

Contribution of New Geological and Aeromagnetic Data to Update Lithostructural Map of Daloa Region (Central-Western Côte d'Ivoire)

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Abstract

This article is a contribution to the understanding of the structuration of the West African Craton (WAC) through an integrated analysis of geophysical and petro-structural data from the Daloa region in west-central Côte d'Ivoire. Airborne magnetic data were used for mapping a regional structure, as this is a forested region. Fourier domain processing (Reduce To Equator, Analytical Signal, and Tilt derivative) was used to produce maps highlighting the main regional structures, which were then confirmed in the field. This method made it possible to define the geometry of the different massifs and the contacts between the different lithological units. The Daloa region is made up of calc-alkaline granitoids (granites and migmatites) and schists elongated in directions ranging from N20°E to N60°E, with subvertical dips (60°SE to 80°SE). The massifs are traversed by a network of fractures oriented E-W, NW-SE, NE-SW, which correspond to the direction of the numerous aplite, pegmatite, tourmalinite, and quartz veins observed there. Brittle deformation is characterized by the formation of vein structures or strike-slip faults. These directions are consistent with the lineament directions observed on geophysical

maps. The structuring of this region occurred in four main phases recognized at the scale of the West African Craton: a NNW-SSE synmagmatic compression phase (D1), followed by an early NE-SW extensional phase (D2) during a period when the massifs still retained some ductility. Next comes a N-S compression phase (D3) responsible for numerous shears, and finally a late tensile phase (D4) leading to the reactivation of the faults from phase D2.

Keywords

Geophysics, Airborne Magnetic Data, Petrography, Structures, Granitoids, Daloa, Ivory Coast

1. Introduction

In regions characterized by dense vegetation cover, the use of indirect methods such as geophysics is of paramount importance for understanding the geology and tectonics of an area. In order to refine knowledge of the large Ferkessedougou batholith, a petrographic and structural study coupled with geophysical imaging was conducted in the Daloa region (Central-West Côte d'Ivoire, **Figure 1**). Processing of geophysical images highlights regional-scale structures such as deformation corridors, faults, and lithological contacts. This investigation was further complemented by structural measurements carried out in the field.

2. Geographical Context and Geology of the Daloa Region

2.1. Geographical Context

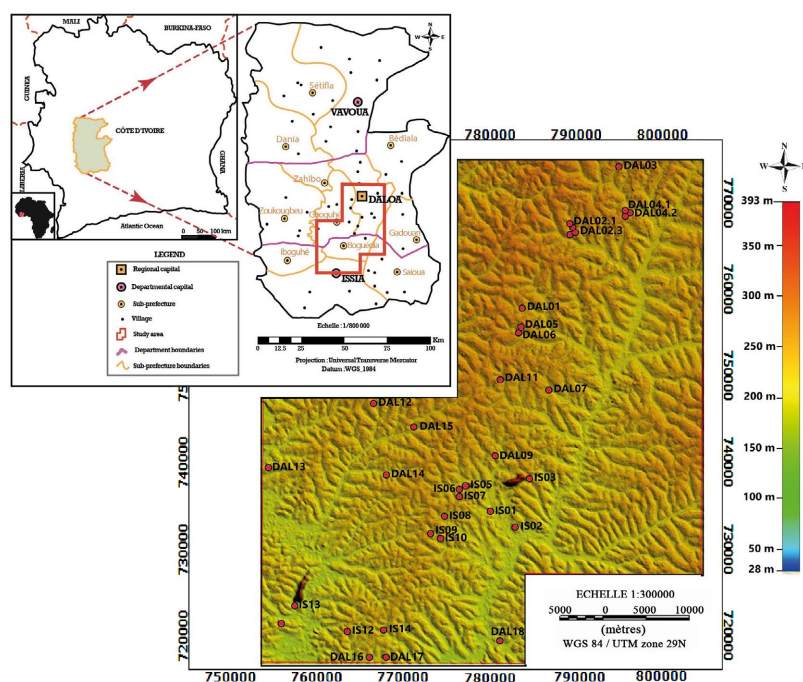


Figure 1. Map showing the location of the Daloa region.

The study area is located in the central-western part of Côte d'Ivoire, spanning the departments of Daloa and Issia. It is bounded by longitudes 6°20'W - 6°40'W and latitudes 6°26'N - 6°54'N.

The main urban centers within this zone, in order of importance, are Daloa, Issia, and Boguedia (see **Figure 1**). The region is predominantly forested and consists of high plateaus averaging 300 m in elevation, surmounted by small chains of hills and isolated reliefs (**Figure 1**). The highest elevations are associated with migmatitic facies in the northern part of the study area.

2.2. Geological Context

The crustal backbone of West Africa is formed by the Precambrian basement commonly referred to as the West African Craton, covering an area of approximately 4,500,000 km² (**Figure 2**). Metamorphosed, polydeformed, and fully stabilized around 1.7 Ga, the craton is expressed through two major ridges: the Reguibat Ridge in the north [1] and the Man Ridge in the south.

This cratonic domain records at least three major tectono-thermal events: (i) the Leonian orogeny (3.5 - 2.9 Ga; [2]), (ii) the Liberian orogeny (2.9 - 2.8 Ga) [2] [3], and (iii) the Eburnean orogeny (2.27 - 1.8 Ga); [4]-[7].

Together, these events highlight the long-lived and complex tectono-metamorphic evolution of the West African Craton, which remains a key reference for understanding Precambrian crustal growth and stabilization.

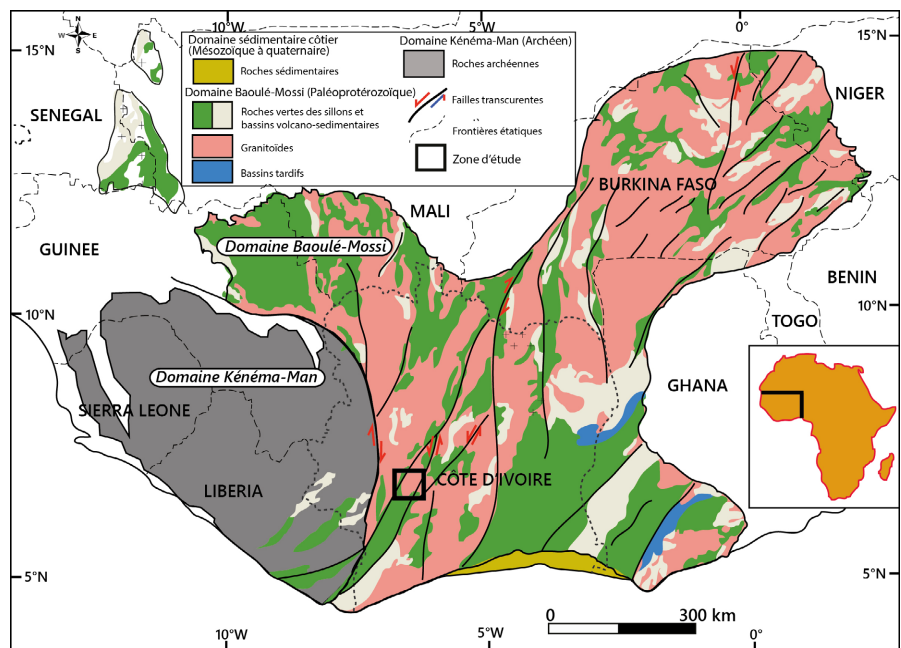


Figure 2. Simplified geological map of the West African Craton (modified after [8]).

From a geological perspective, the Daloa region is dominated by leucogranites and migmatites intruding parametamorphic schist formations. Crystalline formations occupy approximately two-thirds of the area and can be subdivided into

three major groups: (i) granitoids (granites, migmatites, and granitic pegmatites); (ii) crystallophyllian formations (schists and mica-schists); (iii) a few rare volcanites and sedimentary rocks, more or less metamorphosed, are also present [9] [10].

3. Methodology

3.1. Data Acquisition

The dataset was derived from aeromagnetic survey maps produced by Kenting Earth Sciences Ltd. during 1974-1975. Flight lines were spaced at 500 m intervals, with a nominal flight altitude of 150 m (± 15 m) and a sampling interval of approximately 0.75 s.

Isomagnetic contours from three aeromagnetic maps at 1:50,000 scale (Daloa sheets 3b, 4a, and 4c) were compiled using mapping software (ArcGIS 10.2 and Datamine 2017). Aeromagnetic data processing was carried out with Geosoft 8.3.3. To validate geophysical interpretations, a geological map of the Daloa quadrangle at 1:200,000 scale was also employed.

3.2. Aeromagnetic Data Processing

To assign geological significance to magnetic data, various mathematical operations (filters) are applied: total magnetic field, reduction to the equator, analytic signal, tilt derivative, etc. These operations transform raw maps into enhanced maps that highlight specific features, thereby simplifying qualitative analysis and interpretation of geophysical anomalies.

3.2.1. Total Magnetic Field (TMF) Map

The magnetic field measured at the Earth's surface is defined by its intensity, declination, and inclination [11]. To obtain the actual value of the magnetic field in a given area, a regional constant known as the DGRF (Definitive Geomagnetic Reference Field) must be removed prior to any processing [12]. A 3×3 convolution filter is then applied to the raw magnetic data, yielding the total magnetic field map.

The parameters used in our processing were: (i) the magnetic declination of the study area, with a value of -10.45° (DGRF, model 75); (ii) an inclination of -8.58° as of May 27, 1974.

The study area is therefore located at low magnetic latitude, close to the magnetic equator.

3.2.2. Reduction to the Equator (REQ) Map

Magnetic anomalies and the magnetic field are not always well aligned on the Total Magnetic Field (TMF) map. To reposition magnetic anomaly bands directly above their sources; that is, exactly above the rocks that generate them the reduction-to-the-equator filter is applied.

In regions close to the equator (low magnetic latitudes), where the external field is nearly horizontal, the reduction-to-the-pole (RTP) filter becomes unstable. In such cases, as in Côte d'Ivoire, a reduction-to-the-equator (REQ) filter is used.

This operation removes the effects of inclination and reduces the overlap of anomalies on the map, thereby facilitating the definition of geological contacts.

The reduction to the equator is performed in the Fourier domain (FFT: Fast Fourier Transform) according to the following equations. The Fourier transform of the measured anomaly into the spectral domain ΔT is expressed as:

$$\Delta T(k_x, k_y) = F\{\Delta T(x, y)\} \quad (1)$$

where F denotes the Fourier transform, k_x and k_y are the wave numbers in the x and y directions, respectively.

The reduction-to-equator operator is then applied as:

$$REQ(k_x, k_y) = \frac{\Delta T(k_x, k_y)}{\cos I \cos(\theta - D) + \sin I \sin(\theta - D)} \quad (2)$$

Where:

- $\theta = \arctan\left(\frac{k_y}{k_x}\right)$
- I = magnetic inclination,
- D = magnetic declination.

This transformation re-centers anomalies above their causative sources, improving the accuracy of geological interpretation.

This filtering operation for reduction to the equator in the spectral domain depends on the parameters of the local magnetic field [13] [14]:

- I = local magnetic inclination
- D = local magnetic declination
- k = wave number vector

3.2.3. Analytic Signal and Tilt Derivative Maps

To facilitate interpretation by highlighting structures (lineaments, geophysical faults, etc.), we applied both the analytic signal and the tilt derivative filters to the magnetic anomaly map reduced to the equator [15]-[18]. These two filters are based on the three-dimensional combination of gradients of the residual magnetic field.

The analytic signal enables the observation of lithological distribution and their magnetic properties [19].

The analytic signal is obtained from the horizontal and vertical derivatives of the magnetic field intensity gradient. This calculation is particularly useful because the amplitude of this derivative signal is independent of the magnetization direction of the source (remanence). The amplitude A_s of the analytic signal of the magnetic field T is calculated from the three orthogonal derivatives of the field according to the formula of [20]:

$$A_s(x, y) = \sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2} \quad (3)$$

The tilt derivative is used to estimate the depth of the bodies responsible for

magnetic anomalies [20]. The interpretation of magnetic ridges is crucial in analyzing magnetic domains. A key parameter supporting this interpretation is the characterization of banding (magnetic ridges) observed in each magnetic domain. According to [21], the geometric analysis of structural patterns in tectonic fabrics (*i.e.*, magnetic ridges) can be performed based on:

- 1) the shape of trajectories,
- 2) deflection (orientation),
- 3) clustering (density), and
- 4) linearity.

The tilt derivative is used here to delineate the boundaries of magnetic bodies in support of the analytic signal [22]. This processing also highlights deep faults and their connections with faults affecting superficial formations [23]. The tilt derivative, or tilt angle [24] [25], is defined by the equation:

$$\text{Tilt derivative} = \tan^{-1} \left(\frac{\frac{\partial T}{\partial z}}{\sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2}} \right) \quad (4)$$

where:

- $\frac{\partial T}{\partial z}$: first vertical derivative of the magnetic field T ,
- $\frac{\partial T}{\partial x}, \frac{\partial T}{\partial y}$: horizontal derivatives of the field along orthogonal axes x and y ,
- $\sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2}$: total horizontal gradient (THG).

4. Results and Interpretations

4.1. Geophysical Maps

4.1.1. Total Magnetic Field (TMF) Map vs Reduction to the Equator (REQ) Map

Magnetic values show a variation of approximately +360 nanoTesla (nT) between the highest and lowest observed values. The average intensity of the Earth's magnetic field in the study area is about 31,150 nT.

On the resulting map, magnetic anomalies are all displaced relative to their sources (**Figure 3(a)**). This map reveals magnetic structures that are linear or elongated elliptical features trending NE-SW (**Figure 3(a)**). These structures are oriented along the regional Birimian trend. The magnetic anomaly map also highlights an increase in magnetic field intensity from west to east. Elliptical to sub-circular bodies correspond to intrusive formations.

By applying reduction to the equator more suitable for low magnetic latitudes, the anomalies displaced on the TMF map were repositioned directly above their sources, and the contours of magnetic bodies appear smoother (**Figure 3(b)**).

For data validation, the magnetic susceptibility of rocks was measured in the field. High susceptibility values, ranging between 0.15×10^{-3} and 2.83×10^{-3} S.I., are associated with the presence of migmatites and occurred in the northern part of studied area. This result suggests that the principal anomalies are most likely linked to bodies exhibiting induced magnetic behavior.

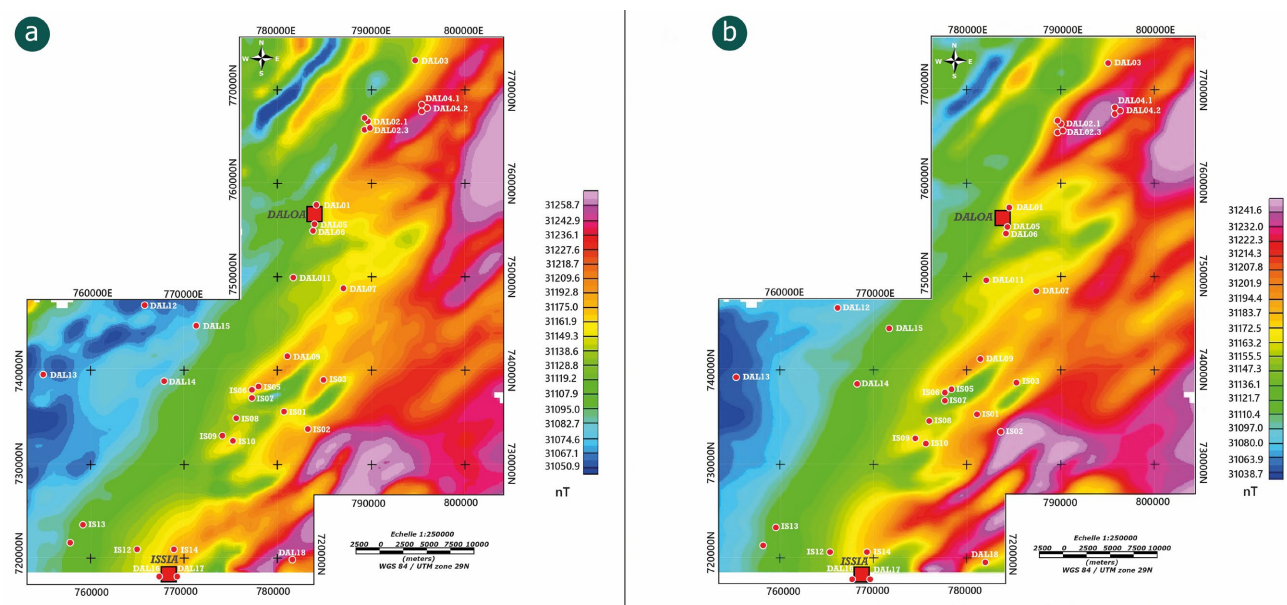


Figure 3. Maps of the total magnetic field (a) and reduction to the equator (b). The reported values correspond to the average magnetic susceptibilities measured *in situ*.

4.1.2. Analytic Signal (AS) Map

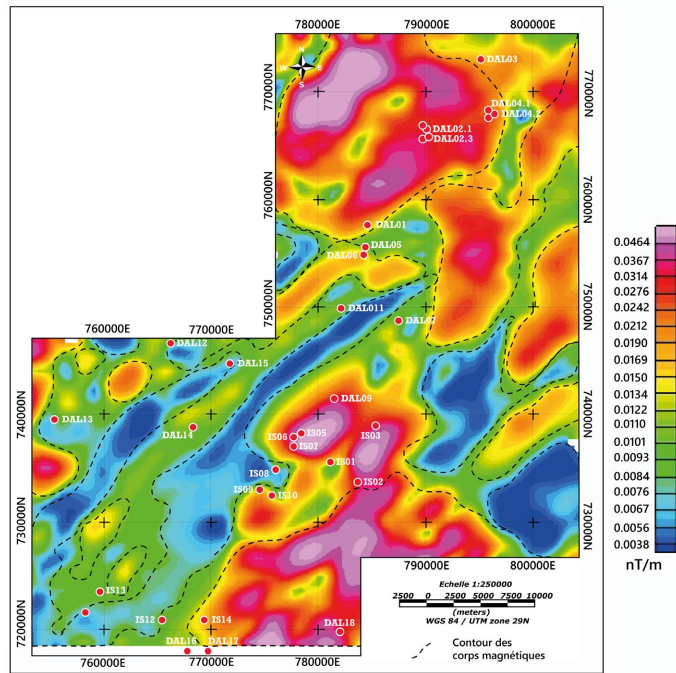


Figure 4. Analytic signal map showing the contours of magnetic bodies.

The analytic signal map reveals two major anomalous domains. High analytic signal values in the northern part of the study area coincide with the zone of anatectic formations (migmatites and anatectic granites). In the south, these high values cover the porphyroid granite of Mimia and the Bitapia granite (**Figure 4**).

Low analytic signal values, extending from east to west, form an arc around the southern anomalous domain. These low values characterize the zone of muscovite-dominant leucogranites and alluvial basins. A few positive circular anomalies are also visible within this domain, indicating the presence of small intrusive bodies.

4.1.3. First Vertical Derivative (1VD) Map

The map of the first vertical derivative (1VD) shows that the anomalies are narrower and more rectilinear than those observed on the first three maps. On this map, the magnetic axes (shown as white dashed lines) follow the general orientation of the region's geological formations (NE-SW). The breaks in the magnetic axes on the map allow the discontinuities to be located within the structures, which are interpreted as probable faults (**Figure 5(a)**).

4.1.4. Tilt Derivative (Tilt Angle) Map

The tilt angle map shows that geological formations are filamentous and oriented along the Birimian trend (NE-SW). On the tilt map, filamentous magnetic ridges appear as linear positive anomalies of higher intensity than their immediate surroundings. These magnetic ridges are accompanied by localized magnetic lows on either side.

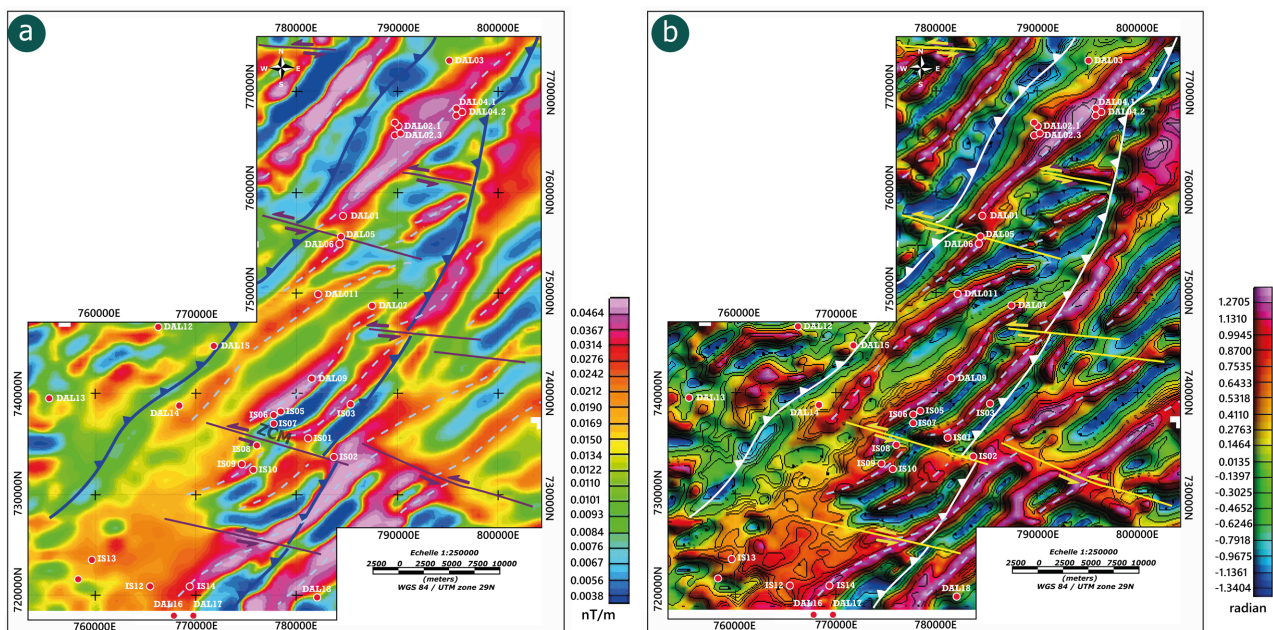


Figure 5. First vertical derivative and Tilt angle derivative map (Dashed lines represent magnetic axes whose interruption or back-thrusting allows the placement of geophysical faults, shown in solid lines).

The tilt derivative map reveals families of faults mainly oriented E-W to NNW-SSE, corresponding to two distinct fracturing events (**Figure 5(b)**). In the central part of the study area, parallel magnetic bundles can be clearly identified on either side of weakly magnetic bands. These bundles are located along the trace of the major Mimia Shear Zone (ZCM).

The Mimia Shear Zone (ZCM) displays flexural structures such as back-thrusts at fault contacts, resulting from transpressive movements (**Figure 5(a)** and **Figure 5(b)**), as previously reported by [26] in the Touba region.

4.2. Structural Study at Outcrop

In the field, regardless of lithology, deformation is expressed by structural elements such as foliation (magmatic and metamorphic), folds, boudins, magmatic and mineral stretching lineations, shear zones, veins, and fractures.

4.2.1. Ductile Deformation

Ductile deformation in these granitoids is marked by banding, folds, lineations, boudins, and sigmoidal structures.

- **Folds:** Folds are observed only in migmatites (**Figure 6**). They consist mainly of pygmy folds and chevron folds, as well as isopaque folds with subvertical axial planes (**Figure 6(c)**). The measured orientations of axial planes range between $N0^{\circ}E - N30^{\circ}E$ and $N60^{\circ}E - N70^{\circ}E$.
- **Mineral Lineation and Banding:** Two types of lineations were identified: (i) metamorphic lineation observed in migmatites, and (ii) magmatic lineation observed in leucogranites.

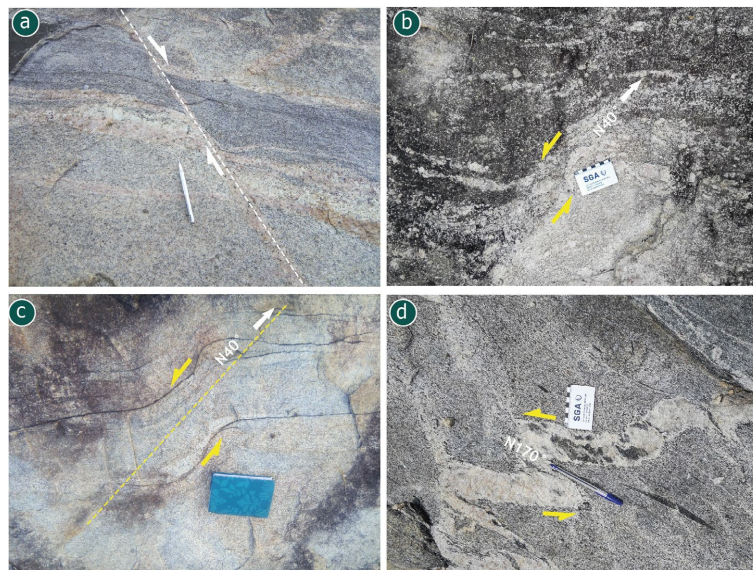


Figure 6. Examples of shear-related deformation observed on migmatite slabs: (a) Strike slip fault indicating dextral movement; (b) Migmatite deformed by sinistral shear; (c) Flow cleavage in granite; the deformation suggests that the shear occurred whilst this rock possessed a certain degree of ductility; (d) A sigmoidal structure showing transtension indicative of sinistral movement.

Magmatic lineation in leucogranites is recognizable in outcrop by the stretching of potassium feldspar porphyroblasts, metas sedimentary enclaves, and mica-rich inclusions.

4.2.2. Brittle Deformation: Veins and Fractures

Brittle deformation is expressed by quartz veins, pegmatite veins, tension gashes, and domino structures (**Figure 7**). Quartz veins are very common, especially in granitic massifs, and rare in migmatites, where pegmatite and microgranite veins are more frequent, with thicknesses ranging from 5 cm to 20 cm.

In granites, there are extensional structures oriented N100°E (**Figure 7(a)** and **Figure 7(b)**) forming domino patterns indicative of l sinistral movement. These domino patterns are reminiscent of the behaviour of a pull-apart basin.

Theses local extensional structures demonstrate the existence of the late-Ebur-nean transtension at the D3, which led to the reactivation of certain structures and the circulation of new fluids.

In migmatites, veins are often composed of aplitic granite leucosome that cross-cut or follow the orientation of migmatitic bands. Other veins are composed of pink potassium feldspar, quartz, and magnetite. The main orientations of veins in migmatites are N50°E - N70°E and N20°E - N30°E.

The fracture system associated with vein rocks observed in large granite outcrops is oriented along the principal directions: N0°E - 30°E, N60°E - 90°E, and N110°E - 150°E. Vein and veinlet orientations are diverse, but based on numerous outcrop observations, N80°E - 100°E and N120°E - 160°E appear to be the preferred directions (**Figure 8**).



Figure 7. Fracturing features on the small Issia dome: (a) and (b) Kink-band veins and openings at the points of dilation suggest the behaviour of a pull-apart basin. (c) Extension structures oriented N100°E showing reactivation of the fracture with the formation of a second-generation vein.

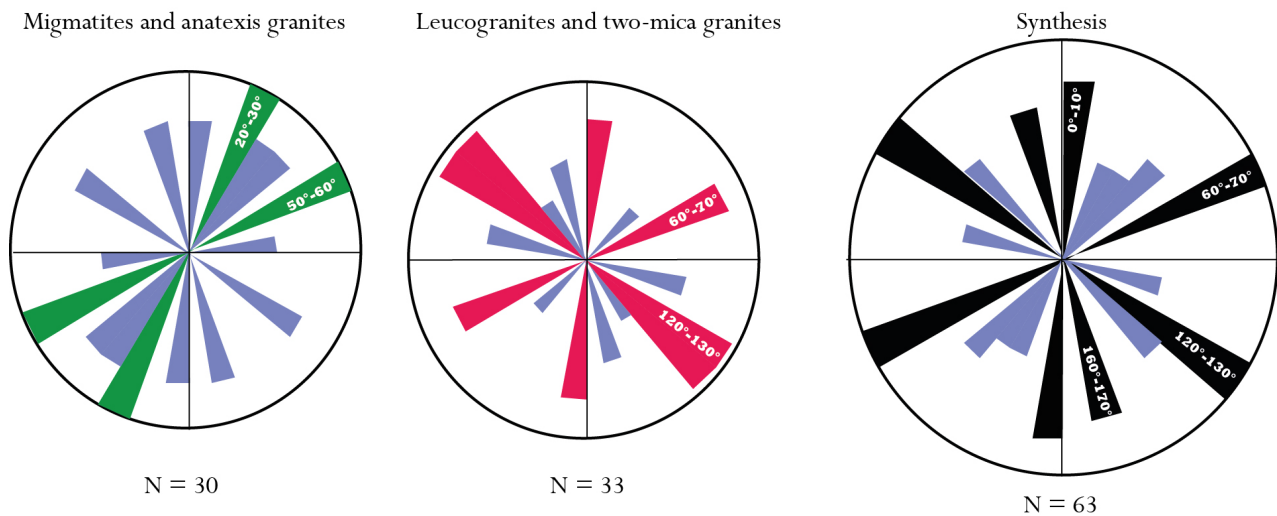


Figure 8. Directional rose diagrams showing the principal orientations of veins and fractures in migmatites and granites.

4.2.3. Shear Zones, Sigmoidal Structures, and Tension Gashes

Shear zones are observed both in granites and in migmatites. These deformation corridors predominantly indicate sinistral movements (**Figure 9**). Four families of shear-related stress orientations have been identified within the various deformation corridors: N0°E - N20°E; N30°E - N60°E; N80° - N100°; and N120°E - N160°E.

In the granites, particularly within the two domes of Issia town, extensional forces acting on the massifs generate deformation corridors that exhibit more or less pronounced dislocations (**Figure 9(a)** and **Figure 9(b)**). Within these corridors, the shearing of pre-kinematic minerals (quartz and feldspar) produces boudinaged lenses around which syn-kinematic minerals crystallize. These minerals, entrained by rotation, form pressure shadows (**Figure 9(b)** and **Figure 9(c)**).

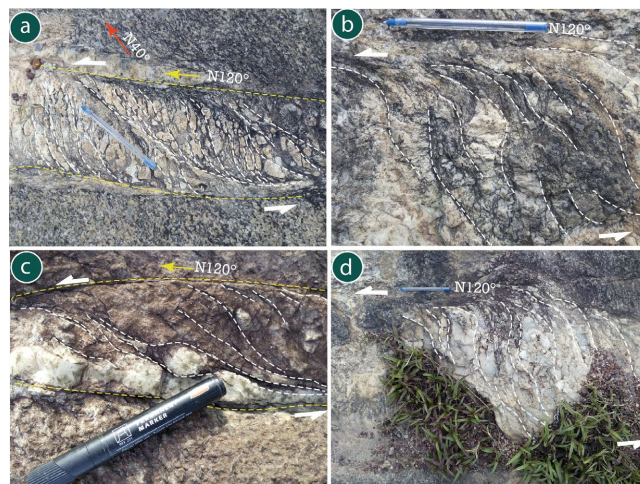


Figure 9. (a)-(c) Fracture schistosity within the deformation corridor (N120°E) and corridor (N120°E) and rotation of porphyroclasts indicating a sinistral movement imposed by N40°E shearing. (d) Structure indicating a sinistral movement (Large Issia dome, DAL17).

5. Geological Synthesis

Field-based structural analyses, integrated with geophysical imagery, provide a refined delineation of lithological contacts and reveal deep-seated structures within the Daloa region. The northern sector is dominated by migmatites and anatectic granites, whereas the southern sector is characterized by schistose formations intruded by two-mica granites and leucomonzogranites (**Figure 10**).

This spatial distribution underscores the contrasting tectono-metamorphic evolution of the area, where basement-derived migmatites and granites in the north transition southward into metasedimentary sequences intruded by late magmatic bodies. Together, these features highlight the interplay between crustal melting, magmatic emplacement, and deformation processes that shaped the regional architecture.

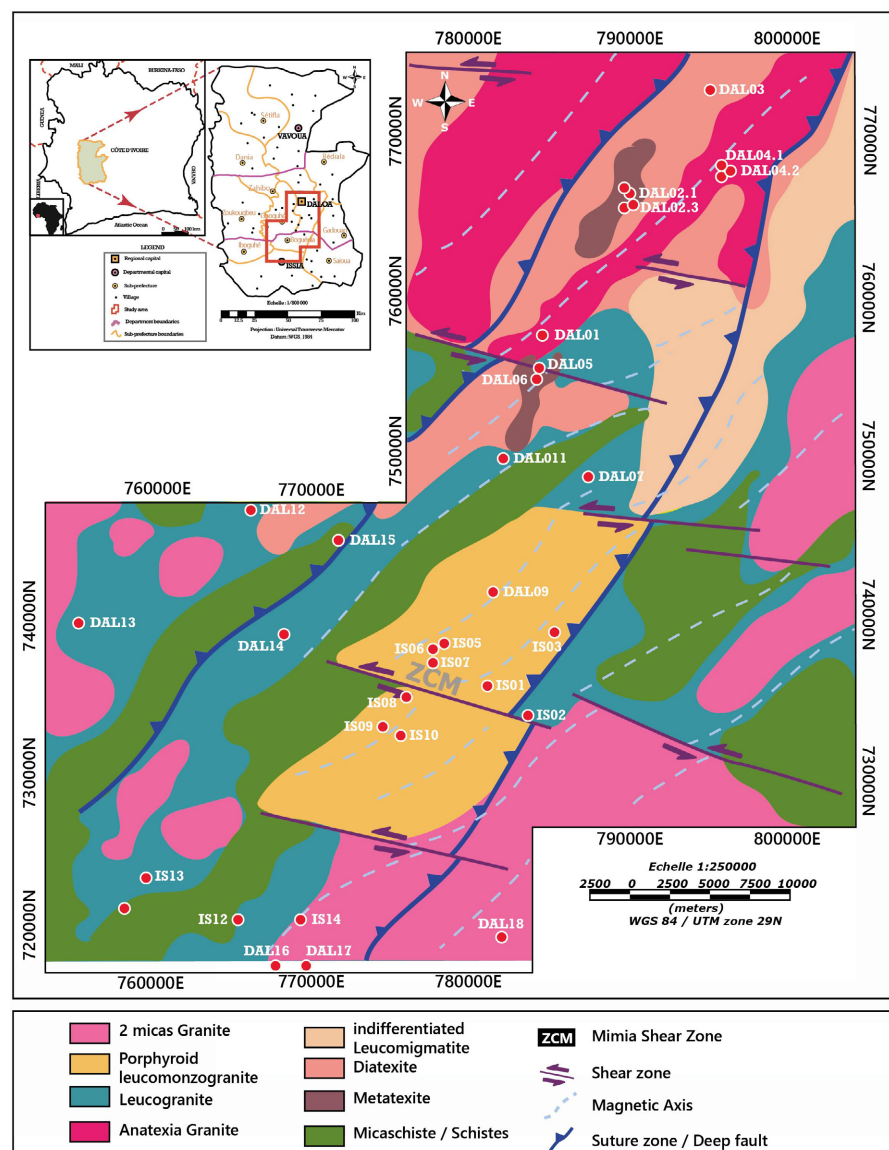


Figure 10. Geological synthesis map of the study area.

6. Regional Kinematic Evolution

Magnetic anomalies and mapped structures display a general NE-SW orientation, consistent with the trend of Birimian formations. This confirms that the Daloa region is part of the broader tectono-metamorphic framework of the West African Craton, where deformation corridors follow this dominant direction.

The network of megafractures proposed on the Daloa geological map (1:200,000; Ahimon *et al.*, 1988) largely coincides with the hydrographic network but does not always match the results derived from interpreted geophysical discontinuities and our field observations.

Major faults have been identified (see **Figure 10**). The various geophysical studies have therefore enabled us to introduce some modifications to this fracture network, which is generally oriented NNW-SSE to E-W.

In the study area, the highest elevations are mainly associated with zones where migmatites crop out (see **Figure 1** and **Figure 10**). Extensional faults and domino structures observed in outcrops are key features providing evidence for the existence of an intracontinental basin, hence the classification of these granitoids as “basin type” by several authors [9] [27] [28]. Numerous ductile (see **Figure 6**) and brittle (see **Figure 7** & **Figure 9**) deformation features indicate that these granites were emplaced within a major NNE-SSW oriented shear corridor. This transpressive shear is expressed by flexures visible on geophysical maps and, in the field, by generally sinistral strike slip faults (see **Figure 5(a)**, **Figure 5(b)**; [26]).

A relative chronology of the identified structures allows us to link them to four major deformation phases:

- **D1.** A first NNW-SSE syn-magmatic compressive (transpressive) phase, causing diapiric uplift of the massifs, with metamorphic lineation and banding N40° - N50°E in migmatites and magmatic lineation N60° - N70°E in granites, both with subvertical dips (see **Figure 7**). [29] associate D1 structures with crustal accretion through the emplacement of extensive granitized peneplains.
- **D2.** A NE-SW extensional phase generating fracture families N120° - N140°E and N160° - N180°E. This stage is linked to tectonic exhumation followed by sinistral strike slip movements [30].
- **D3.** A N-S compressive phase producing N40°E ± 10° shear zones, responsible for fracture schistosity in veins N120° - N140°E and N160° - N180°E, as well as rotation of porphyroclasts (see **Figure 9**), consistent with the D3 phase defined by [31].
- **D4.** A late NE-SW extensional phase reactivating faults N120°E and N160°E, accompanied by magmatic intrusions emplaced along the margins of veins formed during the second phase.

The major structural feature of the region is the presence of deformation at all scales, both in migmatites and granites, suggesting that these rocks were emplaced within a large NE-SW deformation corridor.

7. Conclusions

The study of regional extensional structures, based on the interpretation of mag-

netic maps, reveals a general NE-SW orientation of the massifs, thereby defining a regional magmatic flow consistent with the Birimian trend. The regional magnetic field is induced by basement rocks: high magnetic values are associated with migmatites, anatectic granites, and leucomonzogranites, whereas low magnetic values correspond to leucogranites and metasedimentary formations. These bodies are crosscut by faults oriented E-W to NW-SE. Geophysical maps highlight curved structures resembling back-thrusts, resulting from the presence of strike-slip faults.

Structural analyses conducted on outcrops show that the granitoids of the Daloa region are affected by structural elements such as magmatic and metamorphic foliations, magmatic and mineral stretching lineations, folds, boudins, shear zones, and fractures.

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Author Contributions

Conceptualization, DAGO Aristide Ghislain Beugre and Aka Ehui Beh Constantin; methodology, DAGO Aristide Ghislain Beugre; software, DAGO Aristide Ghislain Beugre; validation, Aka Ehui Beh Constantin, Ouattara Zie, and Coulibaly Yacouba; formal analysis, Ziadjêdé Hervé Siagné, Sawadogo Saga, Kouadio Florentin Tani; investigation, X.X.; resources, DAGO Aristide Ghislain Beugre; data curation, DAGO Aristide Ghislain Beugre; writing—original draft preparation, DAGO Aristide Ghislain Beugre, Aka Ehui Beh Constantin, Sombo Abe Parfait; writing—review and editing, DAGO Aristide Ghislain Beugre and Aka Ehui Beh Constantin, Ziadjêdé Hervé Siagné; visualization, DAGO Aristide Ghislain Beugre, Aka Ehui Beh Constantin; supervision, Ouattara Zie, and Coulibaly Yacouba; project administration, DAGO Aristide Ghislain Beugre; funding acquisition, DAGO Aristide Ghislain Beugre. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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