} to $12.9 \times 10^{-3} SI$ and 0.55×10^{-3} to $9.98 \times 10^{-3} SI$ in the field and laboratory, respectively (Figs. 4b, 5b).

(iii) **Granodiorite** are most often found in contact with or as enclaves within the biotite granite. They occur as circular or slab or meter-size block, and are mesocratic, medium- to coarse-grained (Fig. 3d). The rocks also show a granitic texture and contain feldspar (~60%), quartz (~25%), amphibole (~10%), biotite (~5%) and accessory sulphide minerals. These rocks sometimes show a weak foliation defined by aligned amphibole and biotite grains. Their magnetic susceptibility (MS) is moderate with MS values in the ranges of $1.59 \times 10^{-3} - 7.73 \times 10^{-3} SI$ in the field and $0.07 \times 10^{-3} - 4.33 \times 10^{-3} SI$ in the laboratory (Figs. 4c, 5c).

(iv) **Gabbro** occurs in the shape of small decimeter-size nodules or as enclaves within the biotite granite and is found in the northern part of the study area. The rock is melanocratic, medium- to coarse-grained, and consists of feldspar (~70%), pyroxene (~25%), and rare amphibole (< 5%) (Fig. 3e). The rock is also cut by quartzofeldspathic veins (probably associated with the rhyolite volcanism). The histograms show low to moderate magnetic susceptibility values (Figs. 4d, 5d). Magnetic susceptibility in the field and laboratory varies from ranges $0.22 \times 10^{-3} - 0.36 \times 10^{-3} SI$ to $0.03 \times 10^{-3} - 0.23 \times 10^{-3} SI$, respectively.

(v) **Amphibolite** generally occurs as enclaves within the biotite granite, gneissic and migmatitic granites, granodiorite and tonalite. The rock is dark green, fine- to medium-grained, and is crossed by numerous deformed thin quartz and feldspar veins (Fig. 3f). It is mainly composed of amphibole (~80-70%) and feldspar (~30%). The observation of the histograms shows low to medium magnetic susceptibility values (Figs. 4e, 5e). These magnetic susceptibility values vary within the ranges $0.003 \times 10^{-3} - 0.97 \times 10^{-3} SI$ and $0.01 \times 10^{-3} - 0.35 \times 10^{-3} SI$, in the field and laboratory, respectively.

(vi) **Rhyolite** is less represented in the study area and appears as small meter-size boulders or dome-like outcrops in its central part. To the naked eye, the rock is light in colour, glassy, and composed of quartz and feldspar phenocrysts and some disseminated pyrite crystals (Fig. 3g). It is the only felsic volcanic unit encountered in the Doropo region and show no apparent metamorphic alteration. The magnetic susceptibility displays a low value which varies from 0.009×10^{-3} to $1.5 \times 10^{-3} SI$ (Fig. 5f).

(vii) **Dolerite** is highlighted in the core samples and occurs as dykes (Fig. 3h). The rock is dark to dark gray in colour, and is fine- to medium-grained. It contains feldspar (~50%), pyroxene (~40-30%) and some calcite veins. The histogram shows very high susceptibility magnetic above $26.1 \times 10^{-3} SI$ (Fig. 5g).

4.2. Structural analysis

The Doropo region was submitted to four deformation phases which are denoted as D₁, D₂, D₃ and D₄.

4.2.1 D₁ Deformation phase

D₁ deformation is observed in the gneissic granite in the Doropo, Gbatedjou, Bouko and Enioda areas (Fig. 2). It is marked by an intense S₁ foliation generally oriented E-W with a moderate to subvertical dip (40°-65°) towards the north (Fig. 6a). Following the S₁ foliation, F₁-folds are identified and characterized by their open hinges whose axial planes has an E-W orientation and axes plunging 40° to 45° towards the southwest (Fig. 6b). These F₁-folds are accompanied by drag and intrafolial micro-folds which show both dextral and sinistral shears. NW-SE and NE-SW to NNE-SSW oriented small-scale shear zones are also observed in the gneissic granite (Fig. 6c-d). These shear zones translate a conjugated shear with dextral and sinistral play, respectively. It should be noted that the NW-SE dextral shear is very important in the entire study area. These different shear zones are also evidenced by sigmoid-shaped porphyroblasts. All these field observations show that D₁ was an N-S oriented shortening event which has produced the above mentioned structures.

4.2.2 D₂ Deformation phase

The structures related to the D₂ deformation has been observed in the field within the gneissic granite of Bouko and the migmatitic granite of Danoa where it appears as an intense penetrative S₂ foliation oriented NE-SW (Fig. 7a), and was folded by a later D₃ deformation event near Bouko and Danoa. The dips of this S₂ foliation vary between 50° and 85° towards the northwest at Bouko and Danoa. S₂ is marked by metamorphic differentiated alternating beds of quartz-feldspar minerals, biotite and amphibole. It is also distinguished by a 040°-050° oriented fracturing found in meter wide quartz veins at Enioda. This brittle feature may be presented as thin open fractures without crystallization, which in places can be crosscut by a later NW-SE oriented fracture set. This deformation phase is also distinguished by a stretching lineation (L₂) observed in Bouko's gneissic granite which plunges 10° to 30° towards the northeast (Fig. 7b). In the Bouko sector, the D₂ deformation is characterized by meter to decimeter thick dextral shear zones oriented E-W with a subvertical dip (Fig. 7c). These shear zones are characterized by sigmoid-shaped pods and S-C fabrics. Moreover, a N-S oriented shear zones has been found in the Bouko sector as well as asymmetric intrafolial folds (F₂) in the gneissic granite. The D₂ deformation is also characterized by S-C fabrics reflecting sinistral ductile shear observed in the Lagbo's migmatitic granite (Fig. 7d). D₂ is the most important phase in the region which affected the granitoids. It is a NW-SE shortening phase responsible for the different structures observed.

4.2.3 D₃ Deformation phase

D₃ structures can be observed in the migmatitic granites of Danoa and sometimes rarely in the biotite granite of Kodo. D₃ deformation generated an intense S₃ foliation (Fig. 8a) generally oriented NW-SE to NNW-SSW marked by a metamorphic differentiation of quartzofeldspathic and ferromagnesian (mainly biotite and amphibole) mineral bands. Leucosomes and melanosomes are parallel to this S₃ foliation. The D₃ is also responsible for the E-W oriented sinistral shear zones very often found at Lagbo and rarely at Bouko and Doropo (Fig. 8b). These are small centimeter to decimeter bands, most often with microfolds and sigmoidal clasts. This deformation is also responsible for the F₃ folds with an NW-SE axial plane observed at Gbatedjou and Bouko (Fig. 8c). D₃ can be attributed to a NE-SW shortening phase responsible for these different structures.

4.2.4 D₄ Deformation phase

This is the latest phase that affected the region's granitoids. It is recognized through conjugate fractures and shear fractures which are mainly E-W and NNE-SSW oriented on the one hand. On the other hand, quartz veins and pegmatite dykes are mainly NE-SW and E-W to NW-SE,

and NE-SW oriented, respectively (Fig. 9a-b). ENE-WSW and E-W oriented strike-slip faults are also noted (Fig. 9c). All these structures have the particularity of crosscutting those of previous deformations. In addition, some E-W oriented fractures located in the eastern part of the study area are sometimes filled with chlorite or epidote or both (Fig. 9d).

4.3. Aeromagnetic data

Reduction to pole

The application of the reduction to pole (RTP) filter to the dataset of the total magnetic field (Fig. 10a), allowed to obtain the map of the reduced magnetic field to the pole (Fig. 10b) for the study area. This map shows negative and positive anomalies with magnetic field values between -58.50 nT and 50.39 nT. These anomalies make it possible to highlight two magnetic domains which are:

- A first magnetic domain characterized by negative anomalies (An_1 - An_2) has been observed in the far northeast, a portion of the west and in the centre of the study area. This anomaly is the least representative of the study area;
- A second domain characterized by positive anomalies (Ap_1 - Ap_2), elongated NW-SE to E-W trending, has been observed in the centre.

Figure 10b also highlights numerous linear structures, both strongly and weakly magnetic, oriented NE-SW and NW-SE which crosscut all rock units of the study area.

Upward continuation

The application of the upward continuation filter to the RTP map, allowed to qualitatively analyze the distribution of the magnetic anomaly sources at different depth levels (100 m, 200 m, 500 m and 1000 m). This has helped to enhance the roots of deep magnetic sources. Thus, upward continuation maps are obtained (Fig. 11) at 100 m, 200 m, 500 m and 1000 m. Comparison with the map obtained in figure 10b shows changes in function of elevation.

The upward continuations to 100 m (Fig. 11a) and to 200 m (Fig. 11b) show only very slight variations compared to figure 10b. Similarly, weak and strongly magnetic fields, with positive anomalies but, also linear NE-SW and NW-SE strongly magnetic structures can be recognized. The upward continuations at 500 m (Fig. 11c) and 1000 m (Fig. 11d) however show some changes. In figures 11c-d, both the strongly magnetic sets and a new positive magnetic set (AP_3) can be observed in the northwest of the map. In addition, elongations of these magnetic domains are clearly visible with orientations towards the NW-SE (AP_2) and E-W (AP_1). One also notes the disappearance of the linear NW-SE structures in favour of those oriented NE-SW (AP_3).

Gradients

The particularity of these filters is to increase the contrasts between positive and negative anomalies. This allows to obtain three directional derivative maps according to X, Y and Z (Fig. 12a-c). Unlike the previous maps (Figs. 10, 11), they show the presence of new linear anomalies in addition to the existing ones. Indeed, figures 12a-c all show numerous linear and curvilinear structures strongly to weakly magnetic oriented in several directions (Fig. 12d). These different structures show NE-SW and NW-SE but also ENE-WSW to E-W preferential orientations.

Spectral analysis

The map of the analytical signal (AS) obtained from the application of the filter is represented in figure 13. On this map, important structures oriented in general NE-SW and NW-SE can be observed. They are possibly of the same nature since they have the same analytical signal (Milligan and Gunn, 1997). One can also note a perfect correlation with the gradient maps (Fig. 12) where these structures have been identified.

The tilt derivative map exhibits fair linear and curvilinear features at the edges of structures clearly showing their contours (Fig. 14). The signal/noise ratio is improved and most of the structures observable on the derivative maps (Fig. 12) are better highlighted. Therefore, no possible artefacts can be distinguished by comparison of both techniques. While the AS shows structures which have the same geometry and the same nature, once again corroborating the occurrence of the main massive bodies and linear structures (intrusions, faults/shears). The observation of the power spectrum (Spector and Grant, 1970) revealed three depths of the causative magnetic sources (Fig. 15). Generally, shallow depth of the sources, the maximum of which is about 425 m can be noticed. It can be interpreted as the roof of the basement knowing that the terrains are mainly composed of granitoids. The source of both depths estimated at 125 m and 55 m, respectively, can be interpreted as the potential causative source contacts of intrusions, fractures, fault structures, etc. and their host rocks.

Euler deconvolution

Outcrops exhibiting the different rocks types are rare (see Fig. 2b) and therefore we only present here the 3D Euler deconvolution solutions (3D-EDS) which concern the faults and dykes (Fig. 16). The 3D Euler deconvolution allowed to estimate the position and depth of the causative magnetic sources. Thus, the maps established at increasing depths were drawn over intervals of depths: (i) 50-75 m (Fig. 16a); (ii) 75-100 m (Fig. 16b); (iii) 150-200 m (Fig. 16c) and (iv) 300-400 m (Fig. 16d). Figures 16a-b could be clearly distinguished from the other figures as they show the NE-SW and NW-SE linear structures which can be interpreted as dykes or faults. This confirms the observations on the derivative (Fig. 12) and on the analytical signal (Fig. 13) maps. These structures are located at an average depth of 50 m to 200 m. In addition, from 200 to 250

m depths the structures begin to disappear, as shown in [figures 16c-d](#), this is why the processing of the 3D-EDS ceased at 400 m. This is well corroborated by the depths of the sources given by spectral analysis ([Fig. 15](#)).

5. Discussion

5.1 Aeromagnetic data and field observations integration

The combination of geophysical data and field observations made it possible to establish the first lithostructural map of the Doropo region ([Fig. 17](#)). This region comprises several lithologies which are largely dominated by granitoids such as biotite granite, gneissic and migmatitic granites, granodiorite and tonalite. They generally have low or moderate to high magnetic susceptibility values which vary from 0.01×10^{-3} to 17.1×10^{-3} SI. This could be explained by their mineralogical composition in ferromagnesian minerals and/or oxides or due to alteration. On the RTP and upward continuation maps, they display pseudo-circular to elliptical shaped which are also elongated NW-SE to E-W. They also show weakly to strongly foliation. According to these observations, the granitoid of the Doropo region could be linked to the granitoid types described by [Baratoux et al. \(2011\)](#), [Metelka, et al. \(2011\)](#) and [Block et al. \(2016\)](#) in northwestern Ghana and southern Burkina-Faso. Indeed, these authors subdivided these granitoids based on their: (i) mineralogical composition, (ii) magnetic response, (iii) geochemistry, (iv) age and (v) deformation which occurred during several magmatic events (ME_1 , ME_2 , ME_3 , etc.). These different groups of granitoids are generally characterized by a very pronounced foliation (ME_1 and ME_2), sometimes not deformed (ME_3), with generally (a) elongated to irregular (ME_1), (b) circular to elliptical (ME_2) or (c) elliptical to sigmoidal (ME_3) shapes.

In the presence of these granitoids, gabbro and amphibolites can be distinguished, which appear as enclaves dispersed on outcrops, and show a low to moderate magnetic intensity. The dolerite dykes mainly oriented NE-SW and NW-SE, were identified on aeromagnetic maps ([Figs. 12-14](#)) by their strong and linear signal (e.g., [Jessell et al., 2015](#); [Baratoux et al., 2019](#)), and confirmed in drill core samples. The rhyolite, never been documented in previous studies, was highlighted in the field, this suggests a local volcanic activity within a dominant granitoid domain. [de Kock et al. \(2011, 2012\)](#) has illustrated a crustal relaxation phase between the Eoeburnean and Eburnean phases which could explain the rhyolitic volcanism present in the Doropo area.

Furthermore, the presence of linear structures (mostly dykes, foliation, faults and shear zones) oriented NE-SW and NW-SE, as well as E-W were observed at different scales: (i) in the field

with tectonic structures showing stretching lineation (L_2) in granites, (ii) on aeromagnetic maps (derivatives including tilt derivatives, etc.), where curvilinear magnetic lineaments are observed in the southwest, while they are linear and oriented E-W in the north and east of the map. Together these findings show a good correlation between the structures observed in outcrops and aeromagnetic maps.

5.2 Tectonic and geodynamic implication

The Doropo region owes its structure to four deformation phases (D_1 , D_2 , D_3 and D_4) among which D_1 to D_3 played a major role. All of these deformation events have affected the granitoid terrains. The first deformation phase is characterized by a tectonic fabric obtained during recrystallization and migmatization. This D_1 deformation phase having generated: (i) a E-W S_1 foliation, (ii) conjugate sinistral and dextral shear zones oriented NE-SW and NW-SE, respectively and (iii) F_1 folds with plunging axis 45° towards the southwest. It is the result of a N-S compression which is less expressed in the region. This deformation phase has been reported in other areas of the Man-Leo Shield. It presents variations in terms of its manifestation due to lithological competence and the resulting structures. In addition, elsewhere in the WAC, D_1 has been distinguished by (i) major faults in Sefwi (Ghana), (ii) foliations and folds, (iii) thrusting (Baratoux et al., 2011; Metelka et al., 2011; Perrouty et al., 2012; Amponsah et al., 2015, 2016; Block et al., 2016; McFarlane et al., 2019; Nunoo et al., 2022), (iv) crenulation cleavage (D_3 : Baratoux et al., 2011; D_4 : Baratoux et al., 2015). In the Doropo region this crenulation cleavage was not observed. Block et al. (2016) interpreted this N-S shortening as being at the origin of significant crustal thickening which caused partial crustal fusion in northwestern Ghana.

This first deformation phase (D_1) is followed by a NW-SE transpressive phase (D_2) which is the most important in the Doropo region. It is also recognized as one of the major phases at the WAC scale: (i) Northwestern and Southwestern Ghana (Perrouty et al., 2012; Block et al., 2016; Nunoo et al., 2016; McFarlane et al., 2019), (ii) Northeastern Côte d'Ivoire (Vidal et al., 1996; Lüdtke et al., 1998, 1999), (iii) in Burkina-Faso (Baratoux et al., 2011; Metelka et al., 2011) and (iv) in the Kédougou-Kéniéba Inlier (KKI) in Sénégal (Dabo and Aïfa, 2010, 2011; Dabo et al., 2018). In our study area, it is distinguished by intense NE-SW oriented S_2 foliations, intrafolial F_2 folds, mineral stretching L_2 lineations slightly sloping towards the northeast, NE-SW oriented faults (highlighted on the aeromagnetic maps) plunging, and E-W shear zone. These large scale NE-SW oriented faults are affected by a later NNW-SSE faults. Furthermore, folding observed within granitoids could be explained by the deformation intensity which prevailed in the Doropo region.

1 The D₂ deformation phase is followed by two late phases: D₃ and D₄. D₃ seems to be responsible
2 for the shear bands, micro-folds as well as the S₃ foliation present in the granitoids. It is related
3 to NE-SW compression, described as late by [Vidal et al. \(1996\)](#) and [Block et al. \(2016\)](#). For
4 these authors, it is a compression which is most often accompanied by brittle deformation and
5 NW-SE crenulation cleavage. The D₄ deformation phase is characterized by a set of brittle
6 structures and also the emplacement of the NE-SW and NW-SE dolerite dykes. These dykes
7 may have been emplaced along the large NE-SW and NW-SE oriented faults which were
8 reactivated during this deformation event ([Vidal et al., 1996](#); [Lüdtke et al., 1998, 1999](#);
9 [Baratoux et al., 2019](#)).

10 Previous studies carried out in the WAC have shown that its Paleoproterozoic geodynamic
11 history took place as a polycyclic event characterized by horizontal shortening leading to
12 thickening of the crust followed by transcurrent tectonics forming regional shear zones (e.g.,
13 [Milési et al., 1989](#); [Baratoux et al., 2011](#); [Block et al., 2016](#); [Grenholm et al., 2019](#); [McFarlane
14 et al., 2019](#)). The different deformation phases (D₁-D₄) defined by shortening and shearing in
15 the Doropo area are in accordance with this polycyclic evolution in the WAC. However, the
16 stress regime related to these different deformation phases varies from one zone to another
17 within the WAC. In addition, the scarcity of the stretching lineations and the absence of
18 crenulation cleavage could be explained by: (i) the initial grain size in the deformed lithology
19 as well as the intensity of the flattening ([Piazolo and Passchier, 2002](#); [Baratoux et al., 2011](#);
20 [Teha, 2019](#)) and (ii) the competence of granitoids during the main deformation event.

21 The geodynamic evolution of the WAC is still a matter of debate. Some authors argue that
22 during the Eburnean, the tectonic regime that prevailed was dominated by vertical movements
23 and “dome and basin” structures ([Caby et al., 2000](#); [Pouclet et al., 2006](#); [Vidal et al., 2009](#);
24 [Lompo, 2010](#)). This tectonic regime is considered to be dominant during the Archean, and even
25 during the Lower Proterozoic ([Kouamelan et al., 1997b](#)). Another group of authors rather
26 attribute Eburnean events to a regime similar to that of plate tectonics, involving collisions
27 ([Feybesse and Milési, 1994](#); [Feybesse et al., 2006](#)). This argument is supported by [Baratoux et
28 al. \(2011, 2015\)](#) who proposed an assemblage of two eastern and western blocks in the Boromo
29 Belt (western Burkina-Faso). This amalgamation was initiated during an early N-S to NE-SW
30 shortening phase, well materialized in the eastern domain and absent in the western domain. It
31 probably corresponds to D₁ deformation phase and is a matter of debate. [Grenholm et al. \(2019\)](#)
32 go further by proposing a chronology of the main deformation events that affected the Birimian
33 crust during this collision phase. They proposed an early collisional phase, dated between 2.16
34 Ga and 2.12 Ga, characterized by compressional events both N-S and E-W oriented, and another

1 phase between 2.12 Ga and 2.07 Ga dominated by NW-SE oriented regional compression. All
2 these phases are responsible for the foliations, shear zones, faults, folds and thrusts that affected
3 the lithologies encountered in the Man Shield.

4 Structural data in the Doropo region show an area dominated by a transcurrent displacement
5 characterized by a 10°-30° NE-plunging stretching lineation during the NW-SE regional
6 compressional phase. These observations differ from vertical tectonics theory where
7 deformation patterns observed in the field do not match. Based on all these considerations, the
8 geodynamic model that could have prevailed in the Doropo region occurred in a collisional
9 tectonic context. During collisional phase, D₁ deformation would have occurred during the
10 Eoeburnean phase around 2.16-2.12 Ga along with a N-S compressional event, in an oceanic
11 arc context (Baratoux et al., 2015; Block et al., 2016). Further, (D₂-D₄) deformation phases took
12 place during the Eburnean phase after 2.12 Ga with a prevailing compressional event oriented
13 NW-SE (D₂), based on the geochronological results of Grenholm et al. (2019). The following
14 tectonic model can be suggested for the Doropo region: (i) a crustal thickening followed by
15 emplacement of granitoids in a magmatic arc context during the D₁ compressional phase (2.16-
16 2.12 Ga) (Fig. 18a), (ii) major shears and transcurrent faults occurred during the D₂
17 transpressional phase (2.12-2.07 Ga) (Fig. 18b) and finally (iii) a normal-transpressive
18 reactivation of the faults by dolerite dykes after 2.07 Ga and late granitic intrusions (Fig. 18c).

20 6. Conclusion

21 The geological investigations in the Doropo area have generated new lithological and structural
22 data for the northeastern part of Côte d'Ivoire. A new interpretative lithostructural map of the
23 region at 1:50,000 has been produced by coupling the aeromagnetic data to the field
24 observations.

25 Magnetic susceptibility measurements and the field observations complemented by drill core
26 samples made it possible to distinguish the following lithologies: (i) biotite granite, gneissic
27 and migmatitic granites, granodiorite and tonalite; (ii) gabbro, amphibolite and dolerite; and
28 (iii) rhyolite. All these lithologies were crosscut by pegmatites and quartz veins. Based on
29 adequate filtering on the aeromagnetic maps, the different limits of these formations could be
30 drawn. The spectral analysis and 3D Euler deconvolution maps helped in localizing and
31 estimating the depth of the causative sources of the major structures (faults, intrusions) between
32 50 m and 200 m.

33 The Doropo region was deformed by four tectonic phases: (i) N-S compressional phase (D₁)
34 characterized by an E-W foliation (S₁), conjugate dextral (NW-SE) and sinistral (NE-SW) shear

zones, and as well as F_1 folds with an E-W axial plane; (ii) most prominent NW-SE transpressional phase (D_2) responsible for the regional NE-SW foliation (S_2), slightly steep stretching L_2 lineation plunging towards the northeast, NE-SW faults, and E-W dextral shear zones; (iii) NE-SW compressional phase (D_3) marked by NW-SE foliation (S_3), NW-SE axial plane F_3 folds, and E-W sinistral shears, and finally (iv) late phase (D_4), responsible for brittle structures (faults, fractures, etc.) and also the emplacement of NE-SW and NW-SE dolerite dykes that intersecting all the lithologies of the region. These different deformation events suggest that the geodynamic model that has prevailed in the Doropo region was due to collisional tectonics. These new geological data are a contribution to previous studies in northeastern Côte d'Ivoire where no detailed geological study has been carried out for several decades. With the previous studies carried out in the neighboring regions of Ghana and Burkina Faso, they contribute to a better understanding of the WAC geodynamics.

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Table captions

Table 1: Synthesis of tectonic evolution highlighted during the different studies in the southern part of WAC (modified after [Baratoux et al., 2011](#)).

Table 2: Structural indexes of Euler deconvolution solutions according to geological models responsible for magnetic anomalies ([Reid et al., 1990](#)). SI: structural index, DS: depth to the surface, DC: depth to the centroid.

Table 3: Magnetic susceptibility values measured in the field (see Fig. 4) and in the laboratory (see Fig. 5) and their statistical processing ($10^{-3} SI$). N, Min, Max, Mean, St err, var, St Dev, Median, Geom Mean: number of samples, minimum, maximum and mean values, standard error, variance, standard deviation, median and geometric mean, respectively.

Figure captions

Fig. 1: Schematic geological map of the West African Craton. The inset shows the location map of the WAC (red square).

Fig. 2: (a) Geological map of the study area (modified from Tagini, 1971; Murray et al., 2019). Numbers represent shots of Figs. 6-9. (b) Details of the outcrop area with the sampling sites (stars).

Fig. 3: Field photographs of the main lithologies from the Doropo region. (a) Biotite granite, (b) Gneissic granite crossed by pegmatitic vein, (c) Migmatitic granite with mafic enclaves, (d) Outcrop of granodiorite, (e) Gabbro crossed by quartzofeldspathic vein, (f) Amphibolite with numerous thin quartz and feldspar veins, (g) Rhyolite boulders, and (h) Dolerite dyke in drill core.

Fig. 4: Histogram of the magnetic susceptibility values of the different lithologies measured in the field (in situ) on the following facies: (a) Biotite granite, (b) Gneissic granite, (c) Granodiorite, (d) Gabbro and (e) Amphibolite, with their Gaussian and density distributions.

Fig. 5: Histogram of the magnetic susceptibility values of the different lithologies measured in the laboratory on samples taken from the following facies: (a) Biotite granite, (b) Gneissic granite, (c) Granodiorite, (d) Gabbro, (e) Amphibolite, (f) Rhyolite, (g) Dolerite, with their Gaussian and density distributions and (h) normalized histogram of all these facies.

Fig. 6: Structures of the D_1 deformation observed in the field. (a) E-W Foliation (S_1) in the gneissic granite of Doropo; (b) F_1 Fold in the gneissic granite of Bouko; (c) NE-SW sinistral shear in the migmatitic granite of Lagbo; (d) NW-SE dextral shear in the gneissic granite of Doropo and (e) Directional rose diagram of major structures in the field. The tip of the compass indicates the North direction on the different field photos.

Fig. 7: Representative structures of the D_2 deformation. (a) NE-SW Foliation (S_2) within the gneissic granite of Bouko; (b) Stretching L_2 lineation within Bouko's gneissic granite; (c) E-W dextral shear observed at Bouko and (d) S-C fabrics in the Lagbo's migmatitic granite; (e) Directional rose diagram of the major structures in the field.

Fig. 8: Structures of the D_3 deformation. (a) NW-SE Foliation (S_3) in the migmatitic granite of Lagbo; (b) WNW-ESE sinistral shear in Lagbo migmatitic granite; (c) F_3 Fold with an NW-

SE axial plane observed at Gbatedjou and **(d)** directional rose diagram of the S_3 foliation. P denotes the axial plane of the fold.

Fig. 9: Structures of the D_4 deformation. **(a)** Microgranite dyke dextrally shearing a pegmatite dyke; **(b)** Conjugated fractures within the Gbatedjou microgranite; **(c)** Fault mirror with subhorizontal slickenslide lineations reflecting a sinistral shear; **(d)** Fracture plan showing an infill with epidote or chlorite. Directional rose diagrams for the analyzed structures are also given.

Fig. 10: **(a)** Map of the total magnetic field using shaded relief technique ($I = 45^\circ$ and $D = 45^\circ$); **(b)** Map of the magnetic field reduced to pole. Ap_1 - Ap_3 and An_1 - An_3 are positive and negative magnetic anomalies, respectively.

Fig. 11: Upward continuation maps at **(a)** 100 m, **(b)** 200 m, **(c)** 500 m and **(d)** 1000 m. Same notations as in Fig. 10.

Fig. 12: Gradient maps according to **(a)** X; **(b)** Y; **(c)** Z and **(d)** Structural sketch related to faults, shears, dykes and magnetic lineaments superimposed on the derivative map according to Y.

Fig. 13: Analytical signal map showing geological bodies of the same nature. Areas within the white dotted lines show NW-SE and NE-SW oriented structures.

Fig. 14: Map of the Tilt Derivative showing linear (faults, shears) and massive structures with curvilinear magnetic lineaments (white lines).

Fig. 15: Power spectral diagram (Spector and Grant, 1970) showing three possible depths of the causative sources at 55 m, 125 m and 425 m.

Fig. 16: Map of the 3D Euler deconvolution solutions for depth plans in the ranges **(a)** 50-75 m: shows NE-SW and NW-SE oriented linear structures; **(b)** 75-100 m: highlights the same linear structures as in **(a)**; **(c)** 150-200 m: the linear structures tend to disappear except some NE-SW structures (e.g., northwestern the map) and **(d)** 300-400 m: all linear structures disappeared.

Fig. 17: Lithostructural map of the Doropo region (reduction of the 1:50,000 scale map).

Fig. 18: Tectonic model proposed for the Doropo region during the Eburnean. **(a)** crustal thickening and emplacement of granitoids, **(b)** occurrence of oblique shears, **(c)** reactivation of faults and magmatic inflows. Red arrow indicates the σ_1 direction.

1

2 **Highlights**

3

4 • Four deformation phases (D₁-D₄) recognized in northeast of Côte d'Ivoire.

5 • Evidence of NE-SW and NW-SE dolerite dykes and shear zones from aeromagnetic maps.

6 • Causative magnetic sources at 55 m, 125 m and 425 m depths identified using spectral analysis
7 and 3D Euler deconvolution solutions.

8 • New lithostructural map of the Doropo region at a scale of 1:50,000 derived from field
9 observations and aeromagnetic data processing.

10 • Proposition of a geodynamic model evolution for the Doropo region.

Table 1

Authors	Location	Tectonic evolution
Milési et al. (1989)	Man-Leo shield	Birimian flysch sediment deposition followed by volcanism
		D ₁ : Tectonic Nappe, ENE-suture between Archean and Proterozoic terranes (Burkinian cycle)
		D ₂ : N-E folds, N to N-E shear zones (Birimian cycle), transpression
		D ₃ : N-E shear zones and crenulation cleavage
Vidal et al. (1996)	N-E Côte d'Ivoire	Ante-Birimian (Dabakalian) deposition
		D ₁ : Metamorphic fabric, gently dipping crenulation cleavage (Dabakalian)
		D ₂ : N-E folds
		D ₃ : N-S sinistral and WNW shear zones, transpression
Lüdke et al. (1998)	N-E Côte d'Ivoire	D ₄ : WNW crenulation cleavage, S-thrusting
		D ₀ : Volcanism and deposition sediment Birimian
		D ₁ : Juxtaposition of low and high grade metamorphic, NNE steep shear zones
		D ₂ : N-E folds, NNE sinistral shear zones, metamorphic fabric
Feybesse et al. (2006)	Ghana	D ₃ : NE-SW shear zones and E-shear zones, crenulation cleavage
		D ₄ : Reactivation of existing structures, N-E dolerite dykes
		Volcano-plutonism, Birimian flysch sediment deposition
Hein (2010)	Goren greenstone belt (Burkina-Faso)	D ₁ : Crustal thickening by nappe stacking, shearing to the N-W
		D ₂ -D ₃ : N-E sinistral shear zones, WNW shortening brittle shearing. Steep folds, crenulation cleavage
		Volcanism and deposition sediment (Birimian)
		D ₁ : N-W to NNW folds, thrust faults (Tangaen)
Baratoux et al. (2011)	Western Burkina-Faso	D ₂ : NNE to N-E sinistral shear zones, metamorphic fabric, crenulation cleavage
		D ₃ : WNW dextral thrust faults, E-W folds. Following by mafic dykes (250 Ma)
		Early Eburnean extensional deformation: ca. 2200-2160 Ma, volcanic arc, Birimian sediment deposition
		Early Eburnean ca. 2170-2160 Ma
		D ₁ : ca. 2160-2120 Ma, N-E metamorphic fabrics, shear zones, isoclinal folds WNW-ESE compression
		Late D ₁ : ca. 2120-2110 Ma, detrital sedimentary deposition (Tarkwaian), E-W transtension
		D ₂ : ca. 2110-2109 Ma, N-S to ENE steep shear zones, N-W faults, NW-SE transpression

Perrouty et al. (2012)	Southern Ashanti Belt (Ghana)	D ₃ : Post-2109 Ma, E-W crenulation cleavage, N-W-faults, thrusts, N-S compression
		Mafic dykes: post-2109 Ma, NE-SW, NW-SE and WNW-ESE extension
		Sefwi group volcanism and sedimentation
		D ₁ : N-S shortening, regional scale folding in the Sefwi group, possible gold mineralization
		D ₂ : Extension phase (2154-2125 Ma), Kumasi group sedimentation
		Tarkwa Basin formation (2107-2097 Ma) / D ₃ : Km scale folds in Birimian and Tarkwaian, NE-SW subvertical crenulation cleavage, thrust faults (Ashanti, Damang, ...), peak of metamorphism (2092 Ma)
		D ₄ : NNW-SSE shortening, sinistral shear reactivation of D ₃ thrust, ENE-WSW crenulation cleavage, greenschist retrograde metamorphism, remobilization and concentration of gold particle along the shear zones and at the base of Tarkwa Basin
		D ₅ : Recumbent folds (< m), subhorizontal crenulation cleavage, last pyrite/gold mineralization associated with quartz vein
Block et al. (2016)	N-W Ghana	D ₆ : Shortening NE-SW, low amplitude folds + crenulation cleavage ~N320°/70° (RH), reverse faults oriented NW-SE
		Relics of early deformation
		D ₁ : N-S shortening, penetrative fabric associated with shear zones and large-scale folds
		D ₂ : N-S extension, moderate foliation dip (40-50°), stretching lineation plunging down-dip
		D ₃ : E-W shortening, subvertical schistose cleavage, axial planar to isoclinal or ptygmatic folds, high-strain shear bands
		D ₄ : ENE-WSW shortening and localized sinistral strike-slip shearing, activation of the Jirapa and Jan shear zones under a dominant sinistral strike-slip regime, subhorizontal lineation
		D ₅ : E-W shortening and localized dextral strike-slip shearing, subvertical dextral strike-slip shear zones
		D ₆ : E-W shortening, brittle deformation, E-W quartz tension gashes, conjugate brittle strike-slip faults
McFarlane et al. (2019)	Sefwi Greenstone Belt (Ghana)	D ₇ : NE-SW shortening, brittle deformation, NW-SE subvertical crenulation cleavage
		D ₁ : NNW-SSE Shortening, isoclinal folding, thrusting, high-grade metamorphism, and late-stage partial melting
		D ₂ : ENE-WSW transtension, tight to open folds, stretching lineation, S-C fabrics, NE-subvertical foliation
		D ₃ : E-W shortening, N-S-subvertical crenulation cleavage, axial planar to open gently north-plunging folds, sinistral drag folds, NE-SW S-C fabric
		D ₄ : NW-SE shortening, brittle ductile deformation and NNE-SSW sinistral shear zones
		D ₅ : WNW-ESE shortening, Riedel shear zones, late NW-SE, NE-SW and E-W structures which form conjugate faults

Table 2

Geological model	SI	Depth type
Deep depth contact or high fault offset	0	DS
Contact/limit/fault	0.5	DS
Layer limit (dyke, oblique intrusion, BIF, etc.)	1	DS
Linear sources (pipe, narrow kimberlitic chimney, etc.)	2	DC
Sphere or compact body	3	DC

Table 3

Facies	N	Min	Max	Mean	St err	Var	St Dev	Median	Geom Mean
Amphibolite	30	0.01	0.35	0.1286667	0.01775784	0.00946023	0.09726371	0.1	0.08844865
Dolerite	12	0.009	26.1	11.99658	2.458064	72.50497	8.514985	10.045	6.010357
Gabbro	30	0.03	0.23	0.1116667	0.01020574	0.003124713	0.05589913	0.11	0.09744356
Biotite Granite	222	0.01	12.2	1.593964	0.1099113	2.681867	1.637641	1.175	0.7078828
Gneissic Granite	30	0.55	9.98	3.683667	0.5145313	7.942272	2.818204	2.655	2.673775
Granodiorite	48	0.07	4.33	1.173542	0.1526702	1.118794	1.05773	0.96	0.663975
Rhyolite	30	0.009	1.5	0.1800333	0.06720845	0.1355093	0.3681158	0.02	0.0389743
Amphibolite	7	0.003	0.97	0.2991429	0.121254	0.1029178	0.3208081	0.184	0.1389352
Gabbro	8	0.22	0.36	0.289375	0.01677151	0.002250268	0.04743699	0.293	0.2858414
Biotite Granite	114	0.025	17.1	4.02286	0.3115148	11.06273	3.326068	3.985	0
Gneissic Granite	27	0.093	12.9	4.303963	0.602029	9.785851	3.128234	4.59	2.750815
Granodiorite	11	1.59	7.73	4.801818	0.5793803	3.692496	1.921587	4.42	4.403127

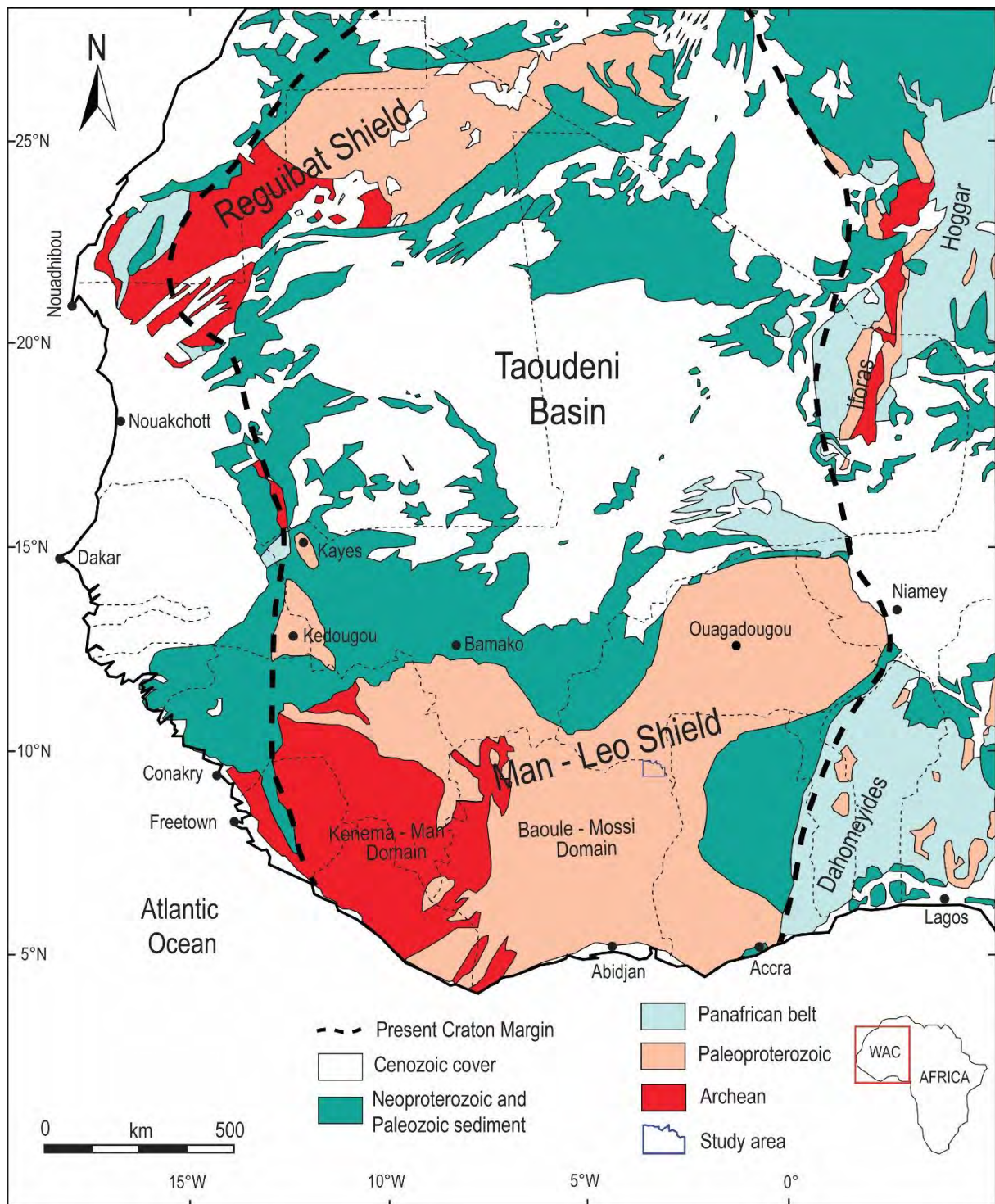


Fig. 1. Schematic geological map of the West African Craton. The inset shows the location map of the WAC (red square).

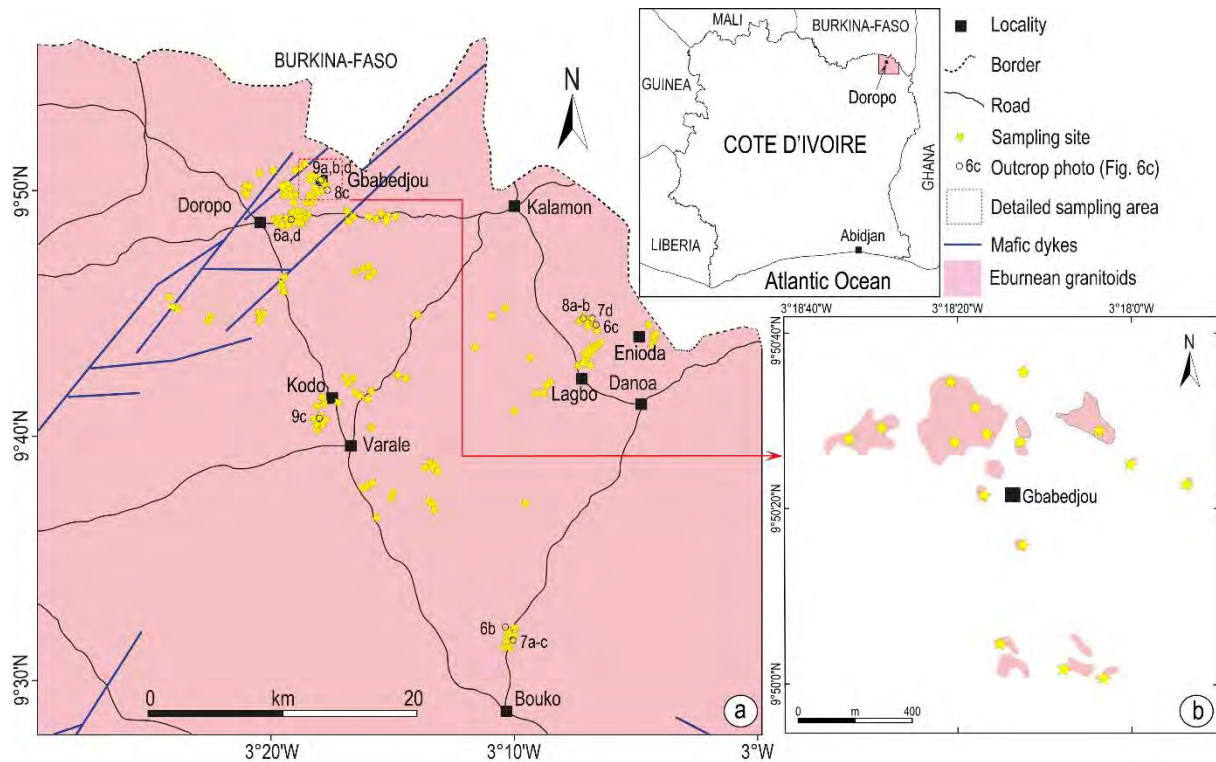


Fig. 2. (a) Geological map of the study area (modified from Tagini, 1971; Murray et al., 2019). Numbers represent shots of Figs. 6-9. (b) Details of the outcrop area with the sampling sites (stars).

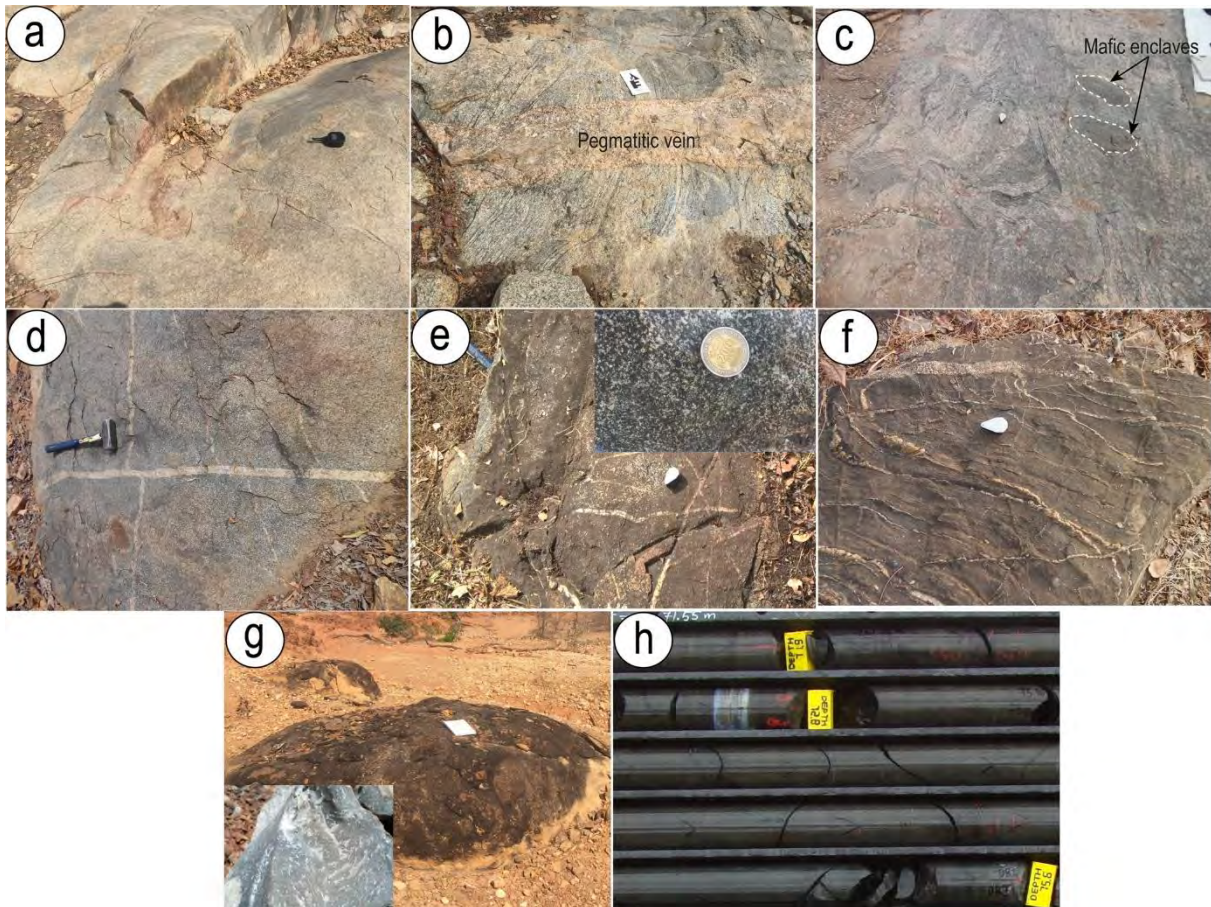


Fig. 3. Field photographs of the main lithologies from the Doropo region. (a) Biotite granite, (b) Gneissic granite crossed by pegmatitic vein, (c) Migmatitic granite with mafic enclaves, (d) Outcrop of granodiorite, (e) Gabbro crossed by

quartzofeldspathic vein, (f) Amphibolite with numerous thin quartz and feldspar veins, (g) Rhyolite boulders, and (h) Dolerite dyke in drill core.

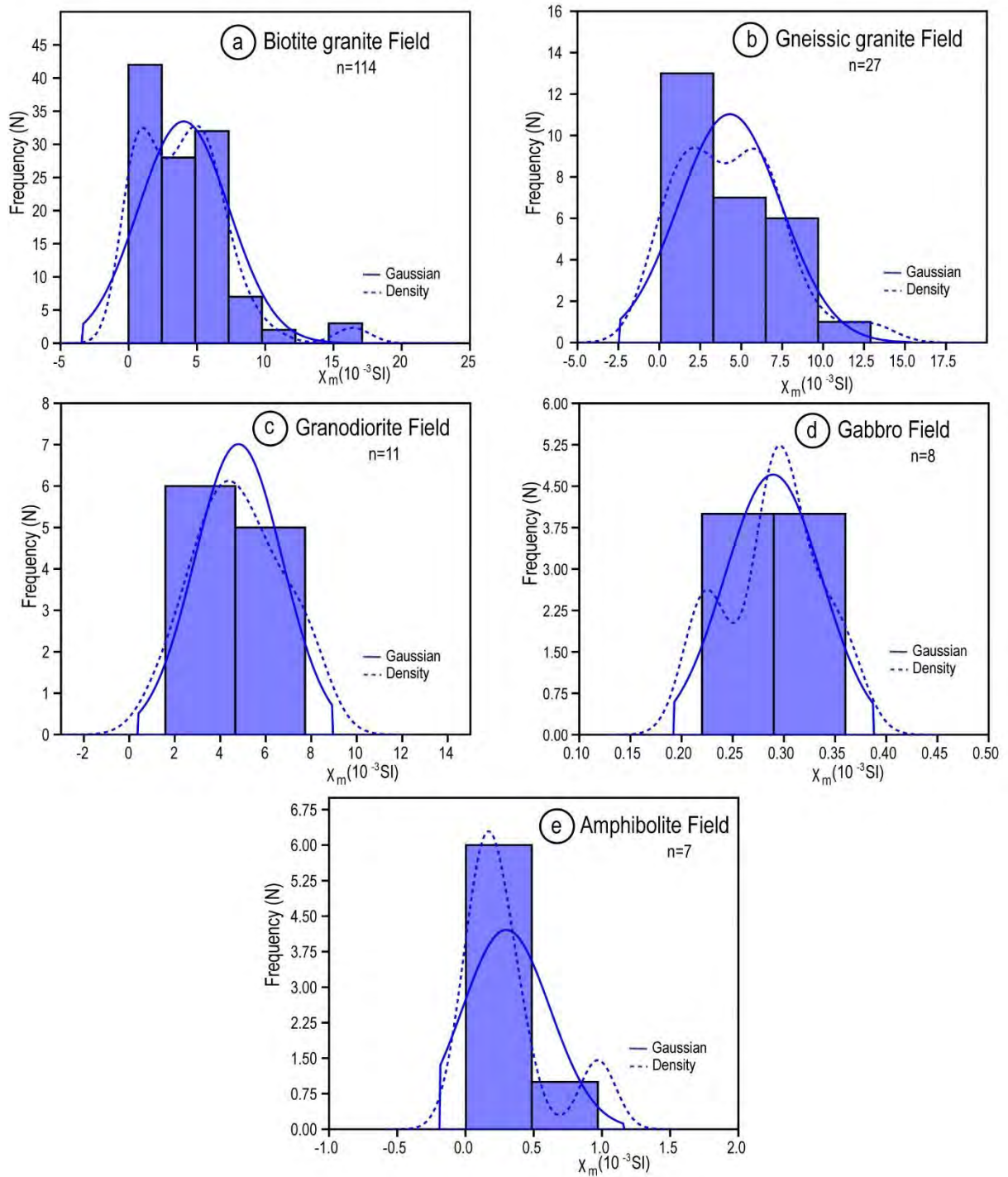


Fig. 4. Histogram of the magnetic susceptibility values of the different lithologies measured in the field (in situ) on the following facies: (a) Biotite granite, (b) Gneissic granite, (c) Granodiorite, (d) Gabbro and (e) Amphibolite, with their Gaussian and density distributions.

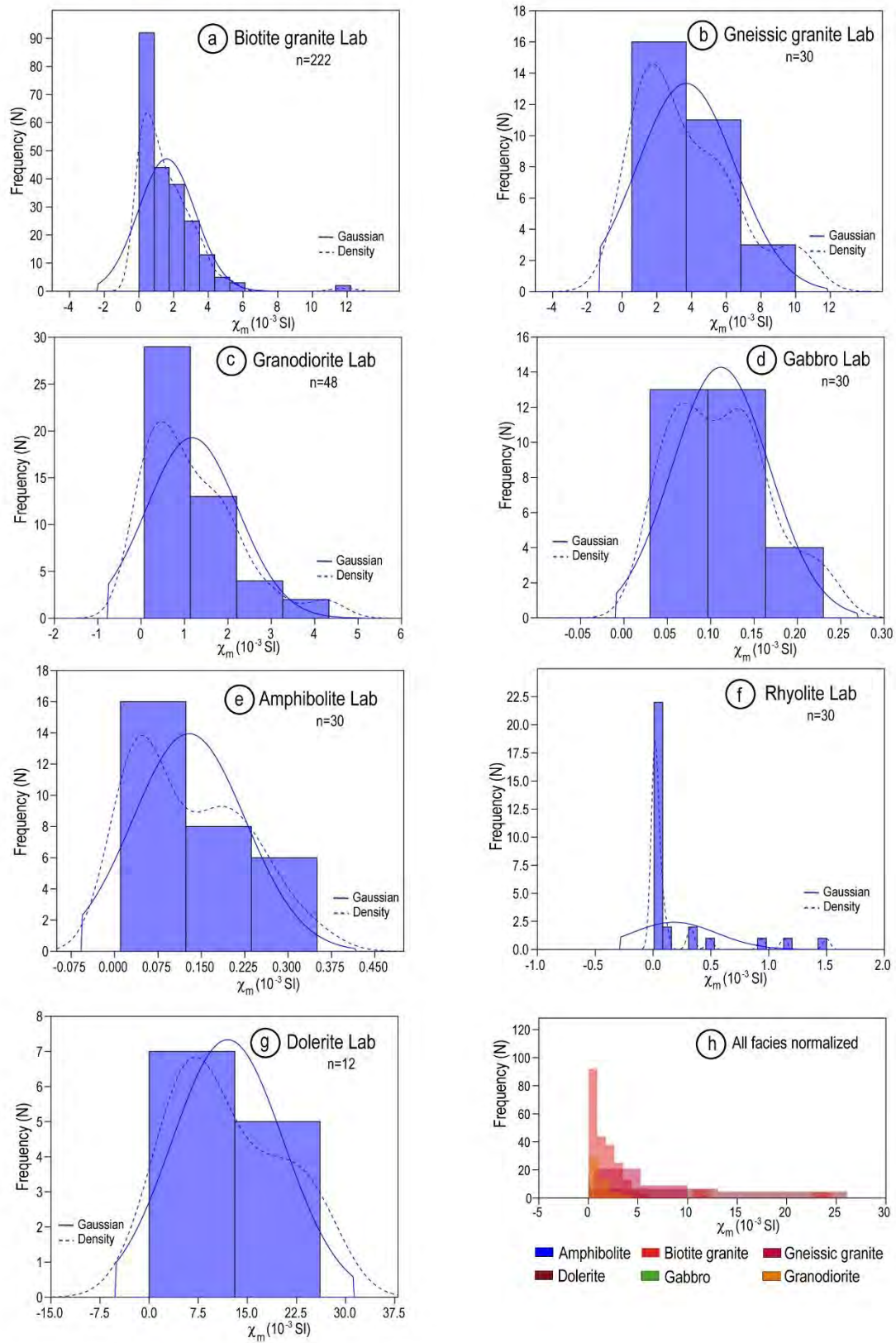


Fig. 5. Histogram of the magnetic susceptibility values of the different lithologies measured in the laboratory on samples taken from the following facies: (a) Biotite granite, (b) Gneissic granite, (c) Granodiorite, (d) Gabbro, (e) Amphibolite, (f) Rhyolite, (g) Dolerite, with their Gaussian and density distributions and (h) normalized histogram of all these facies.

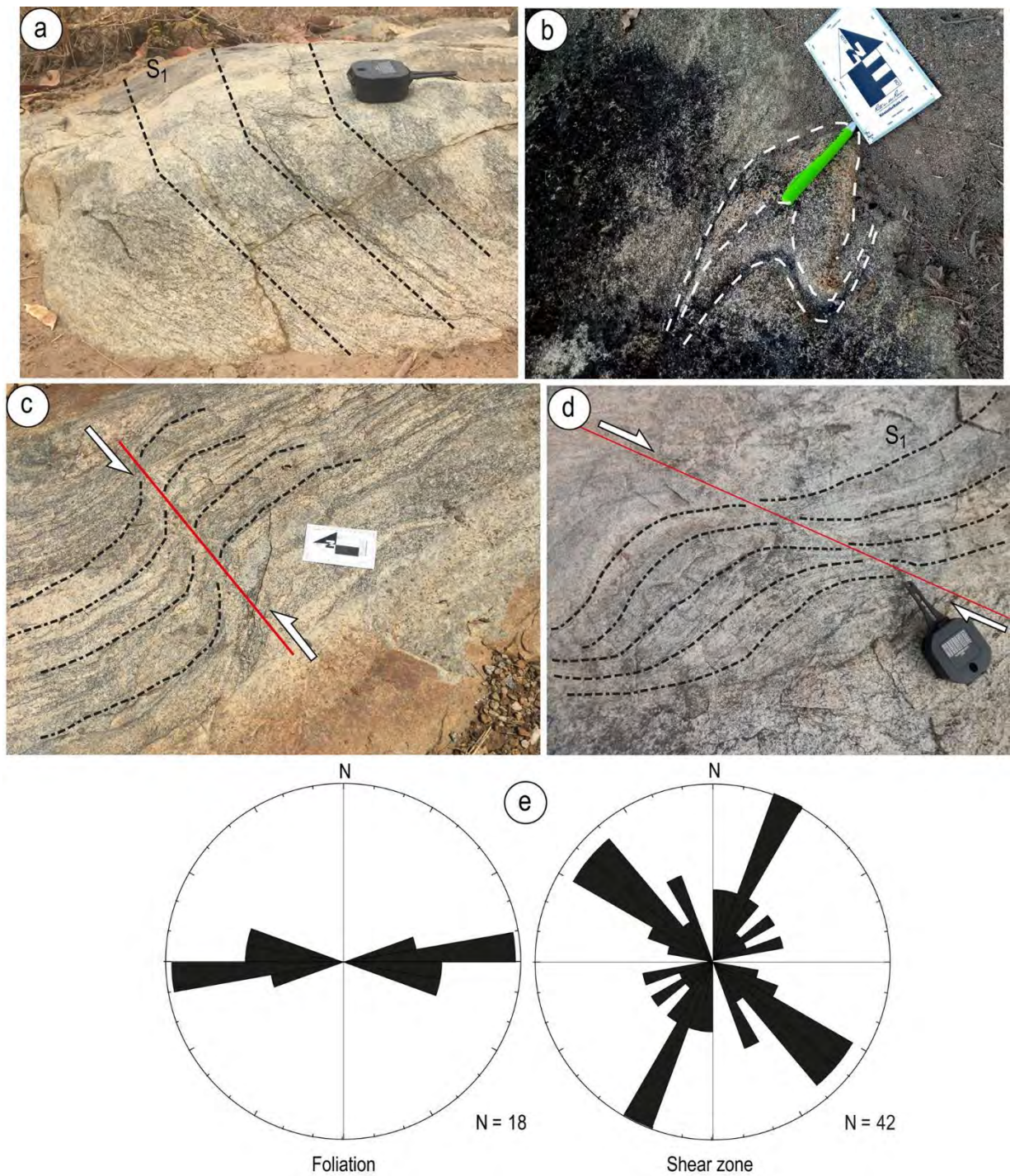


Fig. 6. Structures of the D₁ deformation observed in the field. (a) E-W Foliation (S₁) in the gneissic granite of Doropo; (b) F₁ Fold in the gneissic granite of Bouko; (c) NE-SW sinistral shear in the migmatitic granite of Lagbo; (d) NW-SE dextral shear in the gneissic granite of Doropo and (e) Directional rose diagram of major structures in the field. The tip of the compass indicates the North direction on the different field photos.

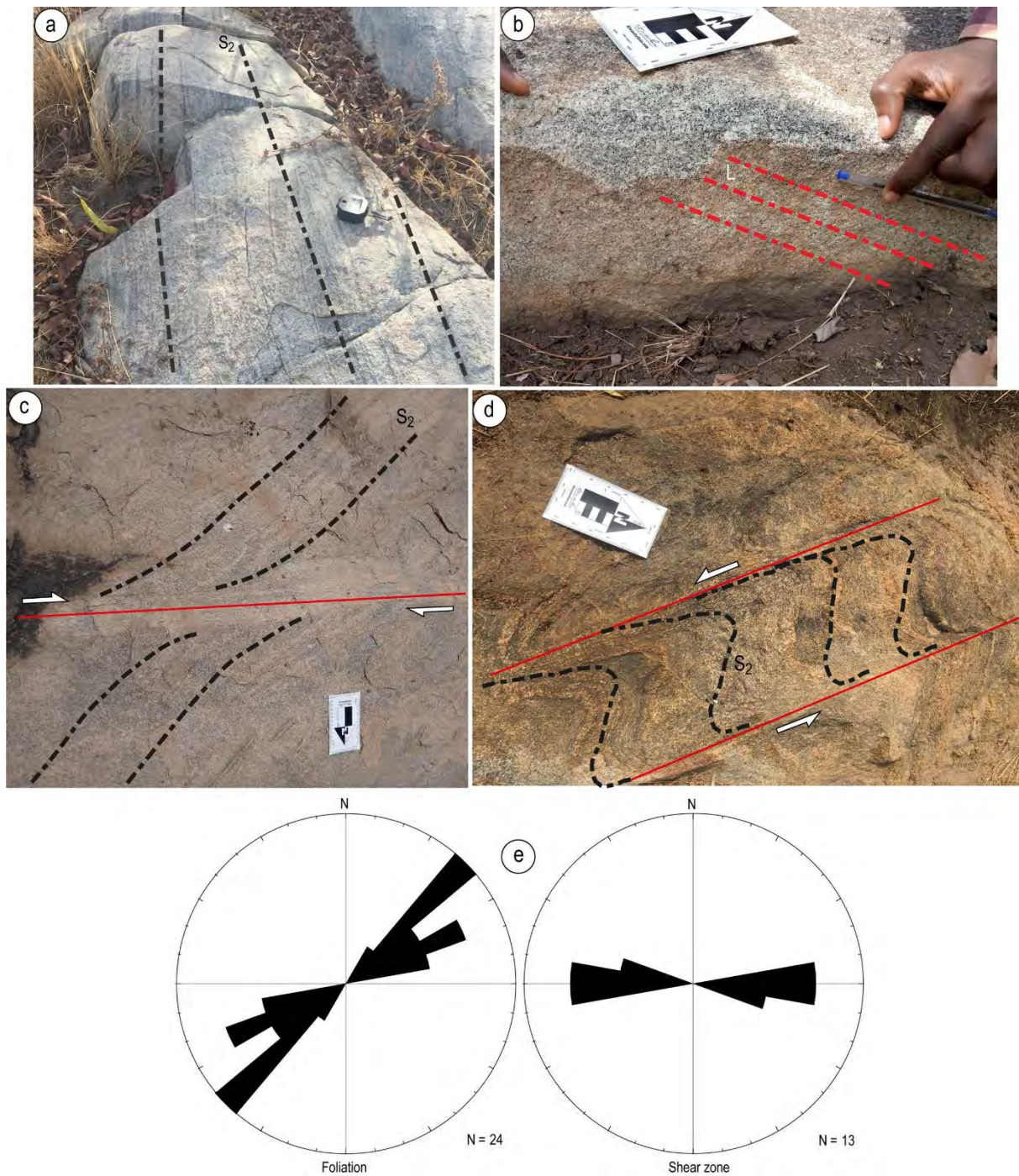


Fig. 7. Representative structures of the D₂ deformation. (a) NE-SW Foliation (S_2) within the gneissic granite of Bouko; (b) Stretching L_2 lineation within Bouko's gneissic granite; (c) E-W dextral shear observed at Bouko and (d) S-C fabrics in the Lagbo's migmatitic granite; (e) Directional rose diagram of the major structures in the field.

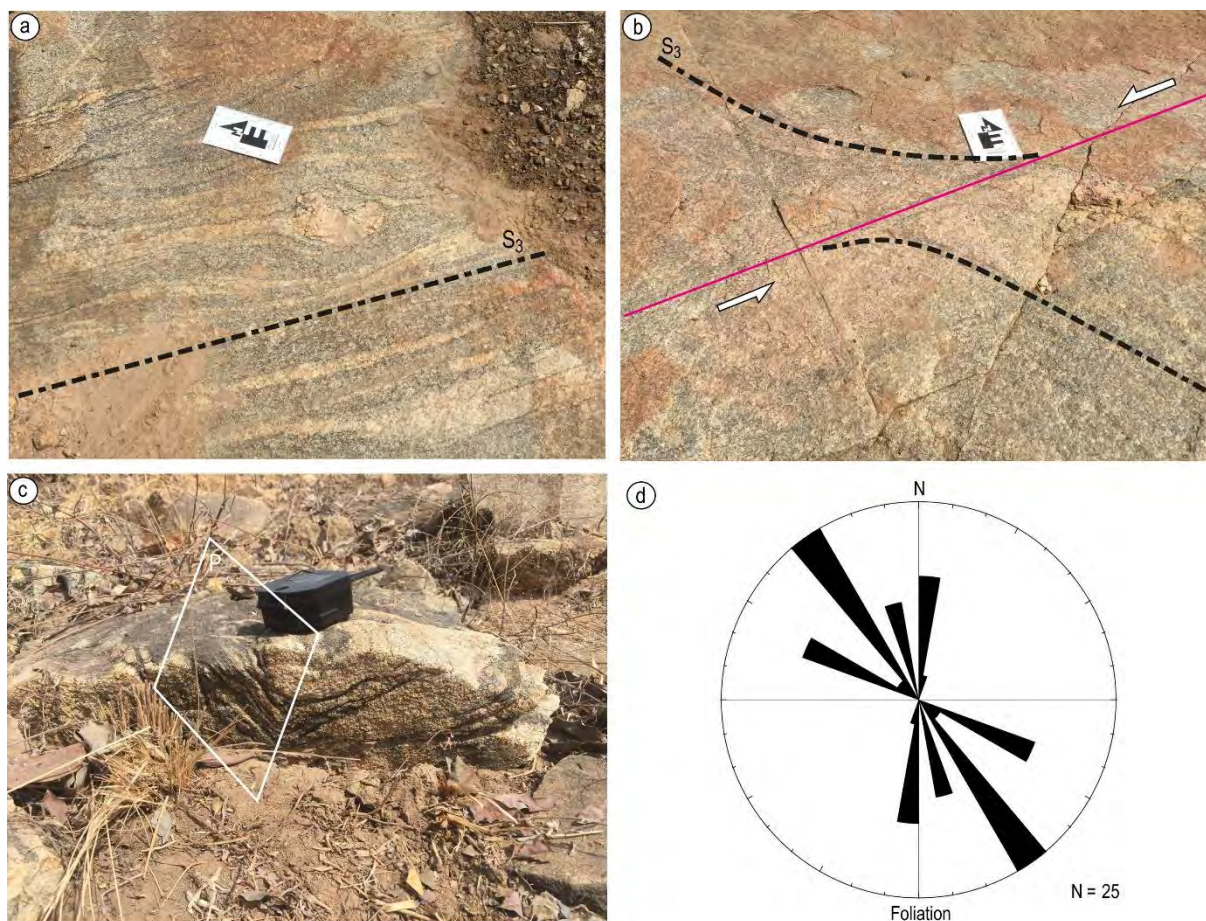


Fig. 8. Structures of the D₃ deformation. (a) NW-SE Foliation (S₃) in the migmatitic granite of Lagbo; (b) WNW-ESE sinistral shear in Lagbo migmatitic granite; (c) F₃ Fold with an NW-SE axial plane observed at Gbatedjou and (d) directional rose diagram of the S₃ foliation. P denotes the axial plane of the fold.

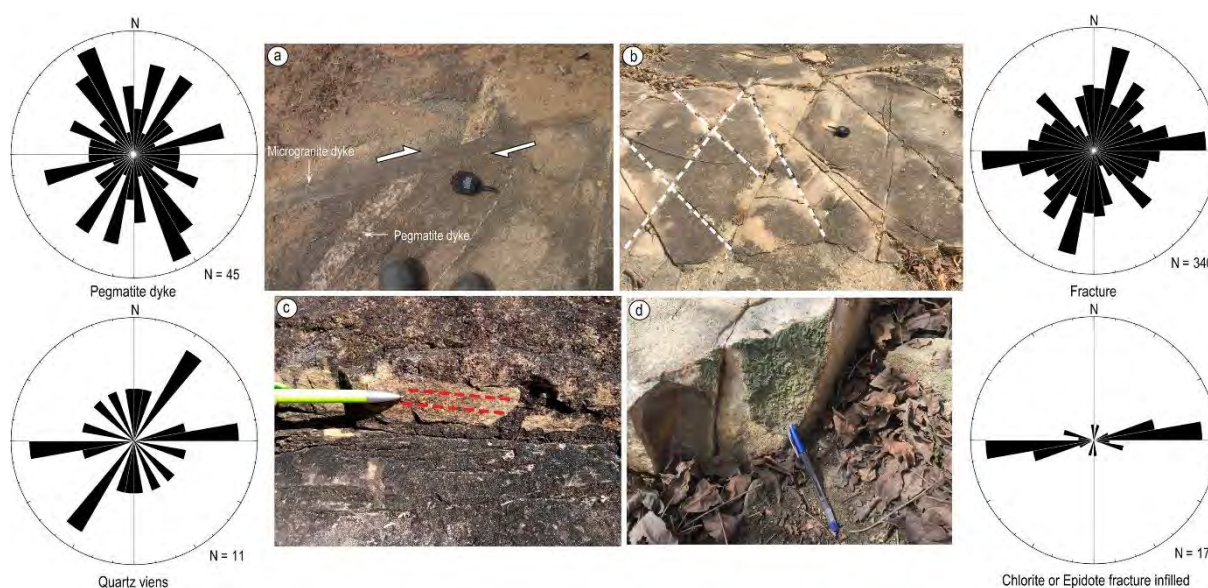


Fig. 9. Structures of the D₄ deformation. (a) Microgranite dyke dextrally shearing a pegmatite dyke; (b) Conjugated fractures within the Gbatedjou microgranite; (c) Fault mirror with subhorizontal slickenslide lineations reflecting a sinistral shear; (d) Fracture plan showing an infill with epidote or chlorite. Directional rose diagrams for the analyzed structures are also given.

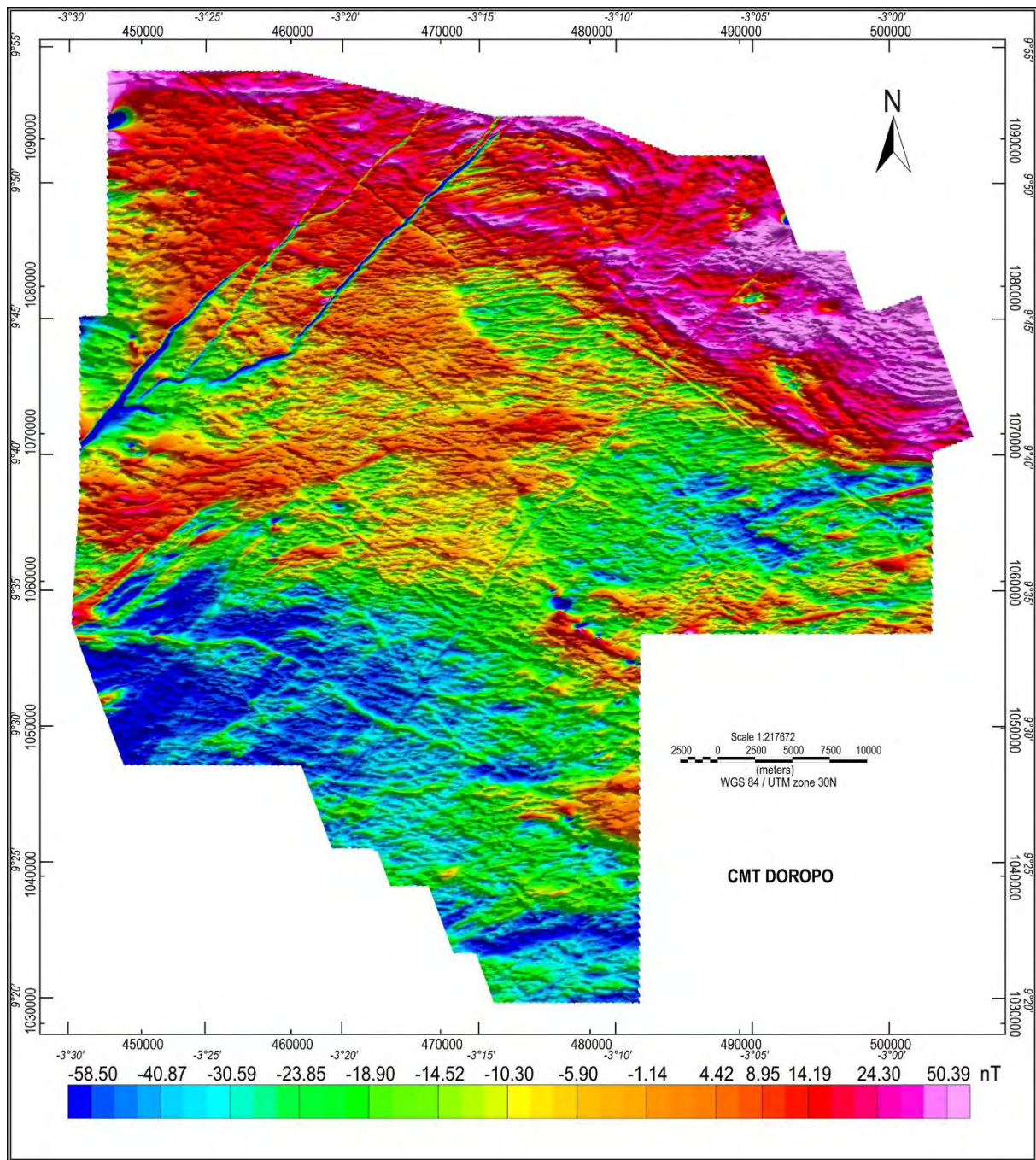


Fig. 10a. Map of the total magnetic field using shaded relief technique ($I = 45^\circ$ and $D = 45^\circ$).

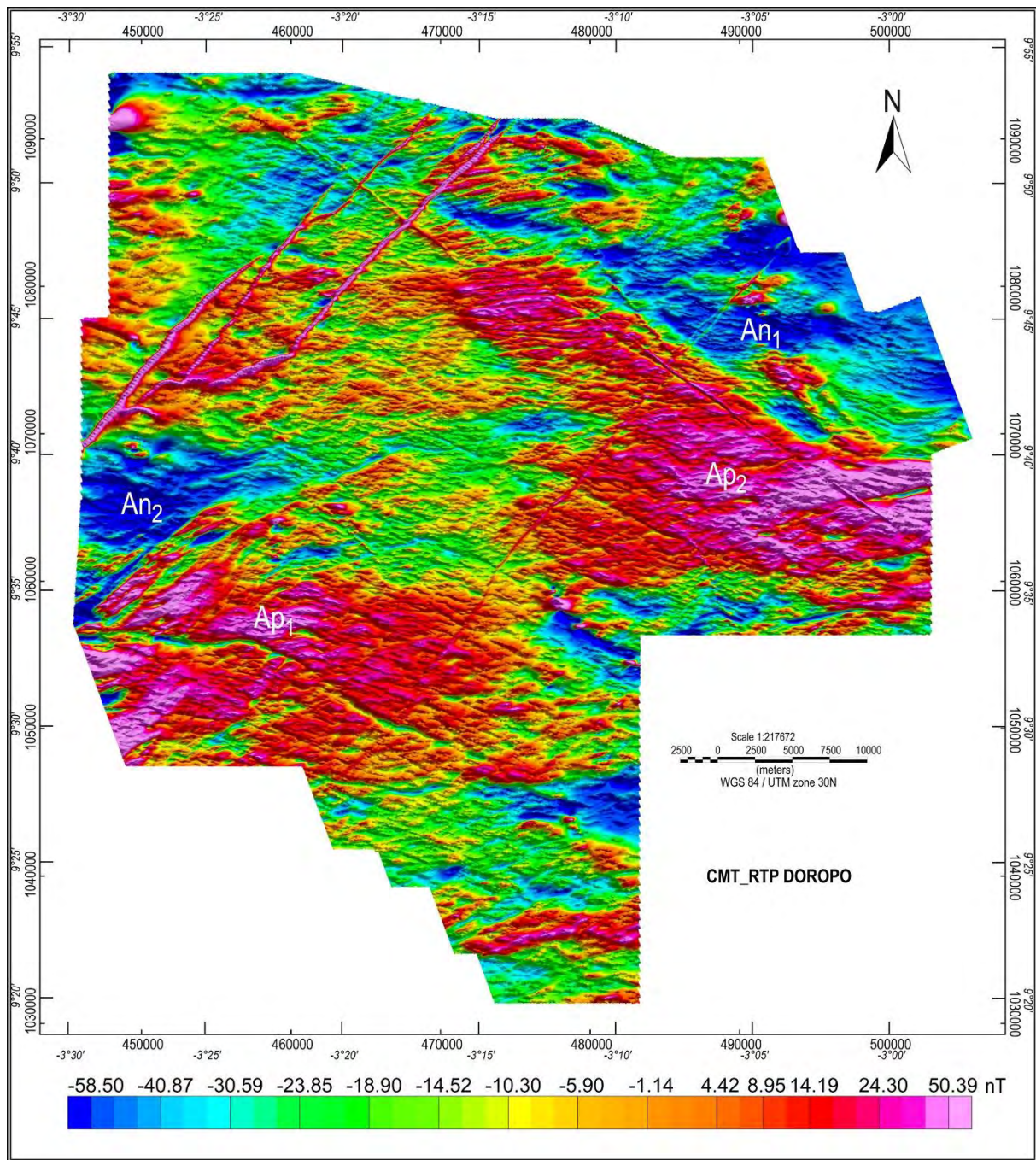


Fig. 10b. Map of the magnetic field reduced to pole. Ap_1 - Ap_3 and An_1 - An_3 are positive and negative magnetic anomalies, respectively.

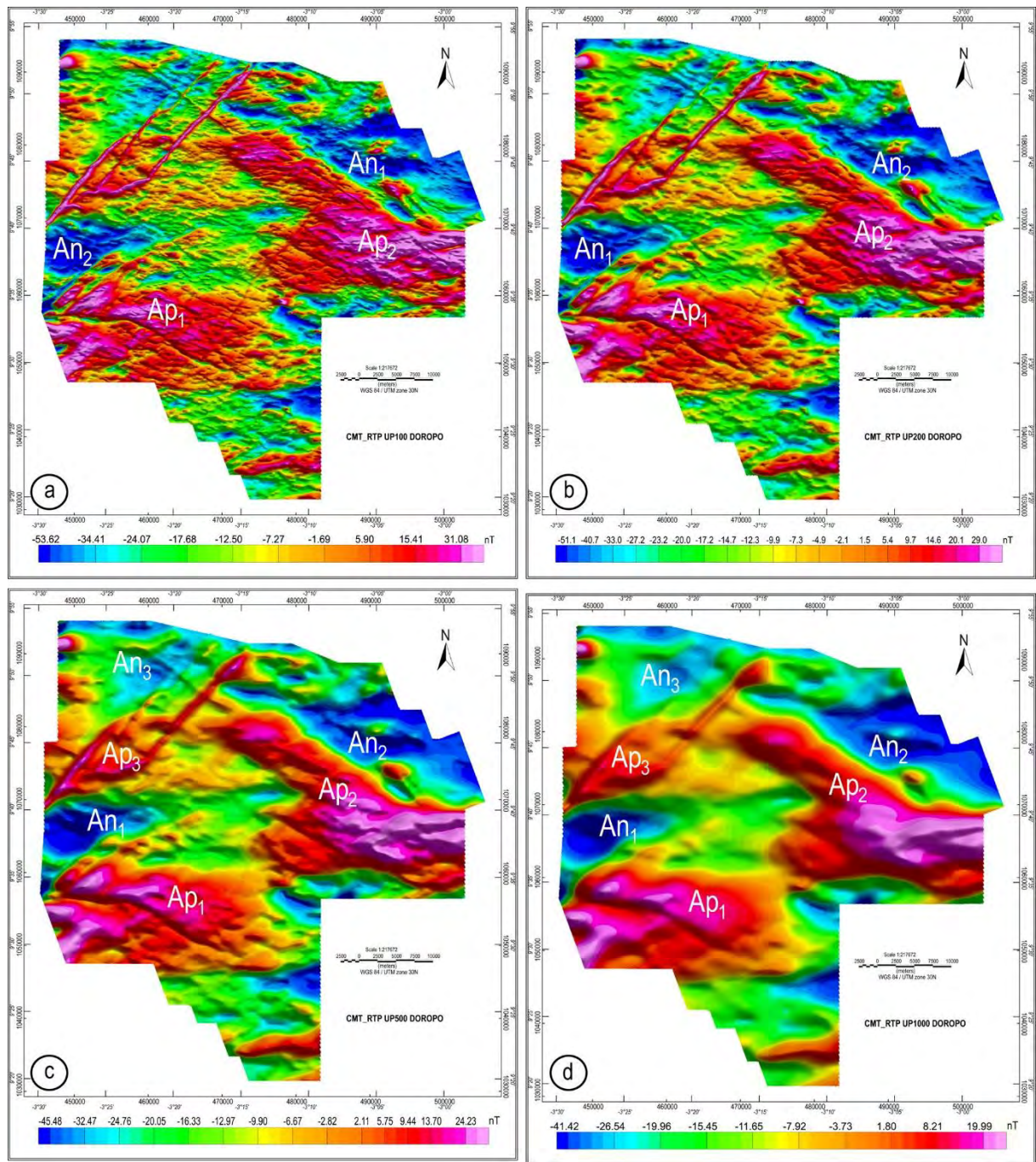


Fig. 11. Upward continuation maps at (a) 100 m, (b) 200 m, (c) 500 m and (d) 1000 m. Same notations as in Fig. 10.

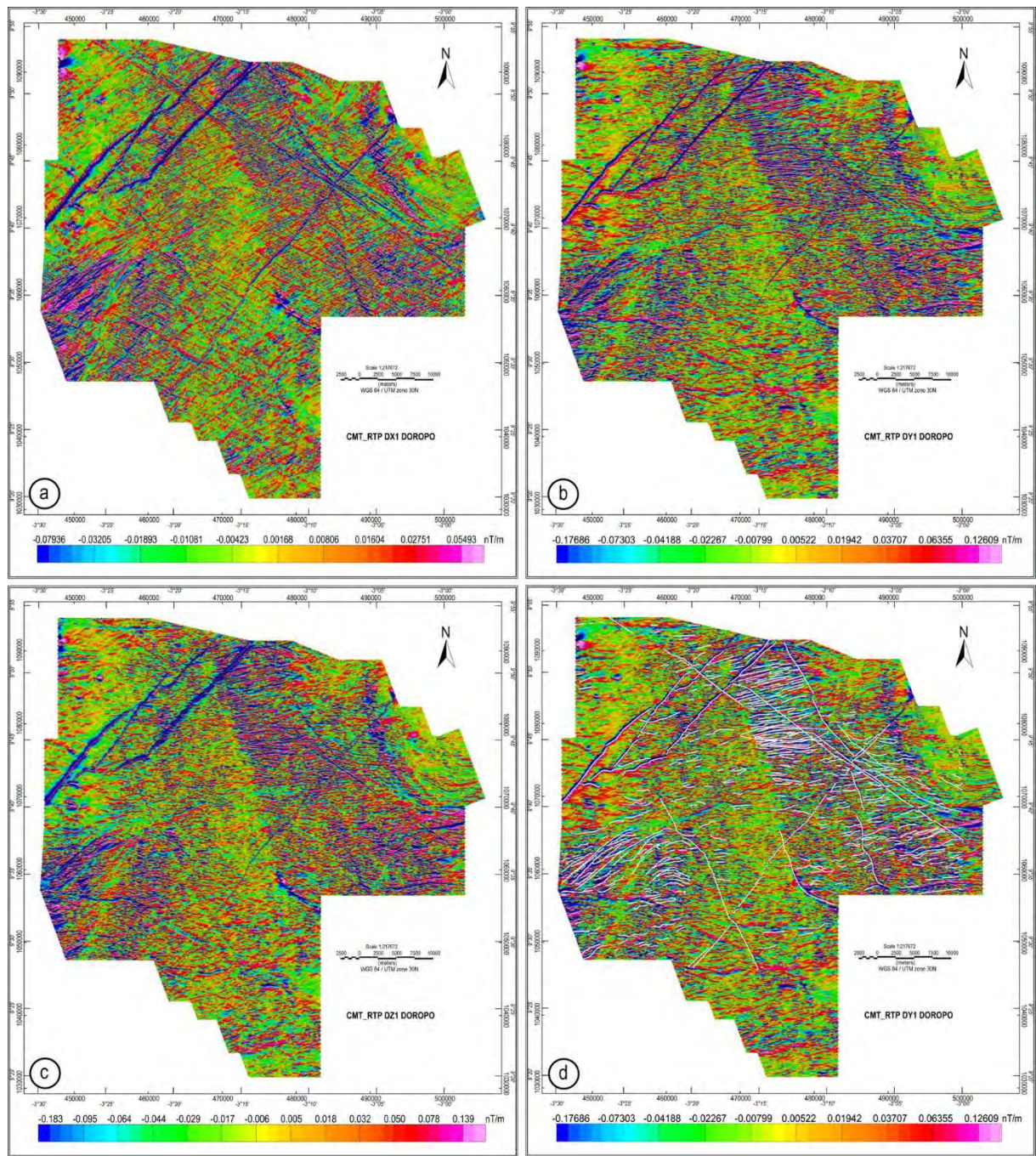


Fig. 12. Gradient maps according to (a) X; (b) Y; (c) Z and (d) Structural sketch related to faults, shears, dykes and magnetic lineaments superimposed on the derivative map according to Y.

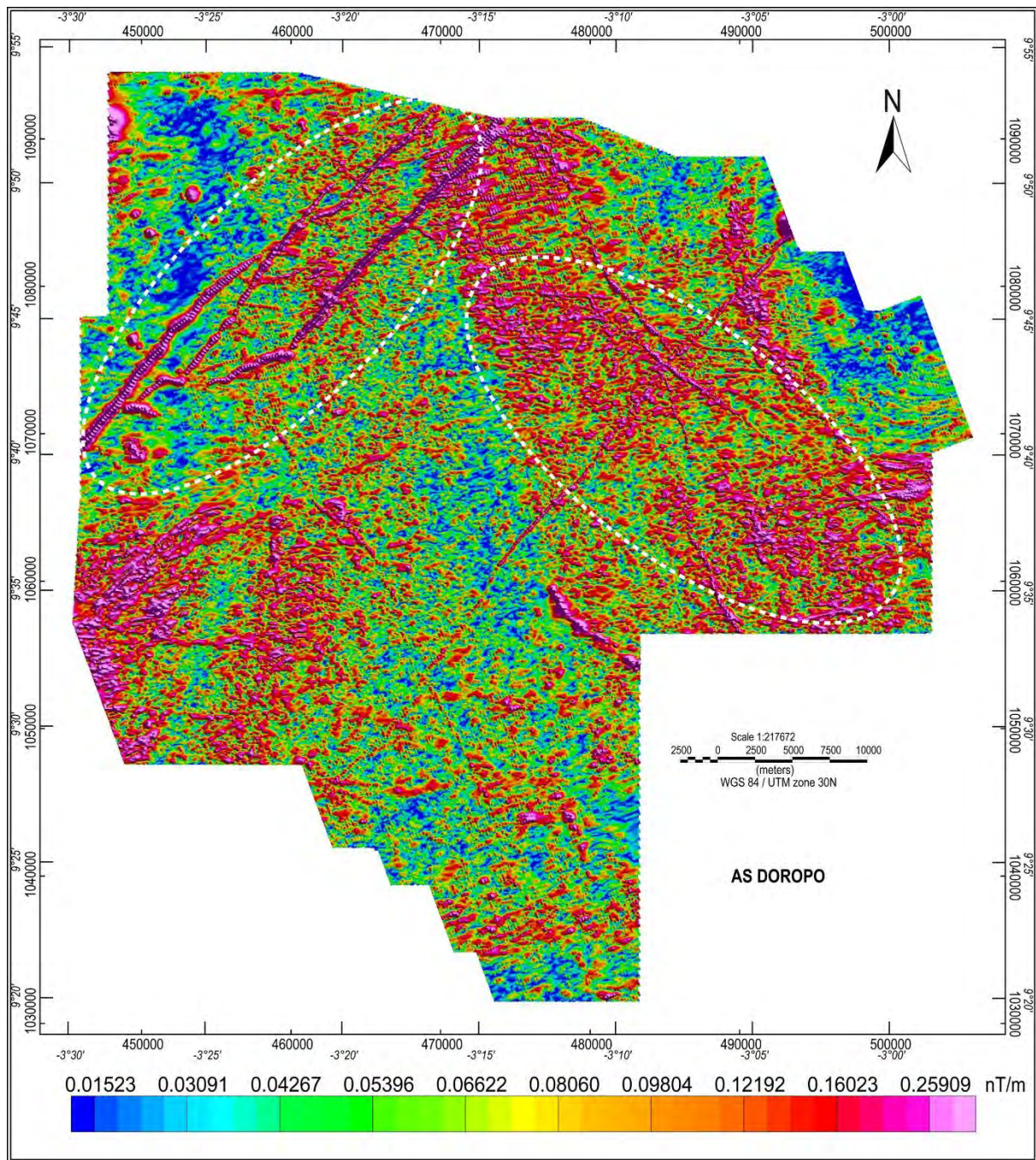


Fig. 13. Analytical signal map showing geological bodies of the same nature. Areas within the white dotted lines show NW-SE and NE-SW oriented structures.

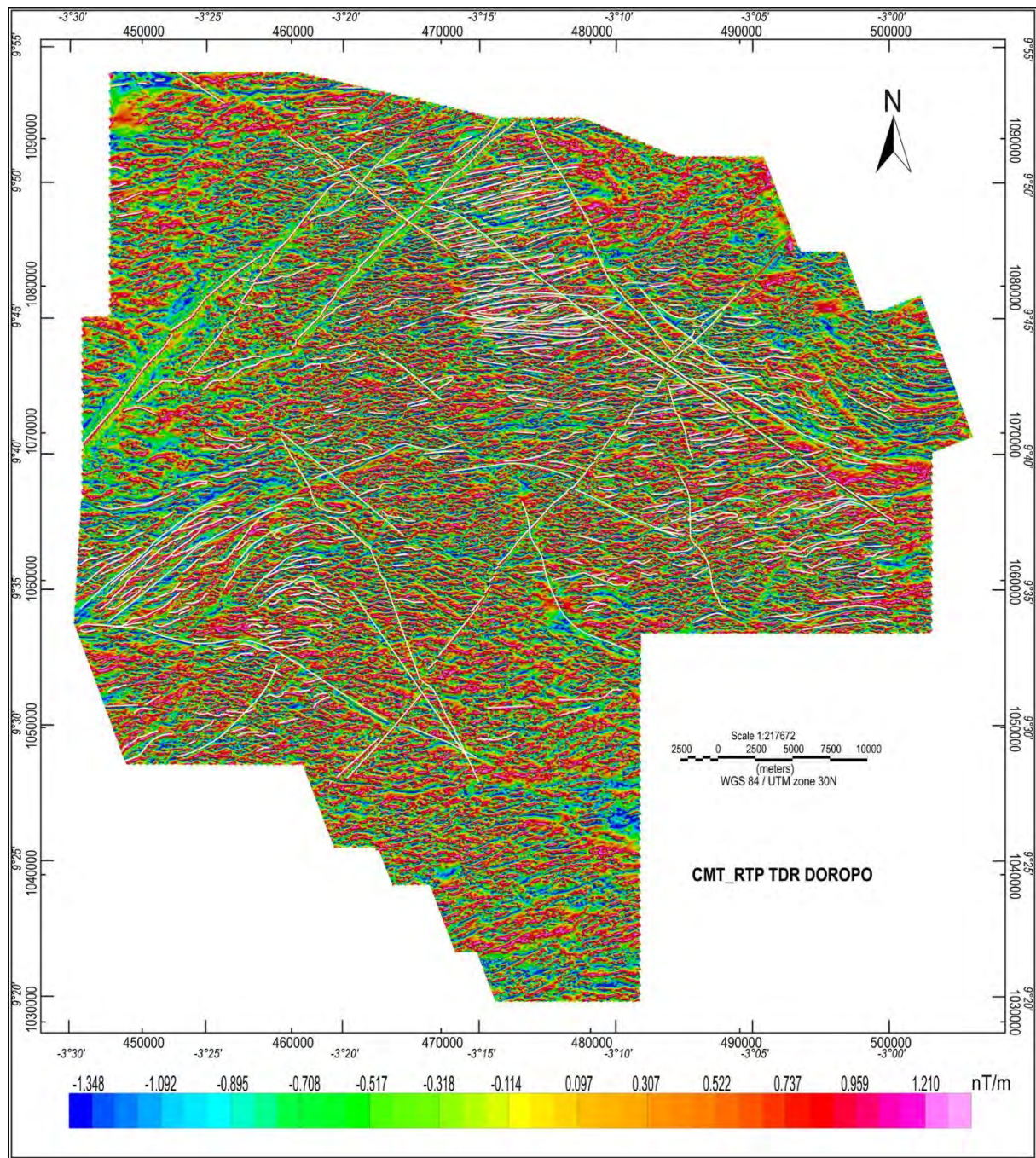


Fig. 14. Map of the Tilt Derivative showing linear (faults, shears) and massive structures with curvilinear magnetic lineaments (white lines).

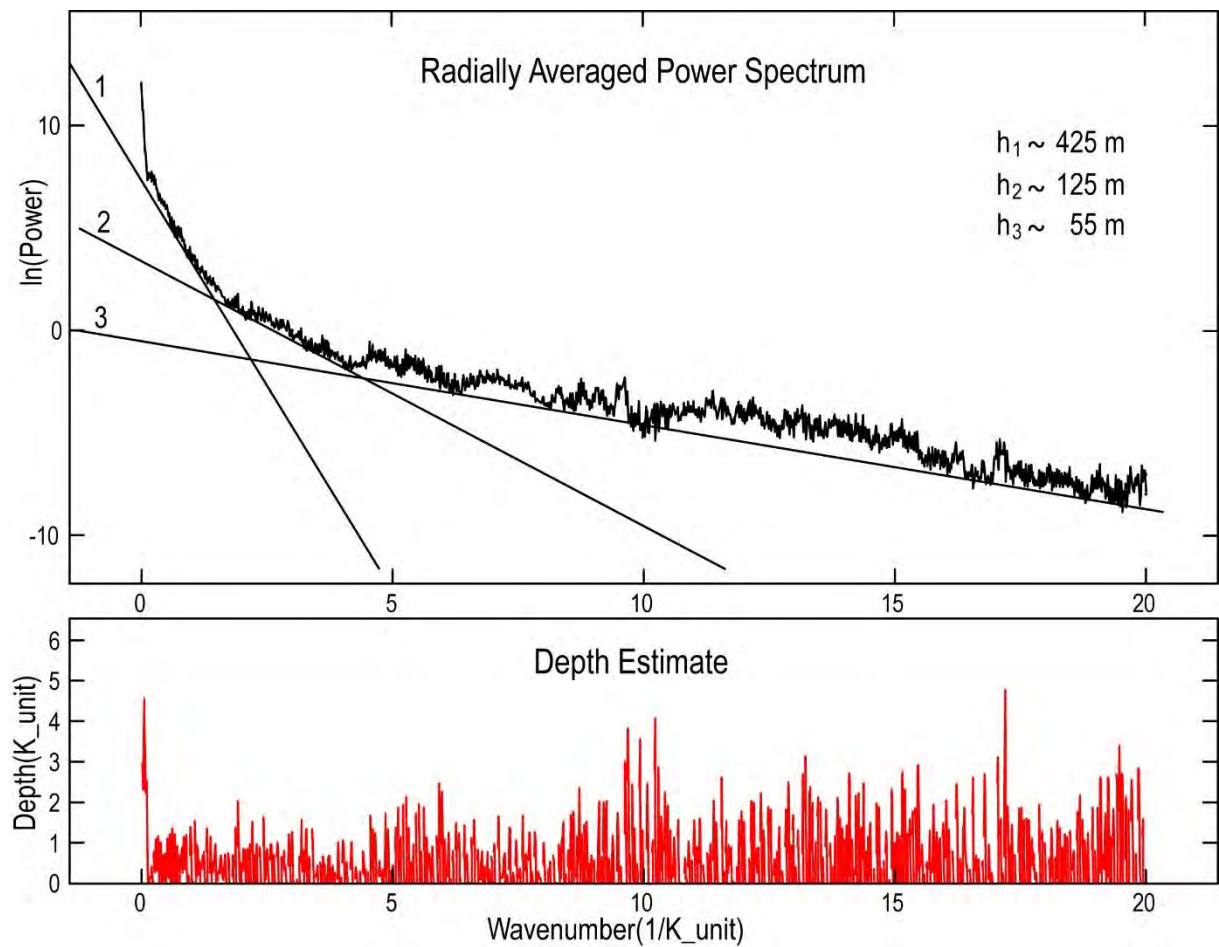


Fig. 15. Power spectral diagram (Spector and Grant, 1970) showing three possible depths of the causative sources at 55 m, 125 m and 425 m.

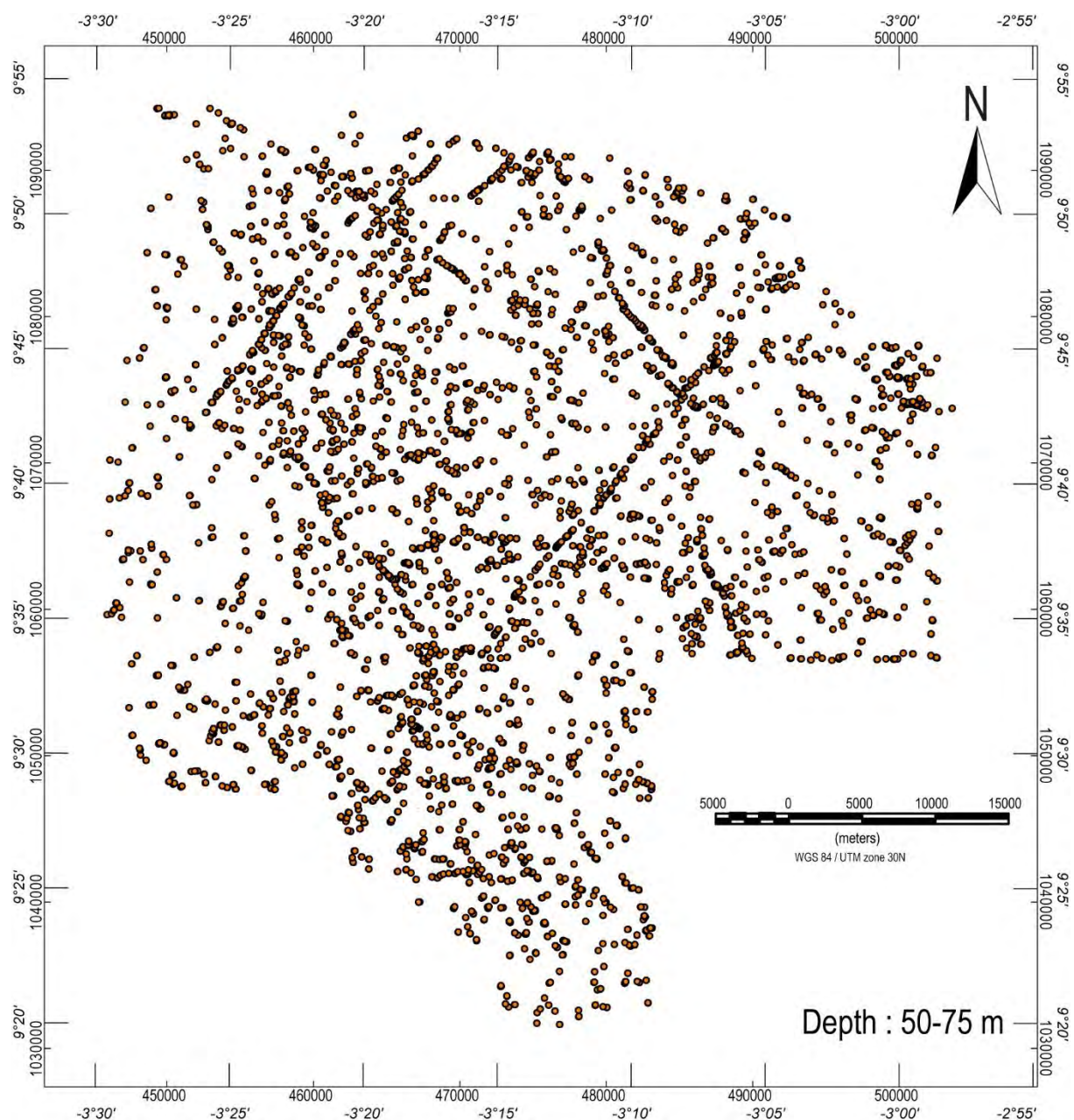


Fig. 16a. Map of the 3D Euler deconvolution solutions for depth plans in the ranges 50-75 m: shows NE-SW and NW-SE oriented linear structures;

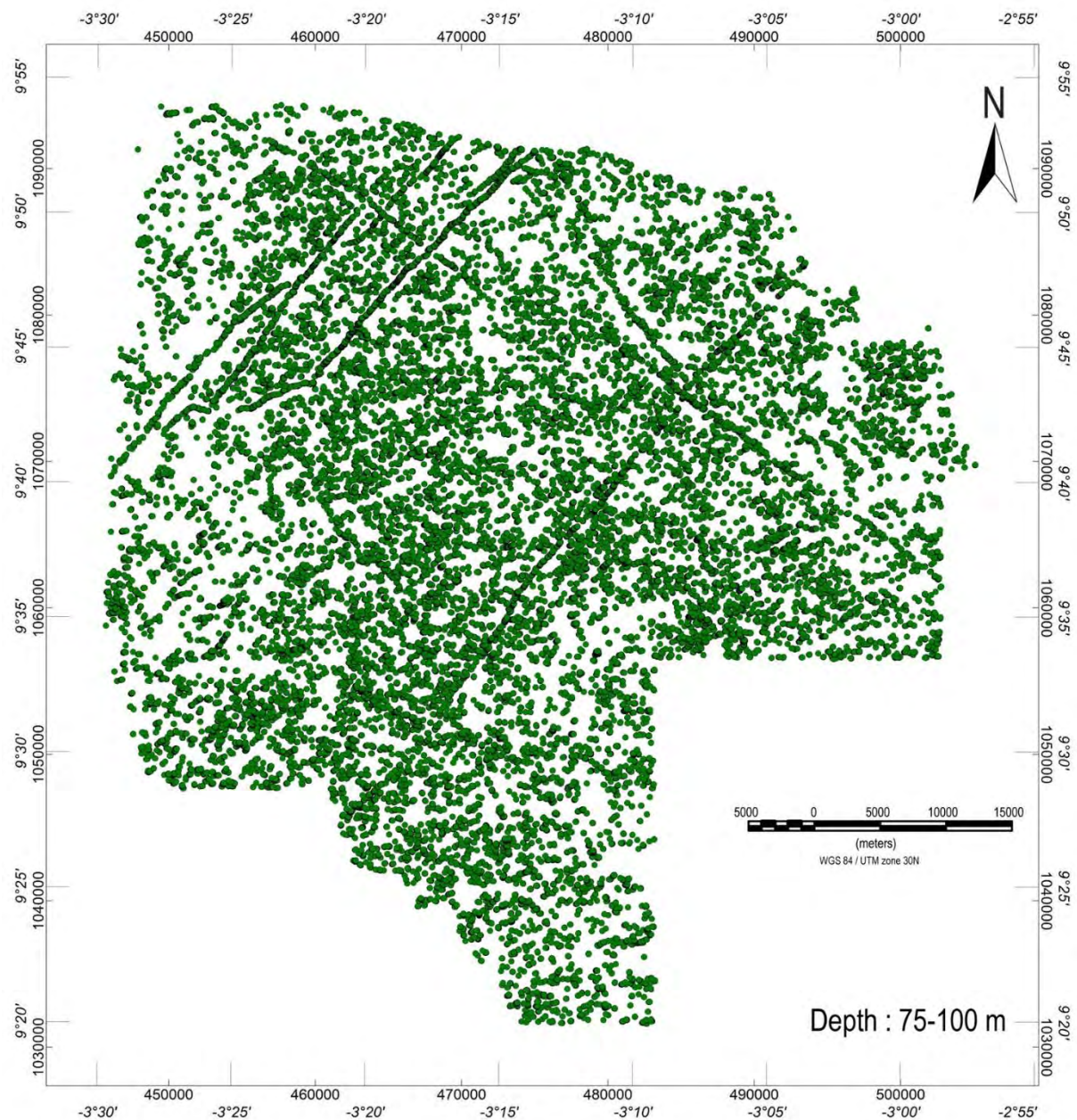


Fig. 16b. Map of the 3D Euler deconvolution solutions for depth plans in the ranges 75-100 m: highlights the same linear structures as in [Fig. 16a](#).

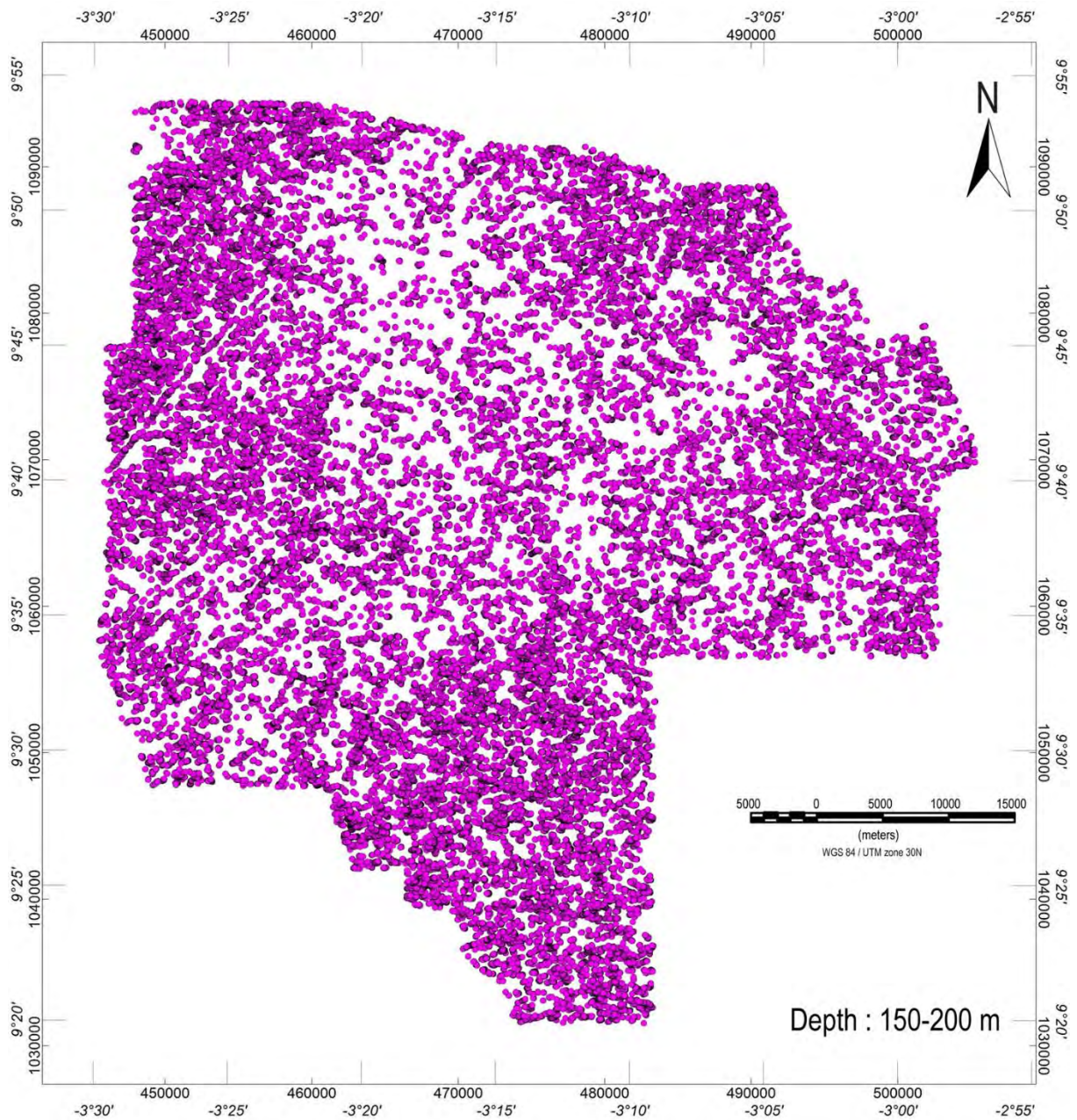


Fig. 16c. Map of the 3D Euler deconvolution solutions for depth plans in the ranges 150-200 m: the linear structures tend to disappear except some NE-SW structures (e.g., northwestern the map).

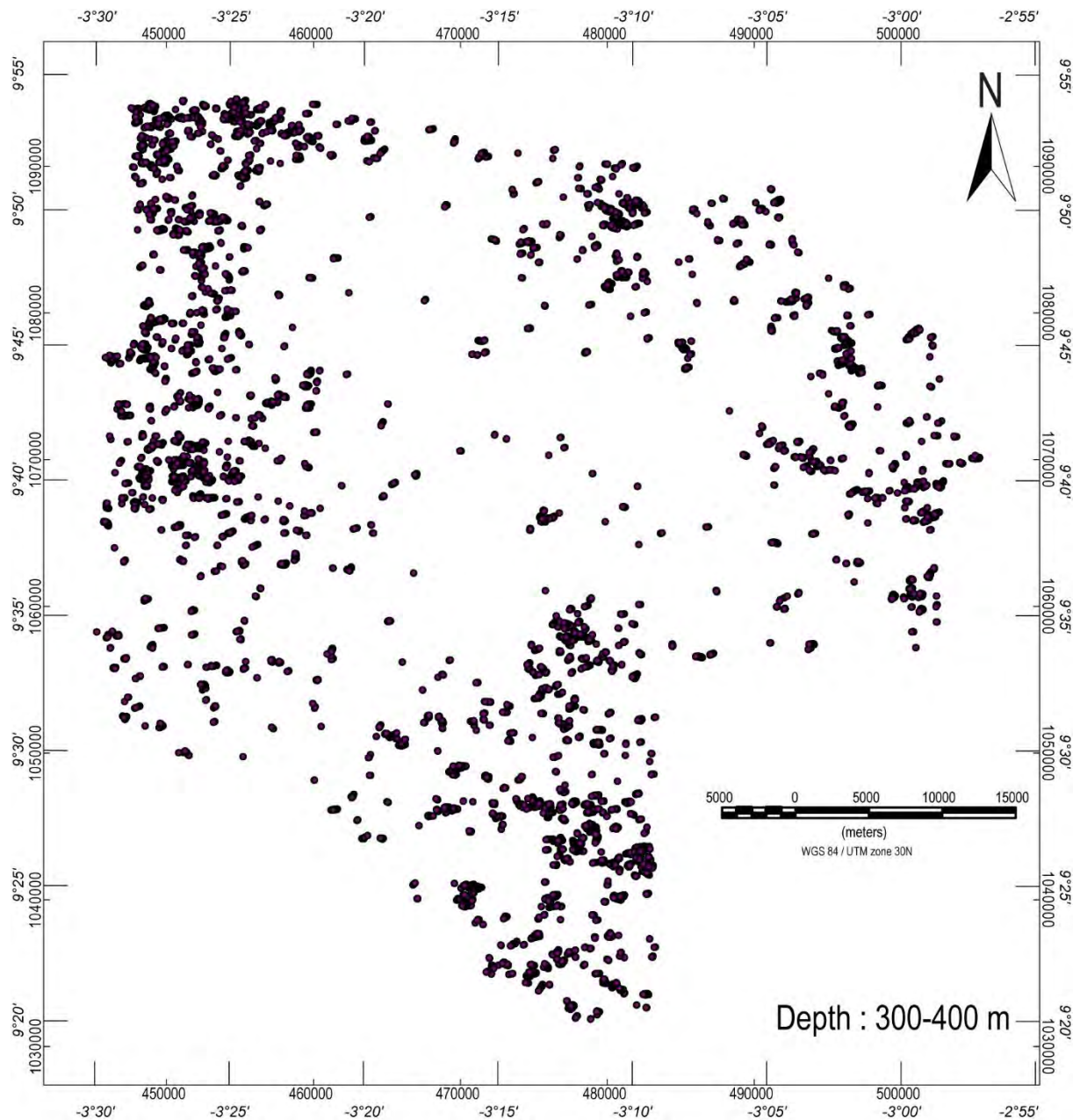


Fig. 16d. Map of the 3D Euler deconvolution solutions for depth plans in the ranges 300-400 m: all linear structures disappeared.

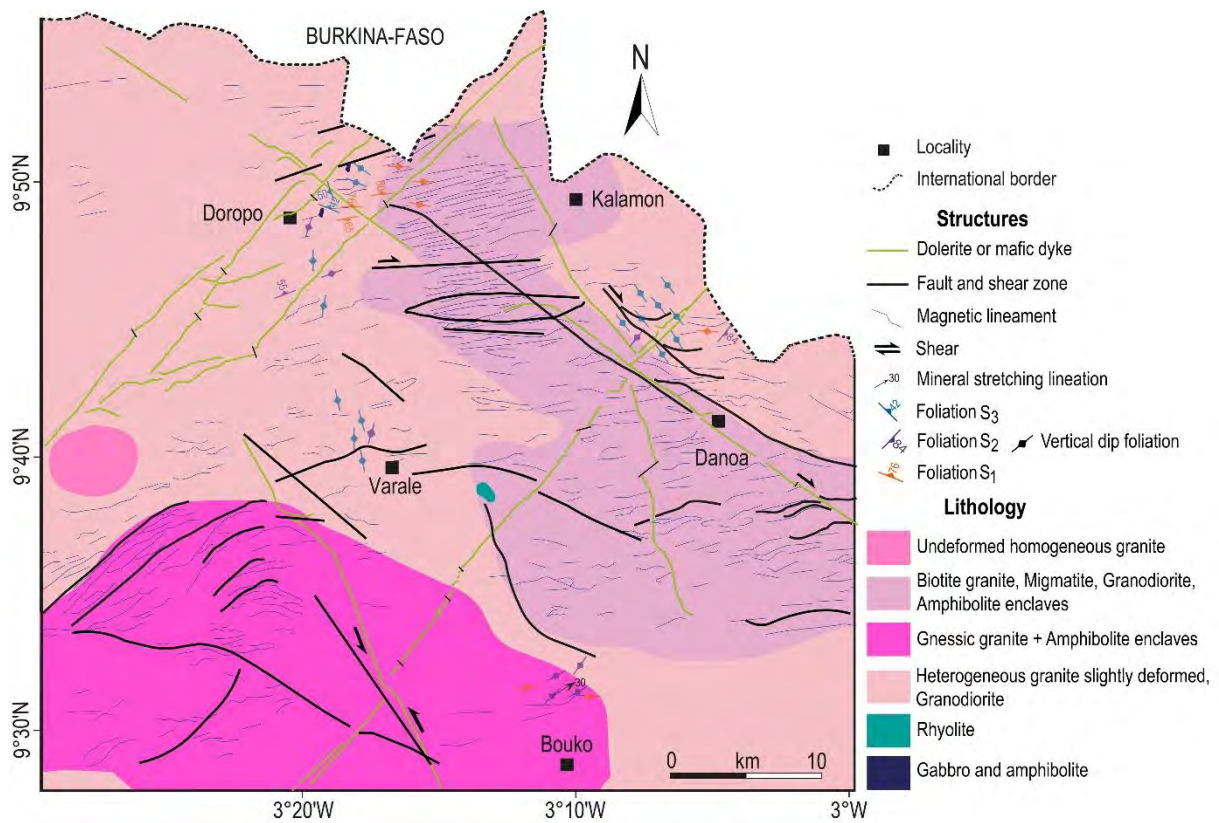


Fig. 17. Lithostructural map of the Doropo region (reduction of the 1:50,000 scale map).

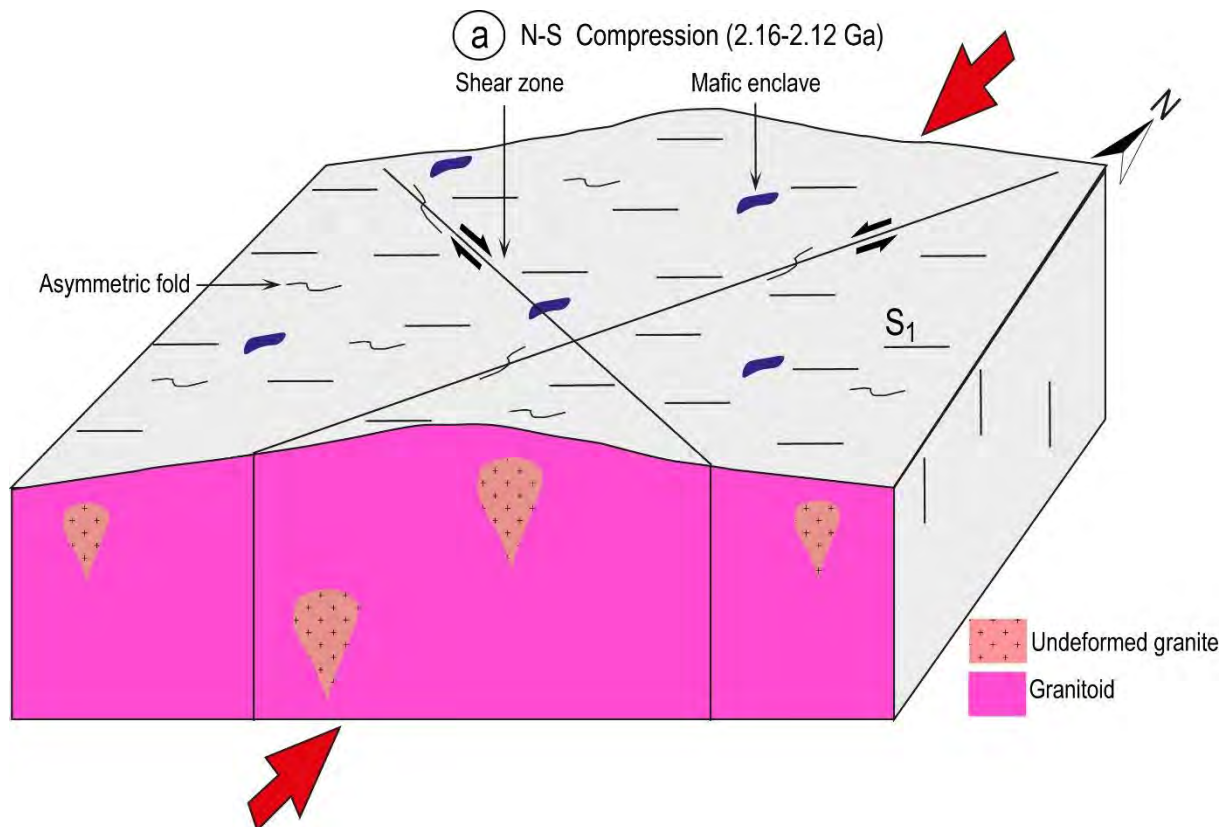


Fig. 18a. Tectonic model proposed for the Doropo region during the Eburnean. Crustal thickening and emplacement of granitoids. Red arrow indicates the σ_1 direction.

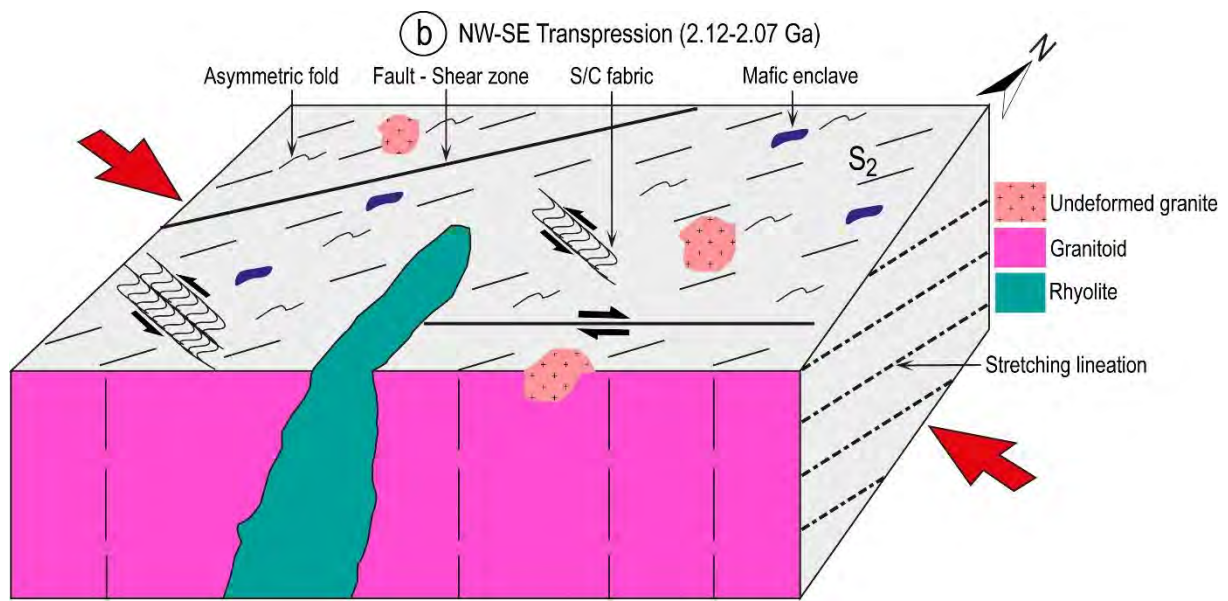


Fig. 18b. Tectonic model proposed for the Doropo region during the Eburnean. Occurrence of oblique shears.

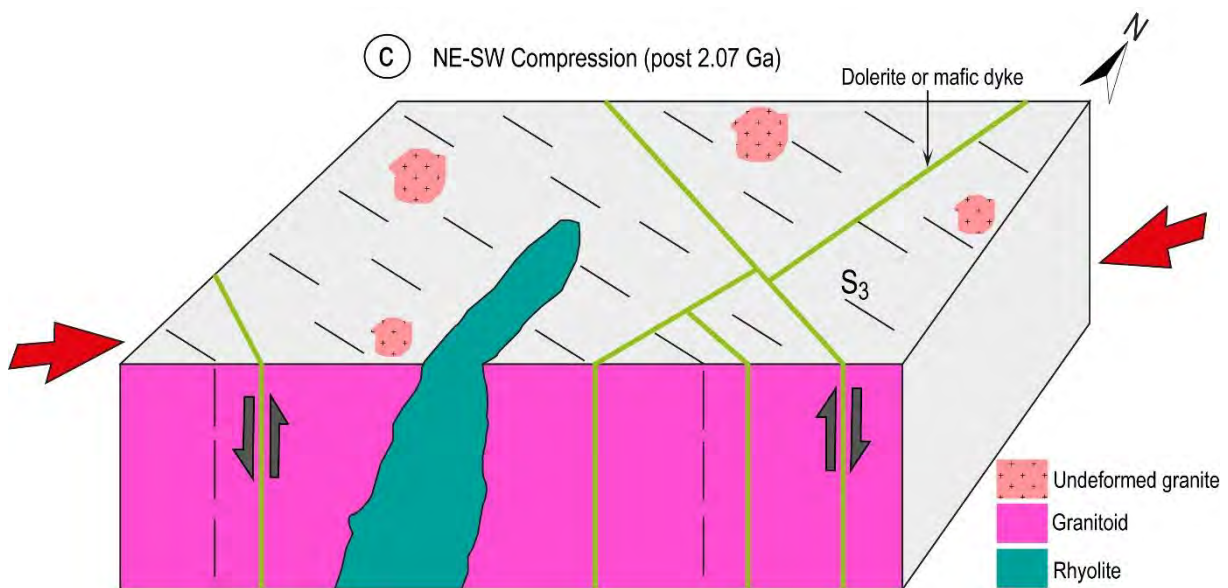


Fig. 18c. Tectonic model proposed for the Doropo region during the Eburnean. reactivation of faults and magmatic inflows.