

Multi-Scale Lineament Mapping and Fracture Network Characterization in the Tenkodogo Square Degree (Burkina Faso): Hydrogeological Implications

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Abstract

Groundwater development in crystalline and metamorphic basement terrains is hampered by the difficulty of locating productive fractures from optical lineament mapping alone, even when it is combined with surface geophysics. This study assesses the influence of geological structures on the geometry and functioning of the aquifers of the Tenkodogo square degree (Burkina Faso) through a multi-scale, multi-sensor approach combining aeromagnetic data, radar imagery and multispectral optical imagery. Magnetic lineaments were extracted manually from derived products and the analytic signal, whereas optical and radar lineaments were extracted automatically (PCI Geomatica) after enhancement (PCA, Laplacian, directional and Lee filters). In total, 502 aeromagnetic, 4476 optical and 39,764 radar lineaments were corrected for anthropogenic and topographic biases, then validated against existing geological data and checked locally through structural measurements at 17 field stations. The three networks were then merged, and the lineament intersection node density, an indicator of fracture network connectivity, was computed by quartic kernel estimation with a search radius of 5 km and a cell size of 100 m. Fracturing displays a scale-dependent hierarchical organization: aeromagnetic lineaments (median lengths of 7 to 16 km, locally exceeding 100 km) delineate regional structural corridors, whereas the shorter and denser optical and radar networks, the latter consisting of surface linear features potentially associated with shallow fracturing, provide local connectivity. The 192,030 retained nodes yield densities of 1.2 to 31.6 nodes/km². Of the 1307 existing boreholes in the study area with a known yield, only 80 (6.1%) exceed 15 m³/h at the end of drilling. The proportion of boreholes yielding 3 m³/h or less decreases from 64.1% where node density is below 15 nodes/km² to 45.1% where it ex-

ceeds 20 nodes/km², but the rank correlation between node density and yield remains weak (Spearman's $\rho = 0.13$). Two boreholes sited at Tenkodogo (23.5 nodes/km²) and Garango (23.7 nodes/km²), *i.e.*, within the densest 6% of the study area, yielded 50 and 18 m³/h (airlift), respectively. These results argue for integrating multi-source structural analysis upstream of drilling campaigns in basement areas.

Keywords

Tenkodogo, Crystalline Basement, Fissured Aquifer, Lineament, Multi-Sensor Remote Sensing, High-Yield Borehole

1. Introduction

Sustainable access to drinking water is a major global challenge, particularly in arid regions where water resources are limited and subject to strong anthropogenic and climatic pressures. In West Africa, and especially in the Sahelian zones, water availability is constrained by the spatio-temporal variability of precipitation, the irregularity of the rainfall regime and rapid population growth, which increases water demand for domestic, agricultural and industrial uses [1] [2]. In this vulnerable context, groundwater is often the main resource for drinking water supply, as well as for irrigation and socio-economic development [3] [4]. Its exploitation nevertheless remains complex in crystalline and metamorphic basement regions, where aquifers are discontinuous, heterogeneous and strongly dependent on the weathered layer and the underlying fracture network [5] [6].

This is the case in Burkina Faso, and particularly in the Tenkodogo square degree where, despite the implementation of numerous water supply programs such as the Integrated Village Water Supply and Health Education Project (PIHVES, 1993-2004), the Village Water Supply Project-Phase II (1995-2000) of the Japan International Cooperation Agency (JICA), the National Drinking Water Supply Program (PN-AEP 2030, 2016-2030) and the investment programs of the National Office for Water and Sanitation (*Office National de l'Eau et de l'Assainissement, ONEA, in French*), the development of groundwater resources remains limited. In this area, the identification of productive fractures remains a major challenge for hydrogeologists [7]-[9]. Lineament mapping at the optical scale alone, even when combined with ground geophysics, shows its limitations for siting high-yield boreholes [7] [10] [11]. This limitation stems from intrinsic methodological constraints: 1) optical sensors capture only surface morphological expressions, vegetation alignments or topographic variations of the regolith, and provide no information on the vertical continuity or actual aperture of structures at depth [12]; 2) thick saprolites and lateritic duricrusts create a "spectral mask" that conceals the underlying fracture network [13]-[15]; 3) two-dimensional surface electrical prospecting suffers from a small lateral radius of investigation, which frequently leads to siting biases [16]-[18].

To overcome these constraints, this study tests the hypothesis that a multi-scale, multi-sensor approach combining aeromagnetic geophysics, radar remote sensing and multispectral optical imagery can identify zones of high hydrogeological potential in basement settings. The main objective of this study is to assess the influence of geological structures on the geometry and functioning of the aquifers of the Tenkodogo square degree. Three specific objectives are pursued: 1) to extract and validate lineament networks at the three selected observation scales (aeromagnetic, optical and radar); 2) to characterize their directional and dimensional organization, and then to locate and count the lineament intersection nodes that reflect network connectivity; 3) to compare the intersection node density map with borehole yields in order to assess its predictive value for borehole siting.

2. Study Area

2.1. Geographical Setting

The study covers the Tenkodogo square degree, located in the Centre-Est region of Burkina Faso, between latitudes 11° and 12° N and longitudes 0° and 1° W (**Figure 1**). It covers approximately 12,000 km². The relief of the area is generally moderate and gently undulating, typical of the Paleoproterozoic basement [19], and is organized into two main morphostructural units: a monotonous, gently rolling peneplain in its central part, at elevations between 175 and 300 m, and residual reliefs made up of inselbergs and isolated hills reaching about 500 m in elevation southeast of Zabré, on the border with Ghana [19]. Three vegetation types dominate: shrub and tree savanna, riparian and lowland formations, and anthropized vegetation [20].

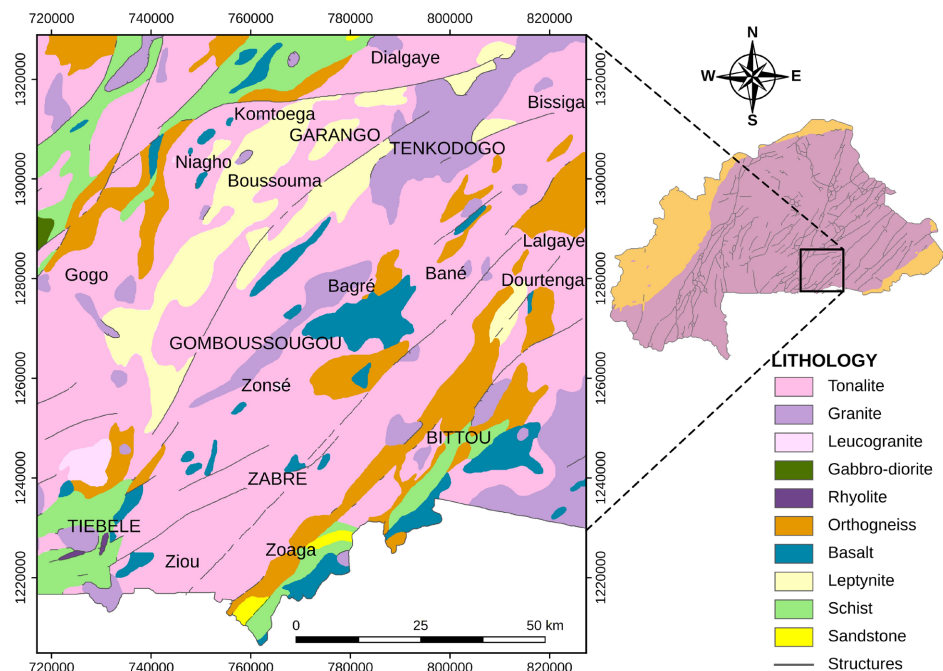


Figure 1. Simplified geological and location map of the Tenkodogo square degree [21] [22].

2.2. Geology and Hydrogeology

2.2.1. Geological and Structural Setting

The regional geology of the area consists of a series of metavolcanic (metabasalts, rhyolites) and metasedimentary (schists, sandstones, leptynites) greenstone belts assigned to the Birimian [23] [24] (**Figure 1**). These formations are intruded by large granitoid batholithic complexes, ranging from syntectonic TTG (tonalite-trondhjemite-granodiorite) suites to late potassic biotite- and amphibole-bearing granites [19] [25]. Structurally, the polyphase tectonic history is dominated by an early major ductile phase (D1/D2), expressed by schist belts and broad synmetamorphic ductile shear zones with a preferential NE-SW to NNE-SSW orientation [24] [26]. The geodynamic evolution ends with late phases (D3/D4) under brittle to semi-brittle conditions, which generated a network of strike-slip faults and associated fractures trending NW-SE to N-S [23] [27].

2.2.2. Hydrogeological Setting

Hydrogeologically, the area displays the general configuration of crystalline and metamorphic basement aquifers. The vertical organization and hydrodynamic behavior of these aquifers follow the conceptual model of [5] (**Figure 2**), whose application to groundwater prospecting has been further developed by geophysical and structural studies [8] [9] [28]. This composite aquifer system comprises two hydraulically connected horizons:

- **The regolith (weathered-layer) reservoir**

Developed near the surface and composed of clays, sometimes capped by a duricrust, and of coarse-grained grus (saprolite), this horizon provides the storage and retention function for groundwater [5] [29]. Its thickness generally ranges from 15 to 45 m, in line with observations made on the crystalline basement of Burkina Faso [8] [9]. The shallow water table hosted in this weathered layer lies at depths of 5 to 18 m and is strongly influenced by the morphology of the bedrock surface and by seasonal fluctuations in recharge [9] [30].

- **The fissured and fractured basement reservoir**

Its upper part consists of the weathering-induced fissured horizon, a few meters to a few tens of meters thick, underlain by a network of subvertical tectonic fractures [5] [28]. This reservoir provides the drainage and hydraulic conduction function [9] [31]. The total depth of boreholes tapping this aquifer generally ranges from 50 to 90 m, with water inflows most often intersected between 35 and 70 m depth, within the network of weathering fissures and at tectonic fracture nodes [8] [31]; deeper water inflows may nevertheless be encountered locally where the hydraulic connectivity of the fracture network is established only at greater depth (see Section 5.3, borehole SE9 at Garango). This two-layer scheme is consistent with the weathering profile concept [6], according to which the fissured horizon generated by weathering, rather than tectonic fractures alone, provides much of the transmissive function of basement aquifers; deeper subvertical fractures may then provide additional, more localized hydraulic connections.

The spatial distribution of groundwater resources remains highly heterogeneous. Boreholes generally show modest to moderate yields (0.5 to 7 m³/h), whereas those sited on major, highly water-bearing tectonic structures achieve high yields ranging from 15 to more than 30 m³/h [8] [9] [32]. In this paper, boreholes yielding more than 15 m³/h are considered high-yield boreholes.

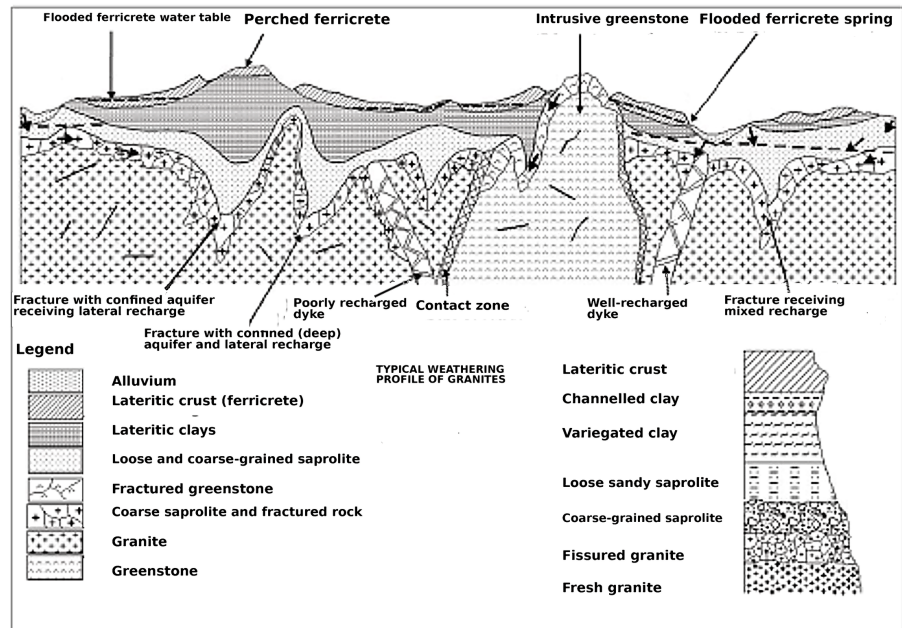


Figure 2. Mode of groundwater occurrence in the crystalline basement of Burkina Faso [5].

3. Materials

The study relies on the combination of three types of multi-source data: 1) an aeromagnetic survey of the total magnetic intensity (TMI) at a scale of 1:200,000, acquired with a flight-line spacing of 500 m and a nominal flight height of 100 m [33]; 2) a Landsat 8 OLI/TIRS scene (Path 194/Row 052), acquired in November 2016, with a spatial resolution of 30 m [34]; 3) a mosaic of eight ALOS PALSAR scenes (L-band, wavelength $\lambda = 23.6$ cm), acquired between June 2008 and August 2009 in Fine Beam Dual polarization mode (HH and HV) and resampled to a spatial resolution of 12.5 m [35].

All geophysical and remote sensing layers were projected into the WGS 84/UTM zone 30N coordinate system. The characteristics and acquisition modes of these data are summarized in **Table 1**.

Table 1. Acquisition characteristics of the geophysical and remote sensing data [33]-[35].

Platform/sensor	Spatial resolution	Band/signal	Depth level
Airborne magnetometer	100 m grid	Total magnetic intensity	Deep basement structures, major shear zones
Landsat 8 OLI	30 m	Optical/NIR/SWIR	Surface morphostructures, weathering
ALOS PALSAR	12.5 m	L-band radar (HH/HV)	Surface linear features, possibly related to shallow fracturing

ENVI, Global Mapper, Geomatica and ArcGIS were used for image processing, Oasis Montaj for aeromagnetic data processing, RockWorks for directional analysis (rose diagrams) and the R environment for spatial and statistical analysis, with ArcGIS also used for computing intersection nodes, and Python (Shapely and SciPy libraries) for checking duplicate removal and computing densities.

4. Methodology

The approach adopted relies on a multi-criteria, multi-source analysis, summarized by the processing workflow shown in **Figure 3**. This strategy builds on the integration of heterogeneous data and on a sequence of preprocessing steps, including geometric and radiometric corrections and filtering, followed by mixed (manual and automatic) lineament extraction phases. These lineaments are validated against existing geological data and field checks. The aim is to draw on the convergence of geological, magnetic and satellite evidence in order to characterize fracturing across the study area in an objective and reproducible manner.

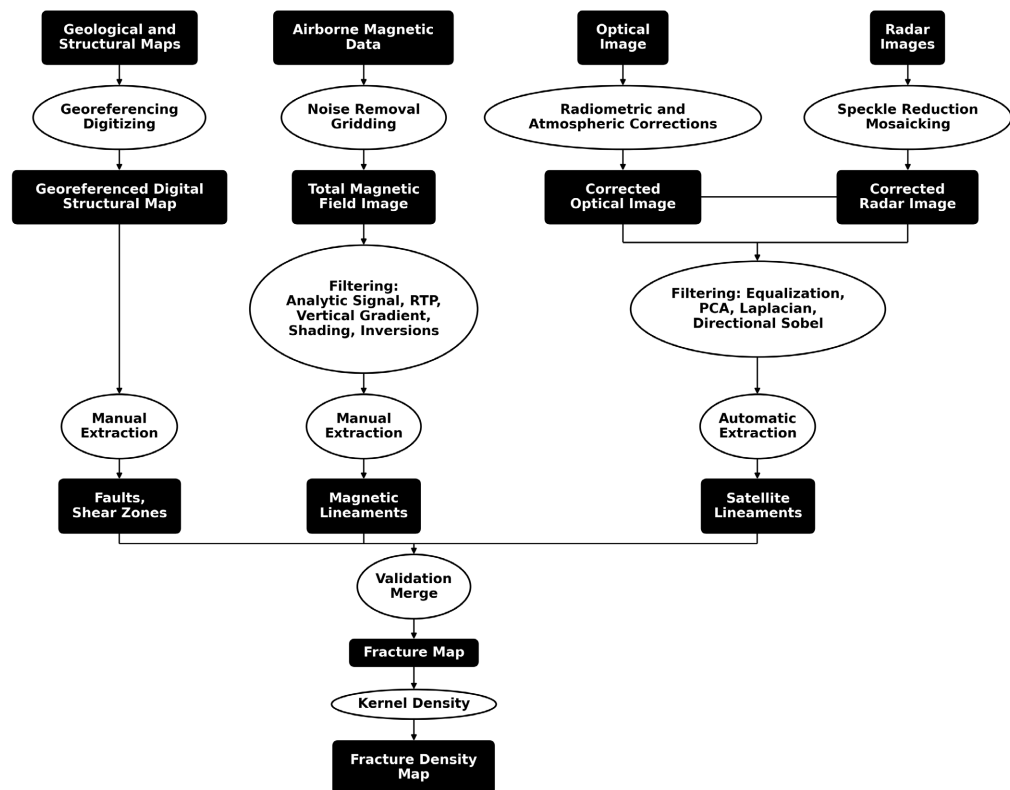


Figure 3. Methodological workflow for the extraction and characterization of fracturing.

4.1. Preprocessing

4.1.1. Landsat 8 OLI Optical Imagery

The Landsat 8 OLI images first underwent radiometric and atmospheric corrections in ENVI 5.3. The RGB 7-2-4 color composite was selected after comparing several band combinations. It combines a shortwave infrared (SWIR) band, sen-

sitive to clay minerals and to hydroxyl groups produced by weathering, with two weakly correlated visible bands, and maximizes the spectral variance rendered, thereby optimizing the discrimination of lithologies and lateritic duricrusts in basement settings [14] [36] (**Figure 4(a)**). Principal component analysis (PCA), applied to decorrelate redundant spectral information, captures more than 95% of the total variance in the first two components (PC1 and PC2); PC1, which carries most of the morphostructural signal, was selected as the basis for extraction (**Figure 4(b)**) [37].

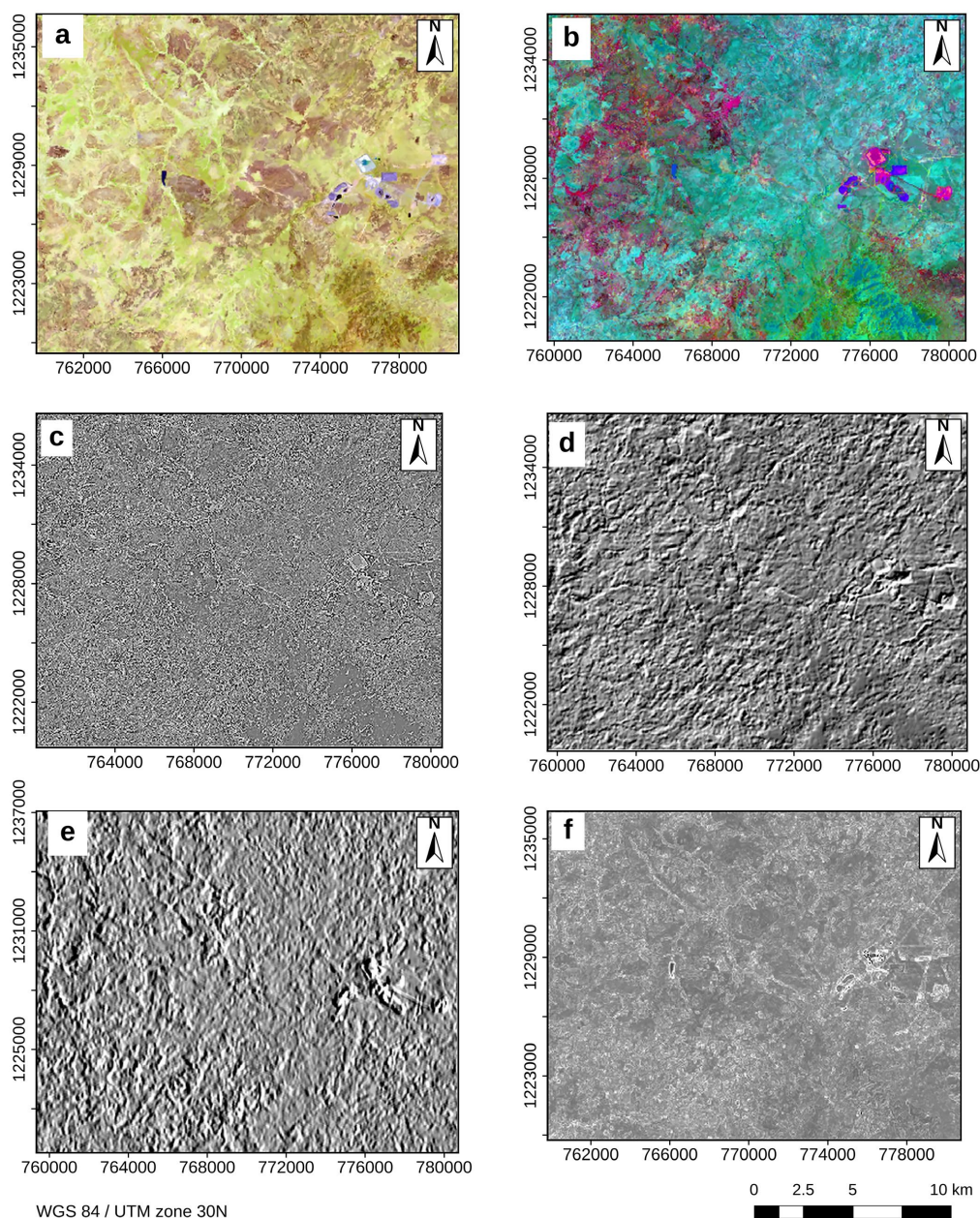


Figure 4. Processing sequence applied to the optical satellite image: (a) RGB 7-2-4 color composite; (b) first principal component (PC1); (c) Laplacian filtering; (d) NW-SE directional filter; (e) NE-SW directional filter; (f) Sobel filter oriented at 30° (NE).

To enhance the morphostructural signature of lineaments, several spatial enhancement operators were applied, following procedures that have proven effective in basement settings [36] [37]: the Laplacian filter (**Figure 4(c)**), which accentuates zones of high luminance gradient (scarps and breaks in slope), supplemented by directional filters (3×3 and 7×7 windows) applied along the preferential NW-SE (**Figure 4(d)**), NE-SW (**Figure 4(e)**) and N30° (**Figure 4(f)**) directions. The use of several filtering directions is intended to compensate for illumination bias, which systematically under-represents structures parallel to the direction of solar illumination [36].

4.1.2. Radar Imagery (ALOS PALSAR)

The PALSAR scenes were mosaicked in ENVI using an edge-feathering algorithm designed to attenuate radiometric discontinuities between scenes. Speckle, the multiplicative noise inherent in synthetic aperture radar imagery, was reduced using the adaptive Lee filter (5×5 window), which smooths areas of uniform backscatter while preserving linear boundaries [38]. Analysis of the polarization modes highlights the complementary contribution of each polarization. HH co-polarization (**Figure 5(a)**) brings out the major morphostructural units, whereas HV cross-polarization (**Figure 5(b)**), owing to its high sensitivity to microtopographic roughness in sparsely vegetated areas, was preferred for mapping surface linear features. At L-band, ground penetration does not exceed a few decimeters, even in dry sandy soils, so that these features reflect surface roughness, moisture and vegetation patterns rather than directly imaged fractures [36].

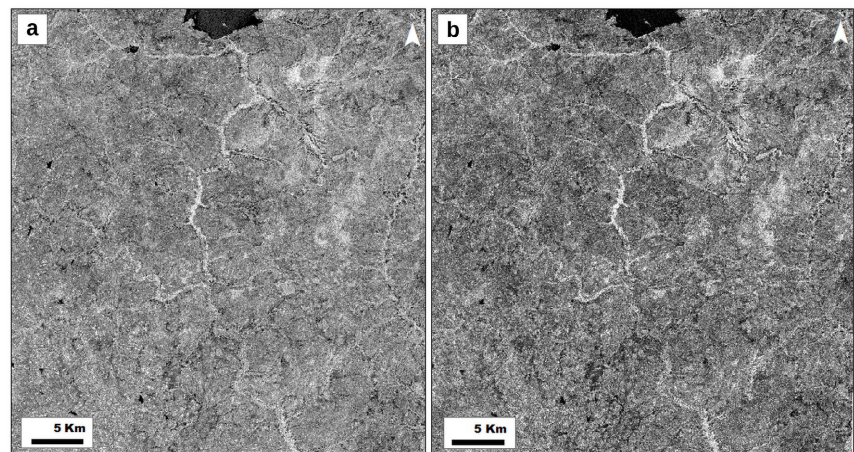


Figure 5. Radar images: (a) HH polarization; (b) HV cross-polarization.

4.1.3. Aeromagnetic Data

The airborne magnetic data were processed in Oasis Montaj (Geosoft). The preliminary steps consisted of removing the International Geomagnetic Reference Field (IGRF) and statistically leveling the flight lines to eliminate flight noise. The corrected total magnetic intensity (TMI) grid was then reduced to the pole (RTP), with low-latitude stabilization, in order to recenter magnetic anomalies over their sources and thus remove the dipolar effect associated with the local magnetic in-

clination [39] [40].

To highlight the signature of shallow to moderately deep geological structures, the first and second vertical derivatives (1VD and 2VD) were computed. As high-pass operators, they enhance the high-spatial-frequency components of the field and sharpen gradients at contacts [40] (**Figure 6(b)**). Directional shading applied to the vertical gradient at azimuths N0°, N45°, N90° and N135° markedly enhanced magnetic contrasts at lithological contacts and shear zones (**Figure 6(a)**). Finally, combining the analytic signal (AS), whose three-dimensional gradient amplitude is independent of the magnetization direction and of the remanent component, with the second vertical derivative completed the filtering for the accurate extraction of structural lineaments [41] [42].

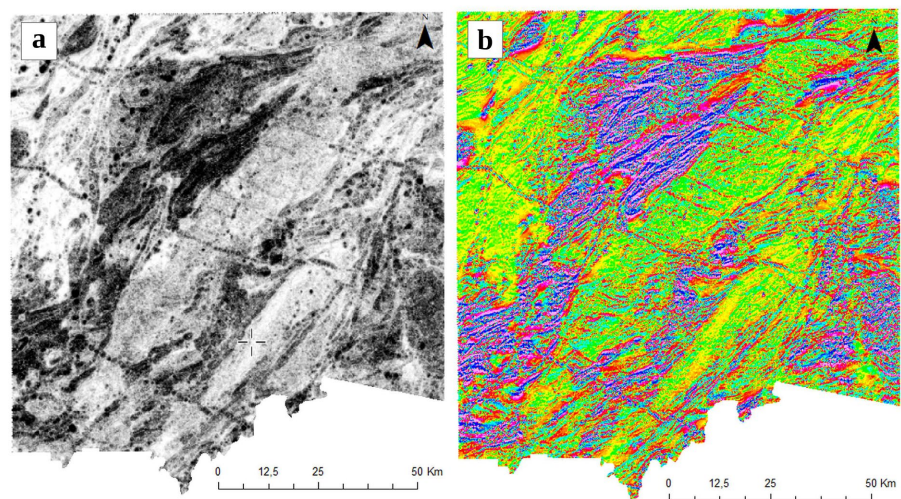


Figure 6. Geophysical processing applied to the reduced-to-the-pole (RTP) aeromagnetic grid: (a) shaded vertical gradient of the total magnetic intensity; (b) first vertical derivative (1VD) map.

4.2. Structural Mapping

A hybrid (manual and automatic) structural extraction approach was adopted to characterize the fracture network at different scales and depths.

4.2.1. Manual Extraction of Geophysical Lineaments

Manual extraction relies on the visual interpretation and on-screen digitizing of structural discontinuities on maps derived from the total magnetic intensity. Magnetic lineaments were digitized by following alignments of gradient maxima, polarity reversals, inflections of magnetic contours and offsets of linear anomalies [42] [43]. The following rules were applied: 1) digitizing was performed on screen at display scales between 1:200,000 and 1:50,000, lineaments being traced as straight or gently curved polylines (3.5 vertices per lineament on average); 2) the minimum accepted length was 200 m (shortest retained lineament: 205 m; 95% of lineaments exceed 2.7 km); 3) a lineament had to be visible on at least three of the four derived products (first and second vertical derivatives, analytic signal and

shaded vertical gradient); 4) aligned segments less than 300 m apart were merged into a single lineament. Digitizing was carried out by the first author, and the resulting map was checked successively by the third and then by the second author; lineaments on which the interpreters disagreed were discarded. This procedure yielded 502 aeromagnetic lineaments. Interactive digitizing on these combined maps (**Figure 7(a)**) made it possible to map accurately the main lineament axes, offsets and structural intersections of the basement (**Figure 7(b)** and **Figure 7(c)**).

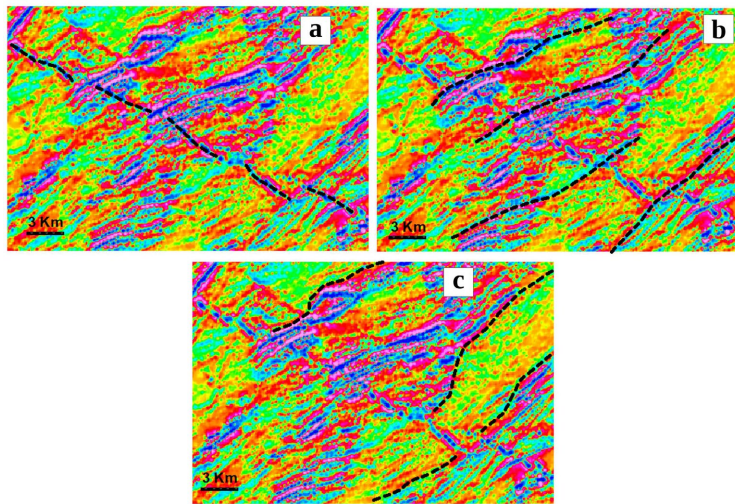


Figure 7. Manual extraction of lineaments on the first vertical derivative of the analytic signal of the total magnetic intensity.

4.2.2. Automatic Extraction of Satellite Lineaments

Automatic extraction was applied to all derived optical products (Landsat 8: PC1, NW-SE and NE-SW directional filters, N30° Sobel filter) and radar products (ALOS PALSAR, HV polarization). Processing was performed with the LINE module of PCI Geomatica (**Figure 8**), which is based on edge detection followed by vector chaining of edge pixels [44]. The threshold parameters were calibrated according to the spatial resolution of each sensor (**Table 2**).

Table 2. Calibration parameters of the LINE module (PCI Geomatica) for automatic lineament extraction.

Threshold parameter	Landsat 8 OLI (30 m)	ALOS PALSAR (12.5 m)	Role and geometric rationale
RADI (filter radius)	3 pixels	5 pixels	Adapted to the spatial gradient according to the native resolution.
GTHR (edge gradient threshold)	30	50	Adjusted to the reflectance/backscatter dynamic range.
LTHR (minimum curve length)	10 pixels (~300 m)	24 pixels (~300 m)	Normalization of the minimum ground length (≥ 300 m).
FTHR (line-fitting error threshold)	3 pixels	3 pixels	Maximum allowable deviation along the segment.
ATHR (maximum angular difference)	15°	15°	Angular continuity threshold between adjacent segments.
DTHR (linking distance threshold)	2 pixels	4 pixels	Maximum linking distance between segments.

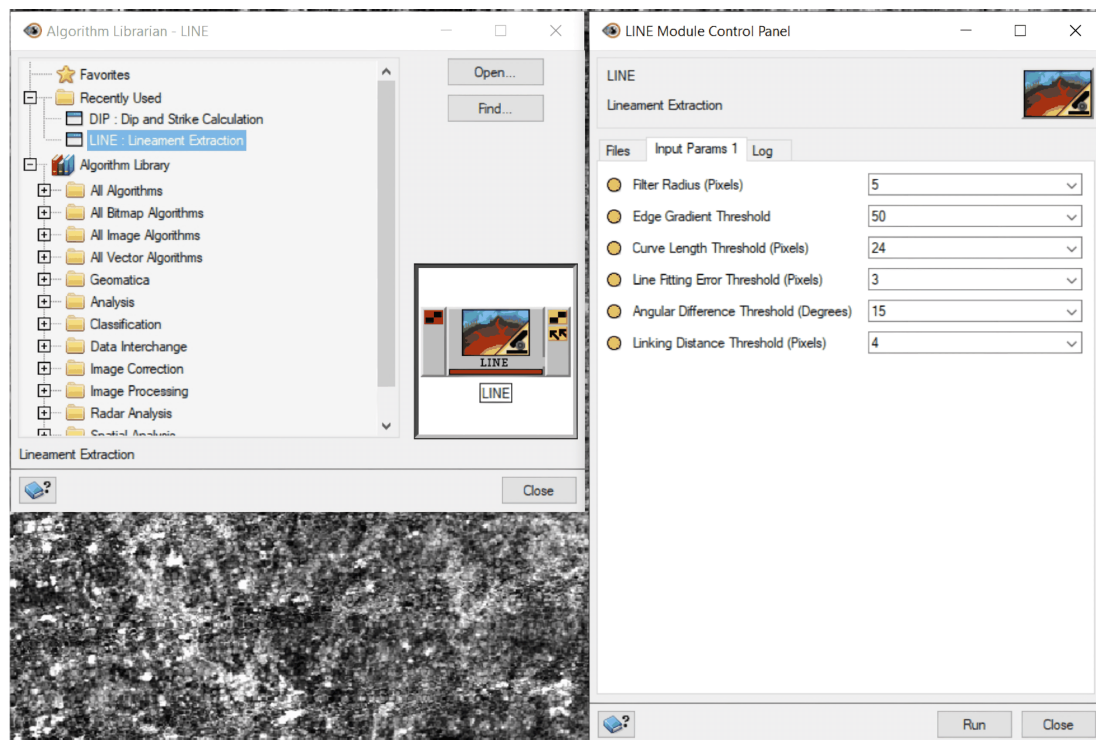


Figure 8. Automatic lineament extraction in PCI Geomatica (LINE module).

4.2.3. Validation, Filtering and Synthesis of the Structural Network

Validation was structured in three steps: 1) removal of anthropogenic and topographic biases by cross-checking against the road and drainage networks [44] [45]; 2) comparison with existing geological maps [14] [21] [46]; 3) field validation and direct structural measurements on rock outcrops [26] [47]. A complementary field campaign was conducted at 17 outcrop stations (ST1-ST17, **Figure 9**): six around Tenkodogo (ST1, ST2, ST4, ST5, ST16, ST17), two around Garango (ST3, ST6), one at Béguédo (ST8), five west of Niaogho (ST7, ST9-ST12) and three at Gomboussougou (ST13-ST15). One structure was measured at each station with a compass-clinometer (joints, sealed fractures, quartz veins, shear bands, a pegmatite dyke, planar fabrics and a relict foliation). Lineaments crossing the surroundings of these stations were identified beforehand on the maps and then checked in the field. The aeromagnetic lineaments were compared with the geological and structural maps of BUMIGEB [21], and those located within 500 m of the stations were also checked in the field, whereas the Landsat and PALSAR lineaments located within 500 m of the stations were checked in the field only. A lineament was considered confirmed when fractures or quartz veins consistent with its trace were observed on outcrop. Of the 99 lineaments checked (21 aeromagnetic, 34 optical and 44 radar), 77 were confirmed (19 aeromagnetic, 27 optical and 31 radar), *i.e.*, an overall agreement rate of 77.8% (**Table 3**). Of the 21 aeromagnetic lineaments checked, 19 were confirmed by the BUMIGEB maps, and the 9 located within 500 m of the stations were also confirmed in the field. These checks concern a small fraction of the networks (99 of 44,742 lineaments)

located around the stations, and they therefore constitute a local check rather than a statistical validation of the whole networks. The measured steeply dipping structures define four sets (N150° - N004°, N029° - N036°, N080° - N085° and N112° - N125°), which match the main lineament trends and the N-S shear direction of the regional structural framework (Section 2.2.1).

Table 3. Field validation of the lineament networks at the 17 field stations (ST1 - ST17).

Source	Retained lineaments	Field-checked (n)	Confirmed (n)	Agreement rate (%)	Basis of verification
Aeromagnetic	502	21	19	90.5	BUMIGEB maps and field
Landsat 8 OLI	4476	34	27	79.4	Field
ALOS PALSAR	39,764	44	31	70.5	Field
Total	44,742	99	77	77.8	–

4.3. Spatial Mapping and Geostatistical Analysis of the Fracture Network

The spatial orientation and geometric distribution of the lineaments were processed in RockWorks and R. Rose diagrams were generated to identify the preferential tectonic directions and the associated fracture sets. The three validated networks were then merged into a composite structural network, which served as the basis for computing intersection nodes.

The lineament intersection node density (D_n) was selected for structural mapping. In basement settings, the productivity of a fissured aquifer depends partly on the connectivity of discontinuities. Crossing points between fracture sets of different orientations are widely regarded as concentrating secondary permeability and increasing the probability of intercepting an open structure, and hence as favorable siting targets [13] [14] [46]. The composite structural network was therefore subjected to a topological intersection computation (ArcGIS 10.8, Intersect tool, point output). Every crossing or contact between two distinct lineaments was retained as a node, without any filter on the difference in trend between the intersecting lineaments. Since the tool records each intersection once for each of the lineaments involved, points with identical coordinates were then reduced to a single node. No tolerance-based merging was applied between segments from different sources, and 19,504 pairs of nodes less than 12.5 m apart (one PALSAR pixel) remain, which has no significant effect at the scale of the 5 km smoothing radius. This procedure yielded $N = 192,030$ intersection nodes within the study area (11,739 km²), *i.e.*, a mean density of about 16 nodes/km². Field validation applies to the lineaments (Table 3), and the nodes were not validated individually, the density of field stations being too low for this purpose. The density D_n was then computed by quartic kernel estimation [48] with a cell size of 100 m and a search radius r of 5 km. The cell size only sets the resolution of the output raster, whereas r controls the degree of smoothing: too small a radius produces noisy maps dominated by isolated nodes, while too large a radius oversmooths the map

and merges distinct structural corridors. As a consistency check, the integral of the D_n surface over the study area equals N (192,030 nodes). D_n expresses the number of intersection nodes per unit area (nodes/km²) and is written, according to the quartic kernel formulation, as:

$$D_n(x, y) = \frac{1}{r^2} \sum_{i=1}^n K\left(\frac{d_i}{r}\right), \text{ with } K(u) = \frac{3}{\pi}(1-u^2)^2, u \leq 1 \quad (1)$$

where $D_n(x, y)$ is the lineament intersection node density at the point of coordinates (x, y) , expressed in nodes/km²; d_i is the distance between the cell center (x, y) and intersection node i (km); r is the search radius or smoothing window (bandwidth, km); n is the number of nodes located within the window of radius r ; and K is the quartic kernel function [37] [48]. In this formulation, nodes are unweighted, so that the indicator reflects network connectivity only, regardless of the length or source of the intersecting lineaments.

5. Results and Discussion

5.1. Directional Frequencies and Spatial Distribution

5.1.1. Magnetic Structures

The aeromagnetic data yield 502 major lineaments, distributed in a bimodal pattern dominated by a major NW-SE trend (N120° - 140°) and a secondary NE-SW trend (N40° - 60°). These structures are characterized by a large spatial extent, with lengths frequently exceeding 15 km and sometimes reaching more than 100 km at the regional scale, reflecting deep crustal structuring (**Figure 9(a)**). They correspond to Eburnean shear zones and dyke swarms [15] [19]. Because magnetic lineaments reflect magnetization contrasts (shear zones, lithological contacts, dykes) rather than hydraulic properties, their hydrogeological role is variable: shear zones may act as regional drains and preferential recharge corridors if they remain open at depth, whereas dykes, mineralized zones or structures sealed by secondary infilling may behave as barriers. In line with the basement aquifer model of [5], this hypothesis remains to be tested by pumping tests carried out on boreholes sited directly on these structures.

5.1.2. Landsat 8 Satellite Structures

Landsat 8 optical imagery yields 4476 lineaments. Unlike the aeromagnetic network, their directional distribution shows a more even, multidirectional spread, with predominant regional modes trending E-W to NW-SE and NE-SW (**Figure 9(b)**). These lineaments have typical (median) lengths of 3.6 to 5.1 km, reflecting the geomorphological imprint of brittle tectonics and of drainage network incision [14] [36].

5.1.3. ALOS PALSAR Radar Structures

ALOS PALSAR radar imagery yields 39,764 lineaments, forming a very dense network of short surface linear features (**Figure 9(c)**) with no marked preferential orientation (each 10° class contains 5% to 6% of the lineaments). Some of them

may be associated with shallow fissuring, through the control exerted by joints and fissures on microrelief, soil moisture and vegetation alignment, but their continuity at depth cannot be established from imagery alone. Where they do reflect fracturing, such a dense network could enhance connectivity between the surface and the weathered-fissured zone, and hence meteoric recharge.

In that case, this network would be linked to the upper part of the weathered-fissured zone, where fissure porosity and a direct connection with rainwater infiltration are expected. Since L-band radar lineaments may also reflect alignments related to drainage, vegetation or land use, only those retained after the validation step (Section 4.2.3) were taken into account.

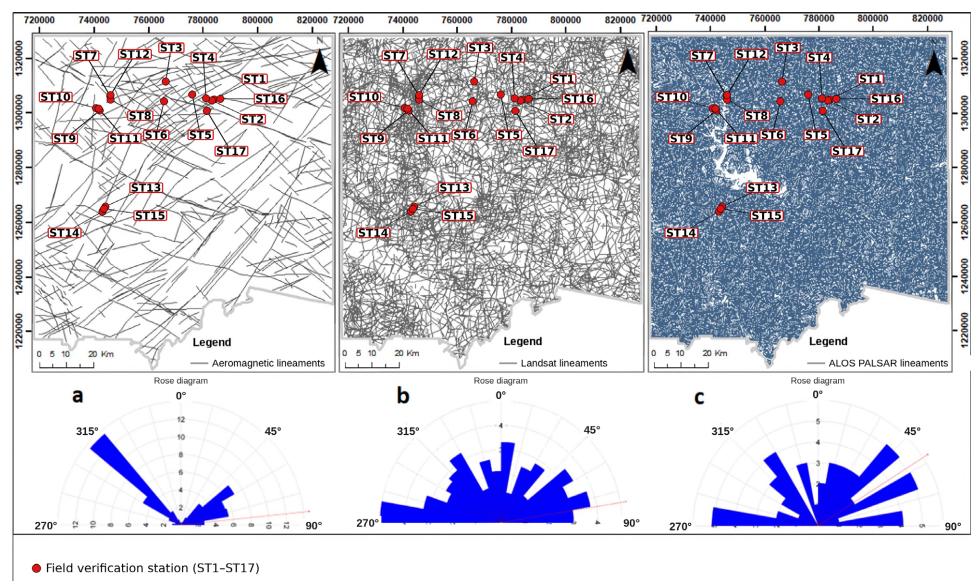


Figure 9. Directional frequencies and spatial distribution of lineaments (a: aeromagnetic, b: optical, c: radar) and location of the field stations ST1-ST17.

5.2. Dimensions and Structural Organization

Statistical analysis of the length distribution by directional class reveals a hierarchical, multi-scale organization of fracturing. Aeromagnetic lineaments (**Figure 10(a)**) show the highest median values (7 to 16 km) together with very high dispersion; the greatest lengths are observed in the $(40^\circ, 60^\circ]$ class (NE-SW), where major structures reach 86 to 120 km, whereas the maxima of the other classes remain below about 60 km. Conversely, the length distribution of optical lineaments (**Figure 10(b)**) is remarkably uniform from one directional class to another, with consistent medians of 3.6 to 5.1 km and maxima between 28 and 58 km, indicating continuous second-order lineaments. Radar lineaments (**Figure 10(c)**), for their part, have the smallest dimensions, with medians below 1 km, and their length shows no significant dependence on orientation class. This progressive decrease in median length from one observation scale to the next suggests a quasi-hierarchical, scale-dependent organization of the fracture network, comparable to that described in the Birimian basement of Côte d'Ivoire and Burkina Faso [14]

[15]; no formal test of scale invariance (e.g., fitting of length-frequency power laws) was performed in this study. Above all, it implies that the three networks sample different ranges of scale and are therefore complementary, which justifies merging them before any counting of intersection nodes.

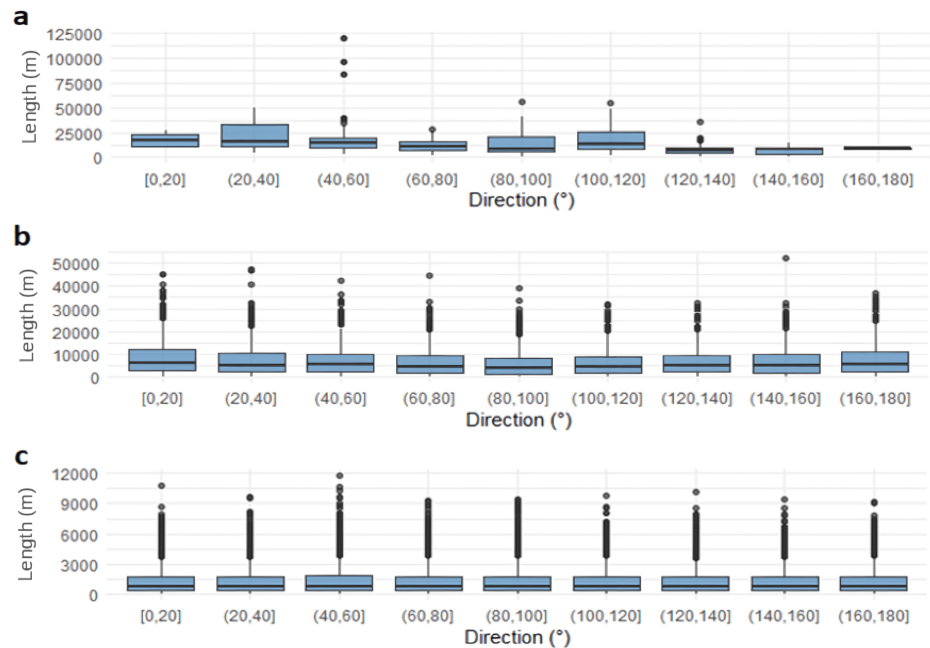


Figure 10. Distribution of lineament lengths by orientation (a: aeromagnetic, b: optical, c: radar).

Aeromagnetic lineaments form the regional structural framework of the crystalline basement. Their spatial continuity confirms the existence of large crustal deformation corridors likely to drain groundwater and to connect the various sub-basins [5] [46]. In the basement aquifer model [5], such structures are interpreted as the preferred pathways for long-distance lateral transfer; although plausible at the scale of the Tenkodogo square degree, this function remains to be demonstrated by dedicated piezometric and hydrochemical monitoring. Conversely, the optical and radar networks, which are highly fragmented and have shorter individual lengths, form a dense network of surface features which, where they reflect shallow fracturing, may promote the infiltration of meteoric water towards the underlying fissured zone and deeper reservoirs [46]. The complementarity observed between these three observation scales corroborates the conclusions of [15] [37], according to which no single sensor captures the full dimensional spectrum of fracturing in a crystalline basement.

5.3. Characterization of Lineament Intersection Node Density and Hydrogeological Implications

Analysis of the lineament intersection node density (D_n) reveals marked structural heterogeneity within the basement of the Tenkodogo square degree, with values ranging from 1.2 to 31.6 nodes/km² (mean 15.9 nodes/km²). This spatial distribu-

tion divides the aquifer medium into intensely tectonized, highly connected corridors ($D_n > 20$ nodes/km², 19.7% of the study area), stable, weakly fractured and poorly connected blocks ($D_n < 10$ nodes/km², 11.3%), and an intermediate class ($D_n = 10$ to 20 nodes/km², 69.0%) corresponding to moderately fractured zones.

Among the boreholes in the ONEA databases [49] located within the study area, 1307 have coordinates and an end-of-drilling yield measured by airlift, including 161 dry boreholes. Overlaying them on the intersection node density map (Figure 11), with extraction of the D_n value at each borehole, shows that they cluster around Tenkodogo and the other main localities: 36.6% of them are located where $D_n > 20$ nodes/km², whereas this domain covers only 19.7% of the study area. This clustering reflects the location of settlements rather than a hydrogeological choice, since most of these boreholes were sited to supply drinking water to localities as close as possible to dwellings, without any prior detailed hydrogeological investigation. Their yields are predominantly low: 53.6% of the boreholes yield 3 m³/h or less, 23.7% between 3 and 7 m³/h, 16.5% between 7 and 15 m³/h, and only 80 boreholes (6.1%) more than 15 m³/h, consistent with the typical range of basement aquifers (Section 2.2.2).

The distribution of these yields by D_n class is given in Table 4. The proportion of boreholes exceeding 15 m³/h does not increase steadily with D_n : it is zero in the $D_n < 10$ nodes/km² class (37 boreholes), 5.8% where $D_n < 15$ nodes/km² and 7.7% where $D_n > 20$ nodes/km², with a maximum of 9.5% above 25 nodes/km². The clearest contrast concerns low-yield boreholes, whose proportion (3 m³/h or less) decreases from 64.1% where $D_n < 15$ nodes/km² to 45.1% where $D_n > 20$ nodes/km². The yield distribution depends significantly on the D_n class (chi-square test, two lowest classes merged, $\chi^2 = 32.3$, df = 9, $p < 0.001$), but the rank correlation between D_n and yield, computed on individual values, remains weak (Spearman's $\rho = 0.13$, $p < 0.001$). Because the boreholes are spatially clustered around towns and villages, these tests overestimate the effective sample size and should be regarded as indicative.

Table 4. Distribution of end-of-drilling yields of the 1307 boreholes in the study area by intersection node density class (number of boreholes, with the percentage of the class in parentheses).

D_n class (nodes/km ²)	n	$Q \leq 3$ m ³ /h	$3 < Q \leq 7$ m ³ /h	$7 < Q \leq 15$ m ³ /h	$Q > 15$ m ³ /h
<10	37	22 (59.5%)	10 (27.0%)	5 (13.5%)	0 (0.0%)
10 - 15	222	144 (64.9%)	36 (16.2%)	27 (12.2%)	15 (6.8%)
15 - 20	569	319 (56.1%)	132 (23.2%)	90 (15.8%)	28 (4.9%)
20 - 25	384	167 (43.5%)	112 (29.2%)	77 (20.1%)	28 (7.3%)
25 - 31.6	95	49 (51.6%)	20 (21.1%)	17 (17.9%)	9 (9.5%)
Total	1307	701 (53.6%)	310 (23.7%)	216 (16.5%)	80 (6.1%)

By contrast, the targeted siting of geophysical stations in zones of high and very high intersection node density led to two productive boreholes, SE1 at Tenkodogo

and SE9 at Garango (Figure 11). The D_n values extracted from the raster at their coordinates are 23.5 nodes/km² for SE1 and 23.7 nodes/km² for SE9, both in the 20 - 25 nodes/km² class (Table 5). Both boreholes therefore lie within the densest 5% of the study area (5.2% for SE1 and 4.7% for SE9). Their end-of-drilling yields, measured by airlift, are 50 m³/h and 18 m³/h, respectively, *i.e.*, well above the range usually observed in the basement aquifers of the area (0.5 to 7 m³/h) [8] [9] [32].

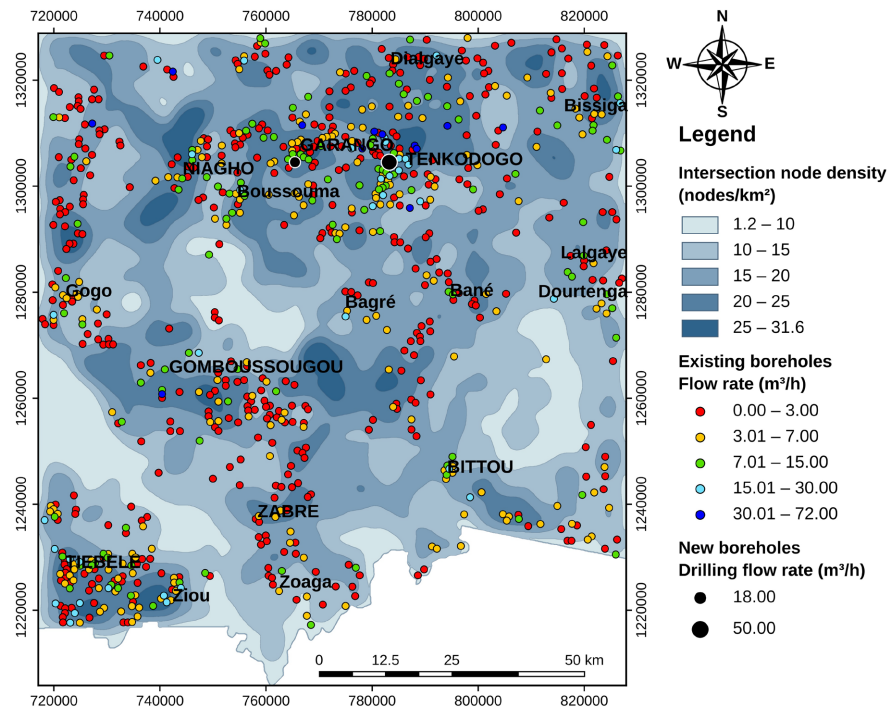


Figure 11. Lineament intersection node density map showing the location of existing boreholes and of the new high-yield boreholes drilled [21] [22] [34] [35] [49] [50]. The D_n values at boreholes SE1 and SE9 are given in Table 5.

These results can be explained by the fact that intersection nodes combine two favorable conditions: they mark the crossing of potentially highly transmissive structures that can act as drains, and they maximize network connectivity, thereby increasing the probability that a borehole intersects an open structure continuously fed by water stored in the surrounding weathered layer [5]. As pointed out by [9], however, lineament density alone does not guarantee success, since a fracture may be sealed by quartz infilling or closed under lithostatic stress. The results from these two boreholes are consistent with open, hydraulically active NE-SW and NW-SE fracture sets at their intersections, but two boreholes cannot demonstrate this at the scale of the Tenkodogo square degree.

- Borehole SE1 at Tenkodogo

Analysis of the lithological and technical log of borehole SE1 at Tenkodogo (Figure 12) reveals a classic and particularly favorable weathering profile of the granitoid basement. A substantial thickness of weathered material (clayey to arenitic saprolite, 0 to 20 m) overlies the bedrock.

Combined with a shallow static water level (SWL = −9.30 m), this horizon acts as a capacitive reservoir and stores infiltrating water. The saturated thickness of weathered material below the static water level reaches 10.7 m, corresponding to the difference between the base of the weathered layer (20.0 m) and the depth of the static water level (9.30 m).

The granitic bedrock shows moderate fissuring between 20 and 35 m, followed by a first highly fractured, water-bearing zone between 35 and 51 m. A second moderately fissured horizon is observed between 51 and 57 m, before another highly productive fractured zone between 57 and 64 m. Two major water inflows are intersected there: WI1 (18 m³/h at 43 m) and WI2 (20 m³/h at 62 m). Following well development operations, the unclogging of fractures raised the end-of-drilling (airlift) yield to 50 m³/h.

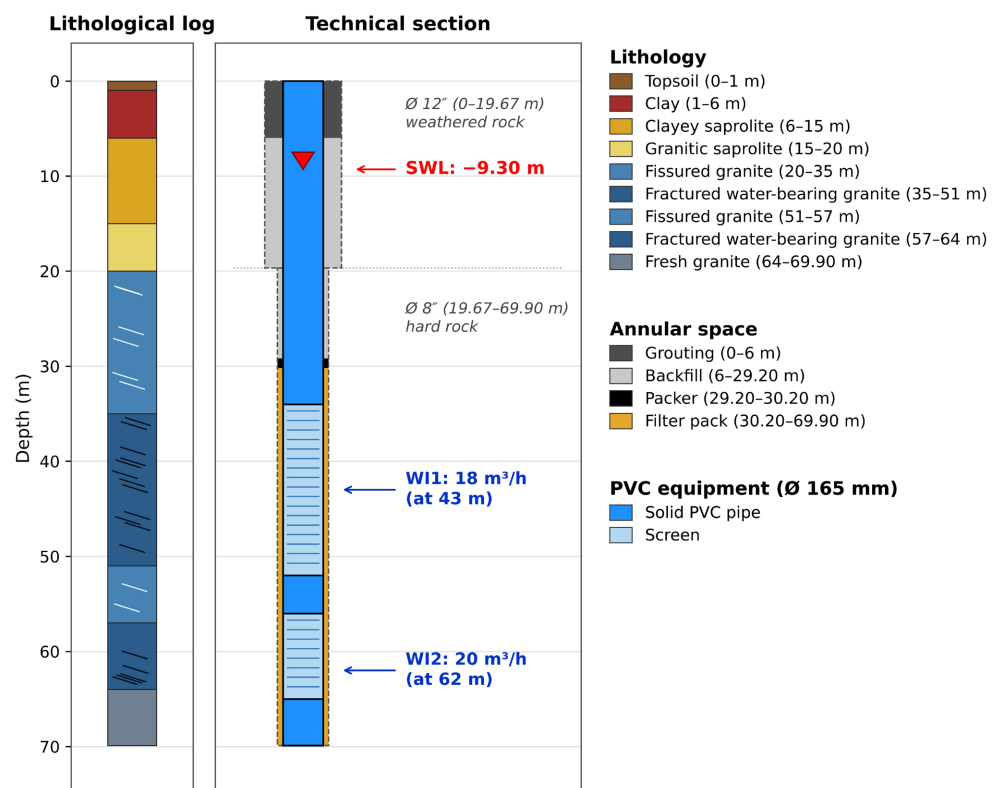


Figure 12. Lithological and technical log of borehole SE1 at Tenkodogo.

- Borehole SE9 at Garango

The lithological and technical log of borehole SE9 at Garango illustrates the influence of the geometry of the deep fractured zone (Figure 13). The weathered mantle is much thinner here (0 - 7 m) and rests directly on weakly fissured granite (7 - 12 m), which is then fractured but dry between 12 and 64 m. Despite a shallower static water level (SWL = −5.32 m), the productive fractures are effectively interconnected and water-bearing only at depth, between 64 and 84 m. The saturated thickness of weathered material below the static water level is only 1.7 m,

corresponding to the difference between the base of the weathered layer (7.0 m) and the depth of the static water level (5.32 m), compared with 10.7 m at borehole SE1 (20.0 m - 9.30 m). This small thickness of the capacitive reservoir may partly explain the lower productivity of this borehole compared with borehole SE1 at Tenkodogo. Two main water inflows are recorded at the bottom of the borehole: WI1 = 12 m³/h at 76 m and WI2 = 6 m³/h at 82 m, giving a cumulative end-of-drilling (airlift) yield of 18 m³/h.

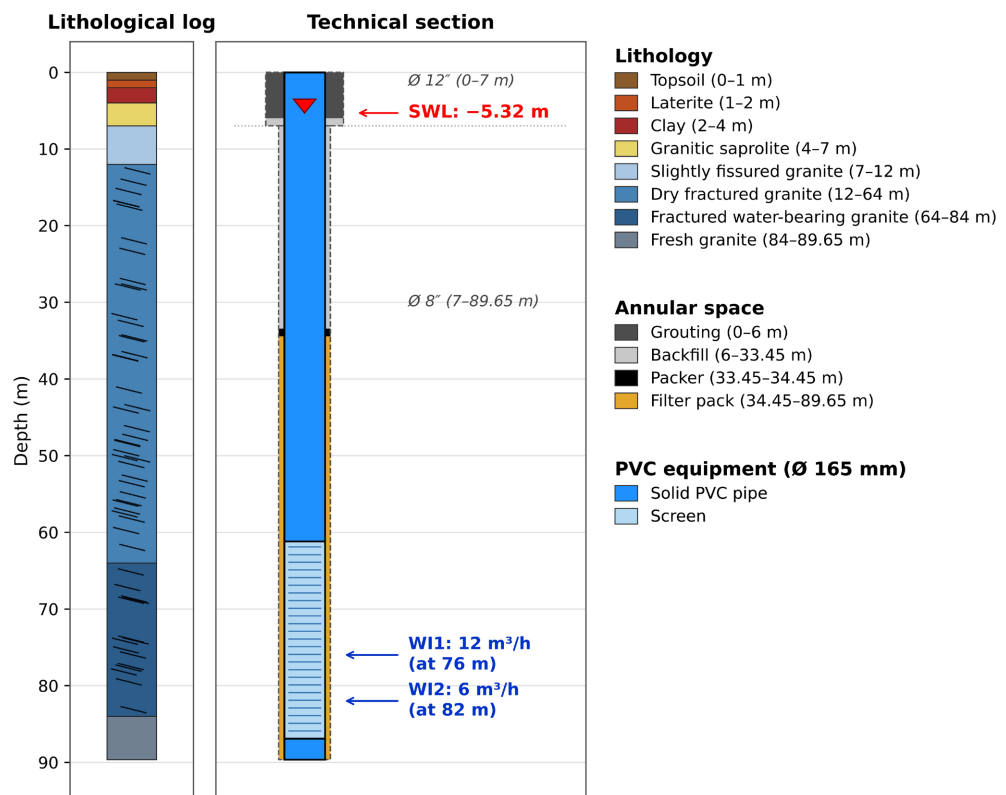


Figure 13. Lithological and technical log of borehole SE9 at Garango.

The main parameters of the two boreholes are summarized in **Table 5**.

The interpretation of the two boreholes is consistent with the conceptual model of groundwater occurrence in the West African basement [5]. The upper weathered layer provides the storage volume, whereas the intersection nodes between the major NE-SW and NW-SE fractures, intersected at depth, are interpreted as high-conductivity structures draining the water stored in the overlying weathered mantle [5] [31]. The difference in productivity between the two boreholes is probably related, at least in part, to the saturated thickness of weathered material below the static water level, which is much greater at Tenkodogo (10.7 m) than at Garango (1.7 m) and may provide more direct and sustained recharge to the underlying fracture network [29] [30]. Other factors, such as fracture aperture, the number and connectivity of water-bearing fractures and the effect of well development, cannot be ruled out.

Table 5. Comparative summary of the technical and hydrodynamic parameters of boreholes SE1 (Tenkodogo) and SE9 (Garango).

Parameter	SE1—Tenkodogo	SE9—Garango
Thickness of the weathered layer	0 - 20 m	0 - 7 m
Static water level (SWL)	−9.30 m	−5.32 m
Saturated weathered thickness below SWL	≈10.7 m	≈1.7 m
Moderately fissured zone	20 - 35 m; 51 - 57 m	7 - 12 m (weakly fissured)
Highly fractured/water-bearing zone	35 - 51 m; 57 - 64 m	12 - 64 m (fractured, dry), productive from 64 to 84 m
Water inflow 1 (WI1)	18 m ³ /h at 43 m	12 m ³ /h at 76 m
Water inflow 2 (WI2)	20 m ³ /h at 62 m	6 m ³ /h at 82 m
D_n at the borehole site (nodes/km ²)	23.5	23.7
End-of-drilling yield (airlift)	50 m ³ /h	18 m ³ /h

In agreement with the observations of [9], these results suggest that lineament intersection node density is a promising prospecting indicator, but one that is insufficient on its own. In crystalline settings, an intersection node may indeed correspond to the crossing of structures closed by silicification or clogged by clayey weathering infill. Consequently, hydrogeological prospecting aimed at obtaining high-yield boreholes must rely on a multi-criteria analysis integrating other geological, geomorphological and environmental factors [11] [13]. Several limitations should also be borne in mind: 1) the direct evidence of targeted siting rests on two boreholes only, and a comparison with boreholes sited using the same procedure in low-density zones would be needed to isolate the effect of D_n ; 2) end-of-drilling airlift yields are not equivalent to sustainable operating yields; 3) D_n depends on the bandwidth r and on the relative density of the three merged networks, and its sensitivity to these factors was not assessed here; and 4) the field check of the lineaments remains local (99 of 44,742 lineaments checked around 17 stations).

6. Conclusions

This study demonstrates the value of a multi-scale, multi-source approach for hydrogeological prospecting in structurally complex crystalline basement aquifers. By integrating airborne geophysics, multispectral optical imagery and radar imagery rather than relying on a single sensor, it contributes to characterizing the multi-scale architecture of the fracture network of the Tenkodogo square degree.

The results suggest that the productivity of basement aquifers depends not only on overall lineament density, but also on the connectivity of the fracture network and on the spatial superposition of deep magnetic structures, which may act as regional drains, and a dense network of surface lineaments which, where they reflect shallow fracturing, may promote recharge. Kernel density analysis of lineament intersection nodes made it possible to map the zones of maximum network connectivity. Among the 1307 boreholes in the study area, the proportion of high-yield boreholes (>15 m³/h) rises from 5.8% where node density is below 15

nodes/km² to 7.7% where it exceeds 20 nodes/km², while that of boreholes yielding 3 m³/h or less decreases from 64.1% to 45.1%, and two boreholes sited directly in zones of high and very high node density delivered high end-of-drilling (airlift) yields (50 m³/h at Tenkodogo and 18 m³/h at Garango). This result is encouraging for the approach, but the correlation between node density and yield remains weak, and node density cannot be regarded as a stand-alone siting criterion.

From a practical standpoint, these results argue for integrating this type of structural analysis upstream of drilling campaigns in basement areas. Future research should address: 1) a statistical analysis relating lineament intersection node density (D_n) to long-term operating yields, rather than to end-of-drilling yields, across the entire available borehole database, together with a sensitivity analysis of D_n to the bandwidth r ; 2) standardized pumping tests (transmissivity, specific capacity) on high-yield boreholes in order to objectively determine their actual productivity beyond end-of-drilling yields; 3) a multi-criteria analysis aimed at quantifying storage volumes and recharge at the main structural nodes; and 4) the integration of this intersection node density into machine learning models for automated groundwater potential mapping.

Author Contributions

Mahama Sawadogo led the fieldwork, processed and analyzed the data, drafted the manuscript and carried out the successive revisions. Julien Nikiema reviewed the manuscript at every stage of its preparation, up to the final version, and ensured communication between the research team and the journal. Hoboubé Nicole Abotsi took part in the fieldwork and reviewed the manuscript.

Conflicts of Interest

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

References

- [1] Taylor, R.G., Scanlon, B., Döll, P., Rodell, M., van Beek, R., Wada, Y., *et al.* (2012) Ground Water and Climate Change. *Nature Climate Change*, **3**, 322-329. <https://doi.org/10.1038/nclimate1744>
- [2] Lapworth, D.J., MacDonald, A.M., Tijani, M.N., Darling, W.G., Gooddy, D.C., Bonsor, H.C., *et al.* (2013) Residence Times of Shallow Groundwater in West Africa: Implications for Hydrogeology and Resilience to Future Changes in Climate. *Hydrogeology Journal*, **21**, 673-686. <https://doi.org/10.1007/s10040-012-0925-4>
- [3] MacDonald, A.M., Bonsor, H.C., Dochartaigh, B.É.Ó. and Taylor, R.G. (2012) Quantitative Maps of Groundwater Resources in Africa. *Environmental Research Letters*, **7**, Article ID: 024009. <https://doi.org/10.1088/1748-9326/7/2/024009>
- [4] Vouillamoz, J.M., Lawson, F.M.A., Yalo, N. and Descloitres, M. (2014) The Use of Magnetic Resonance Sounding for Quantifying Specific Yield and Transmissivity in Hard Rock Aquifers: The Example of Benin. *Journal of Applied Geophysics*, **107**, 16-24. <https://doi.org/10.1016/j.jappgeo.2014.05.012>
- [5] Savadogo, A.N. (1984) Géologie et hydrogéologie du socle cristallin de Haute-Volta:

- Étude régionale du bassin versant de la Sissili. Thèse de Doctorat, Université Scientifique et Médicale de Grenoble. (In French)
<https://theses.hal.science/tel-00764194>
- [6] Lachassagne, P., Wyns, R. and Dewandel, B. (2011) The Fracture Permeability of Hard Rock Aquifers Is Due Neither to Tectonics, Nor to Unloading, but to Weathering Processes. *Terra Nova*, **23**, 145-161.
<https://doi.org/10.1111/j.1365-3121.2011.00998.x>
 - [7] Sander, P. (2006) Lineaments in Groundwater Exploration: A Review of Applications and Limitations. *Hydrogeology Journal*, **15**, 71-74.
<https://doi.org/10.1007/s10040-006-0138-9>
 - [8] Nakolendoussé, S. (1991) Méthode d'évaluation de la productivité des sites aquifères au Burkina Faso: Géologie, géophysique, télédétection. Ph.D. Thesis, Université Joseph Fourier (Grenoble I), 232 p. (In French)
 - [9] Kafando, S., Nakolendoussé, S., Nikiema, J., Koussoubé, Y., Yaméogo, S., Compaoré, Y. and Millogo, C. (2016) Géomorphologie et productivité des aquifères en milieu de socle cristallin: Cas de la région du Centre du Burkina Faso. *Annales de l'Université Ouaga 1 Pr Joseph KI-ZERBO, Série C*, **12**, 45-74. (In French)
 - [10] Adeotan, Y.S.O., Vouillamoz, J., Lawson, F.M.A., Koita, M., Zorom, M., Traore, Y.S., et al. (2025) Beyond Lineaments: Exploring the Influence of Weathered Layers on Borehole Productivity in Basement Rocks of Burkina Faso, West Africa. *Hydrogeology Journal*, **33**, 411-424. <https://doi.org/10.1007/s10040-025-02876-5>
 - [11] Akinluyi, F.O., Olorunfemi, M.O. and Bayowa, O.G. (2018) Investigation of the Influence of Lineaments, Lineament Intersections and Geology on Groundwater Yield in the Basement Complex Terrain of Ondo State, Southwestern Nigeria. *Applied Water Science*, **8**, Article No. 49. <https://doi.org/10.1007/s13201-018-0686-x>
 - [12] Youan Ta, M., Lasm, T., Jourda, J.P., Kouamé, K.F. and Razack, M. (2008) Cartographie des accidents géologiques par imagerie satellitaire Landsat-7 ETM+ et analyse des réseaux de fractures du socle précambrien de la région de Bondoukou (nord-est de la Côte d'Ivoire). *Télédétection*, **8**, 119-135. (In French)
 - [13] Jourda, J.P., Saley, M.B., Djagoua, E.V., Kouamé, K.J., Biémi, J. and Razack, M. (2006) Utilisation des données ETM+ de Landsat et d'un SIG pour l'évaluation du potentiel en eau souterraine dans le milieu fissuré précambrien de la région de Korhogo (nord de la Côte d'Ivoire): Approche par analyse multicritère et test de validation. *Télédétection*, **5**, 339-357. (In French)
 - [14] Youan Ta, M., Lasm, T., Jourda, J.P.J., Bachir Saley, M., Adja Miessan, G., Kouamé, K., et al. (2011) Cartographie Des Eaux Souterraines En Milieu Fissuré Par Analyse Multicritère. Cas De Bondoukou (côte-d'Ivoire). *Revue internationale de géomatique*, **21**, 43-71. (In French) <https://doi.org/10.3166/riig.21.43-71>
 - [15] Metelka, V., Baratoux, L., Naba, S. and Jessell, M.W. (2011) A Geophysically Constrained Litho-Structural Analysis of the Eburnean Greenstone Belts and Associated Granitoid Domains, Burkina Faso, West Africa. *Precambrian Research*, **190**, 48-69.
<https://doi.org/10.1016/j.precamres.2011.08.002>
 - [16] Dahlin, T. and Loke, M.H. (1998) Resolution of 2D Wenner Resistivity Imaging as Assessed by Numerical Modelling. *Journal of Applied Geophysics*, **38**, 237-249.
[https://doi.org/10.1016/s0926-9851\(97\)00030-x](https://doi.org/10.1016/s0926-9851(97)00030-x)
 - [17] Bernard, J. (2003) Short Note on the Principles of Geophysical Methods for Groundwater Investigations. IRIS Instruments.
https://www.iris-instruments.com/Pdf_file/Groundwater_Geophysics/Groundwater_text.pdf
 - [18] Vouillamoz, J.M., Chatenoux, B., Mathieu, F., Baltassat, J.M. and Legchenko, A.

- (2007) Efficiency of Joint Use of MRS and VES to Characterize Coastal Aquifer in Myanmar. *Journal of Applied Geophysics*, **61**, 142-154.
<https://doi.org/10.1016/j.jappgeo.2006.06.003>
- [19] Castaing, C., Billa, M., Milési, J. P., Thiéblemont, D., Le Métour, J., Egal, E., et al. (2003). Notice explicative de la carte géologique et minière du Burkina Faso à 1/1 000 000. BRGM/BUMIGEB, 147 p. (In French)
- [20] Thiombiano, A., Schmidt, M., Kreft, H. and Guinko, S. (2006) Influence du gradient climatique sur la distribution des espèces de Combretaceae au Burkina Faso (Afrique de l'Ouest). *Candollea*, **61**, 189-213. (In French)
- [21] BUMIGEB (Bureau des Mines et de la Géologie du Burkina) (2021) Geological and Structural Data of the Tenkodogo Square Degree. BUMIGEB. (In French)
- [22] BNDT (Base Nationale de Données Topographiques) (2018) Topographic Database of Burkina Faso. Institut Géographique du Burkina (IGB). (In French)
- [23] Naba, S., Lompo, M., Debat, P., Bouchez, J.L. and Béziat, D. (2004) Structure and Emplacement Model for Late-Orogenic Paleoproterozoic Granitoids: The Tenkodogo-Yamba Elongate Pluton (Eastern Burkina Faso). *Journal of African Earth Sciences*, **38**, 41-57. <https://doi.org/10.1016/j.jafrearsci.2003.09.004>
- [24] Ilboudo, H. (2010) Le gîte d'amas sulfuré de Tiébélé: Faciès lithologiques, structures et minéralisations, Burkina Faso (Afrique de l'Ouest). Ph.D. Thesis, Université de Ouagadougou, 158 p. (In French)
- [25] Naba, S. (2007) Propriétés magnétiques et caractères structuraux des granites du Burkina Faso oriental (Craton Ouest Africain, 2,2-2,0 Ga): Implications géodynamiques. Ph.D. Thesis, Université Paul Sabatier Toulouse III, 144 p. (In French)
<https://theses.fr/2007TOU30328>
- [26] Sawadogo, M. (2021) Identification des facteurs de baisse de la productivité des forages en milieu de socle: Cas des forages de l'ONEA du centre de Manga (région du Centre-Sud, Burkina Faso). Master's Thesis, Université Joseph KI-ZERBO, 70 p. (In French)
- [27] Nikiema, J. (2009) Charakterisierung der hydrologisch-hydrogeologischen Potentiale im Gebiet von Tikaré, Provinz Bam, Burkina Faso (Westafrika): Ein Modellbeispiel für Wasserressourcenentwicklung und Management in der südlichen Sahel-Zone. Ph.D. Thesis, Universität Leipzig, 200 p.
- [28] Koïta, M. (2010) Caractérisation et modélisation du fonctionnement hydrodynamique d'un aquifère fracturé en zone de socle: Cas de la région de Dimbokro-Bongouanou (Centre-Est de la Côte d'Ivoire). Ph.D. Thesis, Université Montpellier II, 235 p. (In French)
- [29] Koita, M., Jourde, H., Koffi, K.J.P., Da Silveira, K.S. and Biaou, A. (2013) Characterization of Weathering Profile in Granites and Volcanosedimentary Rocks in West Africa under Humid Tropical Climate Conditions. Case of the Dimbokro Catchment (Ivory Coast). *Journal of Earth System Science*, **122**, 841-854.
<https://doi.org/10.1007/s12040-013-0290-2>
- [30] Filippi, C., Milville, F. and Thiery, D. (1990) Evaluation de la Recharge Naturelle des Aquifères en Climat Soudano-Sahélien par Modélisation Hydrologique Globale: Application à Dix Sites Au Burkina Faso. *Hydrological Sciences Journal*, **35**, 29-48. (In French) <https://doi.org/10.1080/02626669009492403>
- [31] Koussoubé, Y., Nakolendoussé, S., Bazié, P. and Savadogo, A.N. (2003) Typology of Vertical Electrical Sounding Curves for the Recognition of Surface Formations and

- Their Incidence in the Hydrogeology of the Crystalline Basement of Burkina Faso. *Sud Sciences et Technologies*, **10**, 26-32. (In French)
- [32] Courtois, N., Lachassagne, P., Wyns, R., Blanchin, R., Bougairé, F.D., Somé, S., et al. (2010) Large-Scale Mapping of Hard-Rock Aquifer Properties Applied to Burkina Faso. *Groundwater*, **48**, 269-283. <https://doi.org/10.1111/j.1745-6584.2009.00620.x>
- [33] BUMIGEB (Bureau des Mines et de la Géologie du Burkina) (2018) Airborne Magnetic Survey of Burkina Faso at 1:200,000 Scale, Mining Sector Development Support Project (PADSEM). BUMIGEB. (In French)
- [34] U.S. Geological Survey (USGS) and Earth Resources Observation and Science (EROS) Center (2016) Landsat 8 OLI/TIRS Scene, Path 194/Row 052, Acquired in November 2016. <https://earthexplorer.usgs.gov>
- [35] Alaska Satellite Facility (ASF) Distributed Active Archive Center (2008) ALOS PAL-SAR L-Band Dual-Polarization (HH/HV) Scenes, Acquired in June 2008. Original Data © JAXA/METI. University of Alaska Fairbanks. <https://search.earthdata.nasa.gov/search/granules?p=C2011599335-ASF>
- [36] Drury, S.A. (2001) Image Interpretation in Geology. 3rd Edition, Nelson Thornes, 290 p.
- [37] Masoud, A.A. and Koike, K. (2011) Auto-Detection and Integration of Tectonically Significant Lineaments from SRTM DEM and Remotely-Sensed Geophysical Data. *ISPRS Journal of Photogrammetry and Remote Sensing*, **66**, 818-832. <https://doi.org/10.1016/j.isprsjprs.2011.08.003>
- [38] Lee, J. (1980) Digital Image Enhancement and Noise Filtering by Use of Local Statistics. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, **2**, 165-168. <https://doi.org/10.1109/tpami.1980.4766994>
- [39] Baranov, V. and Naudy, H. (1964) Numerical Calculation of the Formula of Reduction to the Magnetic Pole. *Geophysics*, **29**, 67-79. <https://doi.org/10.1190/1.1439334>
- [40] Blakely, R.J. (1995) Potential Theory in Gravity and Magnetic Applications. Cambridge University Press. <https://doi.org/10.1017/cbo9780511549816>
- [41] Roest, W.R., Verhoef, J. and Pilkington, M. (1992) Magnetic Interpretation Using the 3-D Analytic Signal. *Geophysics*, **57**, 116-125. <https://doi.org/10.1190/1.1443174>
- [42] Ajakaiye, D.E., Hall, D.H., Millar, T.W., Verheijen, P.J.T., Awad, M.B. and Ojo, S.B. (1986) Aeromagnetic Anomalies and Tectonic Trends in and around the Benue Trough, Nigeria. *Nature*, **319**, 582-584. <https://doi.org/10.1038/319582a0>
- [43] Isles, D.J. and Rankin, L.R. (2013) Geological Interpretation of Aeromagnetic Data. Society of Exploration Geophysicists and Australian Society of Exploration Geophysicists. <https://doi.org/10.1190/1.9781560803218>
- [44] Hung, L.Q., Batelaan, O. and De Smedt, F. (2005) Lineament Extraction and Analysis, Comparison of LANDSAT ETM and ASTER Imagery. Case Study: Suoimuoi Tropical Karst Catchment, Vietnam. *Proceedings of SPIE*, **5983**, Article ID: 59830T. <https://doi.org/10.1117/12.627699>
- [45] Abdullah, A., Akhir, J.M. and Abdullah, I. (2010) Automatic Mapping of Lineaments Using Shaded Relief Images Derived from Digital Elevation Model (DEMs) in the Maran-Sungi Lembing Area, Malaysia. *Electronic Journal of Geotechnical Engineering*, **15**, 949-958.
- [46] Kouamé, F.K., Gioan, P., Biémi, J. and Affian, K. (1999) Méthode de cartographie des discontinuités-images extraites d'images satellitaires: Exemple de la région semimontagneuse à l'ouest de la Côte d'Ivoire. *Téledétection*, **1**, 139-156. (In French)
- [47] Mabee, S.B., Hardcastle, K.C. and Wise, D.U. (1994) A Method of Collecting and

- Analyzing Lineaments for Regional-Scale Fractured-Bedrock Aquifer Studies. *Groundwater*, **32**, 884-894. <https://doi.org/10.1111/j.1745-6584.1994.tb00928.x>
- [48] Silverman, B. W. (1986) Density Estimation for Statistics and Data Analysis. Chapman and Hall, 175 p. <https://doi.org/10.1007/978-1-4899-3324-9>
- [49] ONEA (Office National de l'Eau et de l'Assainissement) (2026) Water Borehole Databases of the Tenkodogo Area. ONEA. (In French)
- [50] NASA/USGS (2024) Shuttle Radar Topography Mission (SRTM) Digital Elevation Model. <https://earthexplorer.usgs.gov>