World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(RESEARCH ARTICLE)

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Petrographic and structural characteristics of the pozzolanic formations and associated rocks in the Brobo area, northern part of the Fêtêkro belt, central Côte d'Ivoire: Implications for potential pozzolan exploitation

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World Journal of Advanced Research and Reviews, 2025, 28(02), 2107-2119

Publication history: Received 13 October 2025; revised on 22 November 2025; accepted on 24 November 2025

Article DOI: https://doi.org/10.30574/wjarr.2025.28.2.3928

Abstract

The Brobo area, located in the northern Fêtêkro Belt within the Baoulé–Mossi domain of the West African Craton, offers significant potential for understanding crustal evolution and developing natural pozzolanic resources. Despite growing industrial interest, the geological and structural controls of pozzolan occurrences in this region remain poorly constrained. This study combines petrographic and structural analyses to characterize the volcanic, plutonic, and metamorphic rocks associated with pozzolanic materials and to assess their exploration significance. Field and microscopic investigations reveal that the area is dominated by acid to intermediate volcanic rocks—rhyolites, rhyodacites, and pyroclastic formations—spatially associated with granitoid intrusions (granite, granodiorite, tonalite) and minor quartzites. The pyroclastic facies display microlitic to porphyritic textures and mineral assemblages (quartz, feldspar, sericite, epidote) comparable to recognized natural pozzolans. Structurally, two deformation regimes are identified: ductile (N010°–N040° foliations and shear bands under NE–SW compression) and brittle (N070°–N110° faults and en-echelon quartz veins). These features correspond to the regional Birimian tectonic pattern, indicating syn- to late-Eburnean emplacement. The mineralogical and textural characteristics of the pyroclastic formations suggest favorable pozzolanic reactivity, highlighting the Brobo area as a promising target for expanding Côte d'Ivoire's pozzolan exploitation.

Keywords: Brobo; Fêtêkro Belt; Pozzolan; Petrography; Côte d'Ivoire; West African Craton

1. Introduction

As part of efforts to revitalize its mining sector—long focused on gold and diamonds [1]—and to expand into quarry materials such as aggregates and pozzolan, Côte d'Ivoire has, over the past decade, undertaken an extensive campaign to explore these resources [2]. According to data provided by the Ministry of Mines, Petroleum and Energy through the DGMG, pozzolan production in Côte d'Ivoire, which began in 2019, increased from 126,577 tonnes to 394,880 tonnes in 2023—an average annual growth rate of 32.9% [2]. Pozzolan plays an essential role in the cement industry as an additive that enhances the mechanical properties and durability of hydraulic binders. It is mainly associated with acid and intermediate volcanic formations (rhyolites, rhyodacites) and their pyroclastic derivatives [3, 4]. Natural pozzolans are typically characterized by silica contents of 42–55%, alumina of 12–24%, and iron oxide of 8–20%. To optimize cement production, reduce import-related costs, and promote local resource autonomy, it is essential to valorize locally available materials such as pozzolan. Although pozzolan production has recently expanded in Côte d'Ivoire, the geological and structural controls governing its occurrence in the Brobo area remain poorly documented. This study

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aims to improve geological and structural knowledge of the rocks associated with pozzolan in the Brobo area. A combined petrostructural approach was adopted to (i) describe and identify the geological formations associated with pozzolan, (ii) analyze the structures and deformations of the rocks to determine their genetic mechanisms, and (iii) propose a possible relationship between rock type, structure, and pozzolan occurrence to serve as a guide for future exploration.

2. Geological setting

The West African Craton (WAC) comprises two major geological domains: the Reguibat Ridge in the north and the Leo Ridge in the south [5–7]. Both are composed of Paleoproterozoic and Archean terranes (Figure 1). The WAC was shaped through three major orogenic cycles: the Leonian (3200–2900 Ma), the Liberian (2900–2800 Ma), and the Eburnean megacycle (2500–1600 Ma) [8, 9]. The Man Ridge, which hosts the study area, is divided by the north–south Sassandra Fault into an Archean Kenema–Man domain to the west and a Paleoproterozoic Baoulé–Mossi domain to the east, with a transitional zone between them [9].

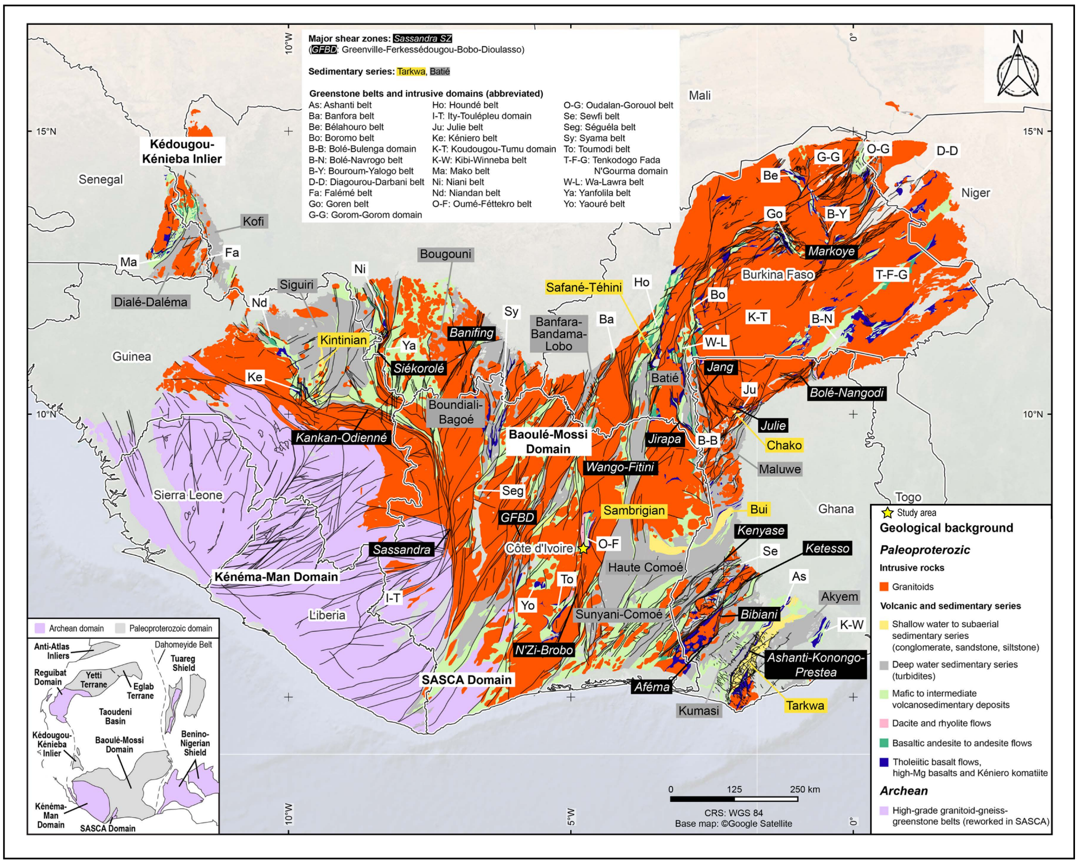

Figure 1 Geological map of the southern West African Craton (sWAC), including the Paleoproterozoic Baoulé-Mossi Domain and Kédougou-Kénieba Inlier, Archean Kénéma-Man Domain, SASCA Domain, and study area (modified after [10, 11])

The Brobo area lies in central Côte d'Ivoire, in the northern part of the Fêtêkro Belt. Its geological formations can be subdivided into three main groups (Figure 2; [12]): (i) a granito-gneissic complex occupying the western part; (ii) a median Belt formed by lavas, breccias, and volcano-sedimentary rocks interlayered with schists and quartzites; (iii) sedimentary and volcano-sedimentary formations in the eastern part. These units are intruded by granitic, granodioritic, and mafic bodies. Structurally, the area is dominated by a major north–south Brobo Fault, expressed as a deformation zone mainly affecting the granitoids [13].

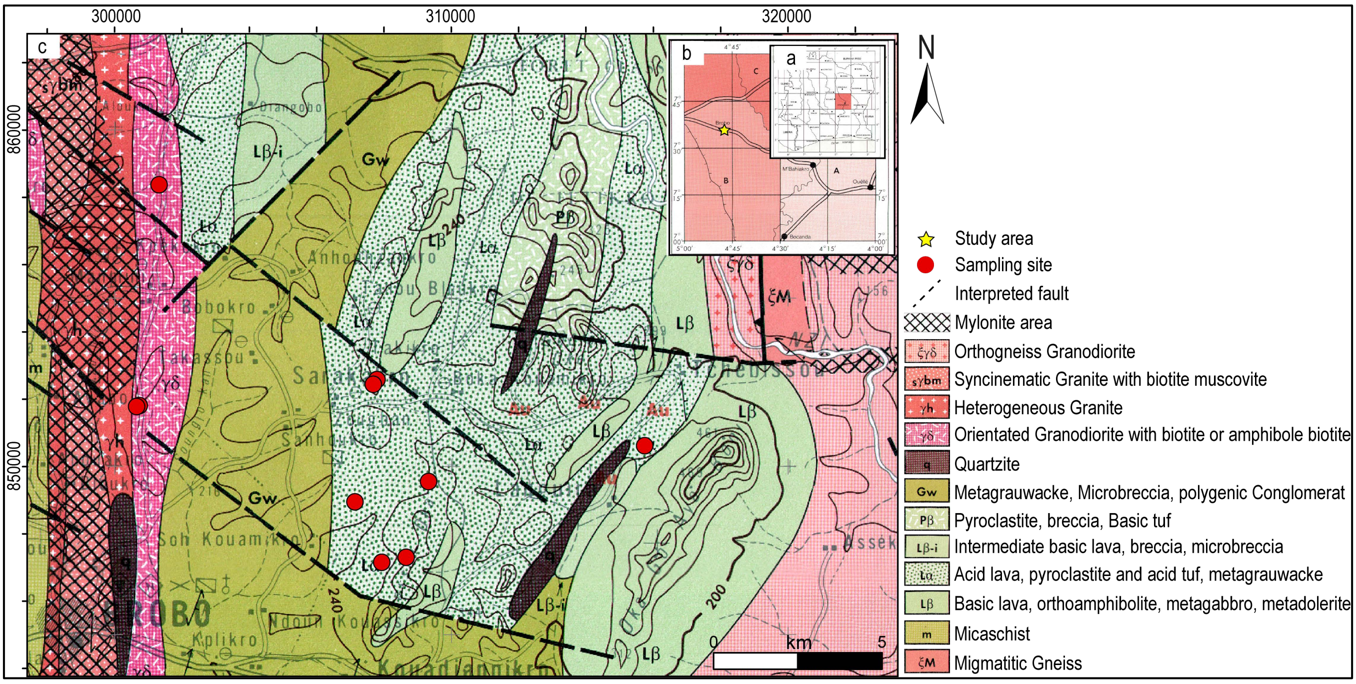

Figure 2 Simplified geological map of study area (modified after [12]). The inserts (a and b) show the location of the study area

3. Material and methods

It began with a field phase, during which rock samples were collected and described macroscopically. Each sampling site was systematically recorded using GPS for precise location. These samples were subsequently used to prepare fourteen thin sections at the Geology Laboratory of Félix Houphouët-Boigny University, Abidjan-Cocody. The thin sections were examined under a polarizing optical microscope to refine the petrographic study, emphasizing the identification of mineral parageneses and lithological facies.

The structural framework of the area was established by describing the deformation structures affecting the various lithologies, specifying their orientation and dip where possible. Special attention was given to their spatial relationships and to the relative chronology of the successive deformation events. The structural measurements obtained were then used to construct directional rose diagrams, allowing the identification of the predominant structural trends.

4. Results

4.1. Petrography of plutonic rocks

4.1.1. Granodiorite

The granodiorite occurs as slab-like bodies. It is a medium- to coarse-grained, locally oriented, mesocratic rock. The orientation observed in certain facies in the field may reflect variations in the temperature and pressure conditions of the parent magma during emplacement or crystallization. Mineralogically, it is composed mainly of quartz, feldspar, amphibole, and biotite. Quartz crystals vary from medium to coarse and commonly display well-developed undulatory extinction. Feldspars include both plagioclase and orthoclase. Plagioclase, recognized by its polysynthetic twin, appears as coarse xenomorphic to sub-idiomorphic grains with cores and rims variably altered to sericite. In the oriented facies, plagioclase occurs as rounded and slightly bent crystals molded by a cataclastic matrix rich in sericite (Figures 3a–c). Orthoclase, less abundant than plagioclase, is identified by Carlsbad twin and shows strong alteration along its borders to sericite and amphibole (Figures 3a–c). Perthitic intergrowths between orthoclase and plagioclase are also common. Amphibole occurs as greenish, sub-idiomorphic crystals with distinct cleavage in basal sections; it is generally fresh and locally marks the dark foliation bands (Figures 3d–f). Biotite is sparse (~1%), brown in color, and forms thin colored layers in thin section.

4.1.2. Granite and metagranite

Granite and metagranite crop out as elongated slabs. Both belong to the group of felsic magmatic rocks. Fresh granite contains about 60% quartz and displays a pinkish hue, with orthoclase generally dominating over plagioclase. Under the microscope, granite exhibits a typical coarse-grained, whereas metagranite shows a lepidoblastic texture. Locally, metagranite is coarse-grained and displays a poorly defined foliation marked by alternating dark, ferromagnesian-rich bands and light-colored (white, gray, or pink) quartz–feldspar bands. Both rocks have a similar mineral assemblage composed mainly of: (i) Quartz, locally forming small, recrystallized grains (Figures 3g–i); and (ii) Plagioclase, commonly showing cores and rims altered to sericite.

4.1.3. Tonalite

Tonalite occurs as enclaves within the granites and granodiorites (Figure 3j). These enclaves are subrounded to rounded and display a melanocratic appearance. Under the microscope, tonalite has a granitic texture and is mainly composed of abundant, medium-grained plagioclase. Perthitic feldspars rimmed by sericite are also present. Biotite crystals occur either individually or clustered with other minerals (Figures 3k-l); they are brown to reddish-brown and show bright pleochroic colors. Quartz is xenomorphic and fine-grained, while amphibole is less abundant and typically associated with sericite.

4.2. Petrography of volcanic rocks

4.2.1. Rhyolite and rhyodacite

Acid lavas occur either as dome-shaped bodies or elongated (Figure 4a). Rhyolites and rhyodacites are typically homogeneous, massive, and often aphanitic, occasionally containing scattered quartz phenocrysts ("quartz eyes"). Under the microscope, these rocks display microlithic to microlithic-porphyritic textures. The principal minerals include quartz and plagioclase, the latter being extensively altered to sericite and epidote. Quartz crystals, which are abundant (> 50%), commonly form small aggregates (< 0.3 mm) within the matrix (Figures 4a–c). In porphyritic rhyolites, subhedral to euhedral quartz porphyroblasts exhibit pronounced undulatory extinction and recrystallization, producing subgrains (neoblasts) and small polygonal textures (Figure 4b). Most clasts consist of feldspar (plagioclase and orthoclase), which may reach centimeter size and display cores and rims altered to sericite (Figure4b). These feldspars, generally subhedral to euhedral, locally deflect the schistosity. Sericite, derived from feldspar alteration, forms fine ribbons that define the foliation in metarhyolites (Figure 4c) and occasionally occurs as coronas around quartz phenocrysts. Accessory minerals are mainly opaque phases.

4.2.2. Pyroclastite

Pyroclastic lavas occur widely and display variable facies—tuffaceous with fine particles, conglomeratic with subrounded clasts, or brecciated with angular fragments. The volcanic breccias, abundant in the study area, are predominantly pyroclastic in origin (Figures 4d-f). These rocks exhibit a microlithic-porphyritic texture. Their angular fragments are cemented by a grayish-white to greenish matrix. The grayish cement results from quartz–feldspar recrystallization, while the greenish color indicates a higher content of epidote and chlorite (Figure 4f).

4.2.3. Basic lava

The basic lavas consist mainly of volcanic rocks of basaltic to andesitic composition (Figures 4g-h). They are massive and dark-colored. Basalt, the predominant basic lava described here, typically forms large domes or blocks, though some occurrences display pillow-like structures known as pillow lavas. Under the microscope, basalt exhibits a microlithic texture, composed largely of volcanic glass, pyroxenes, and microlith, some of which are partially altered.

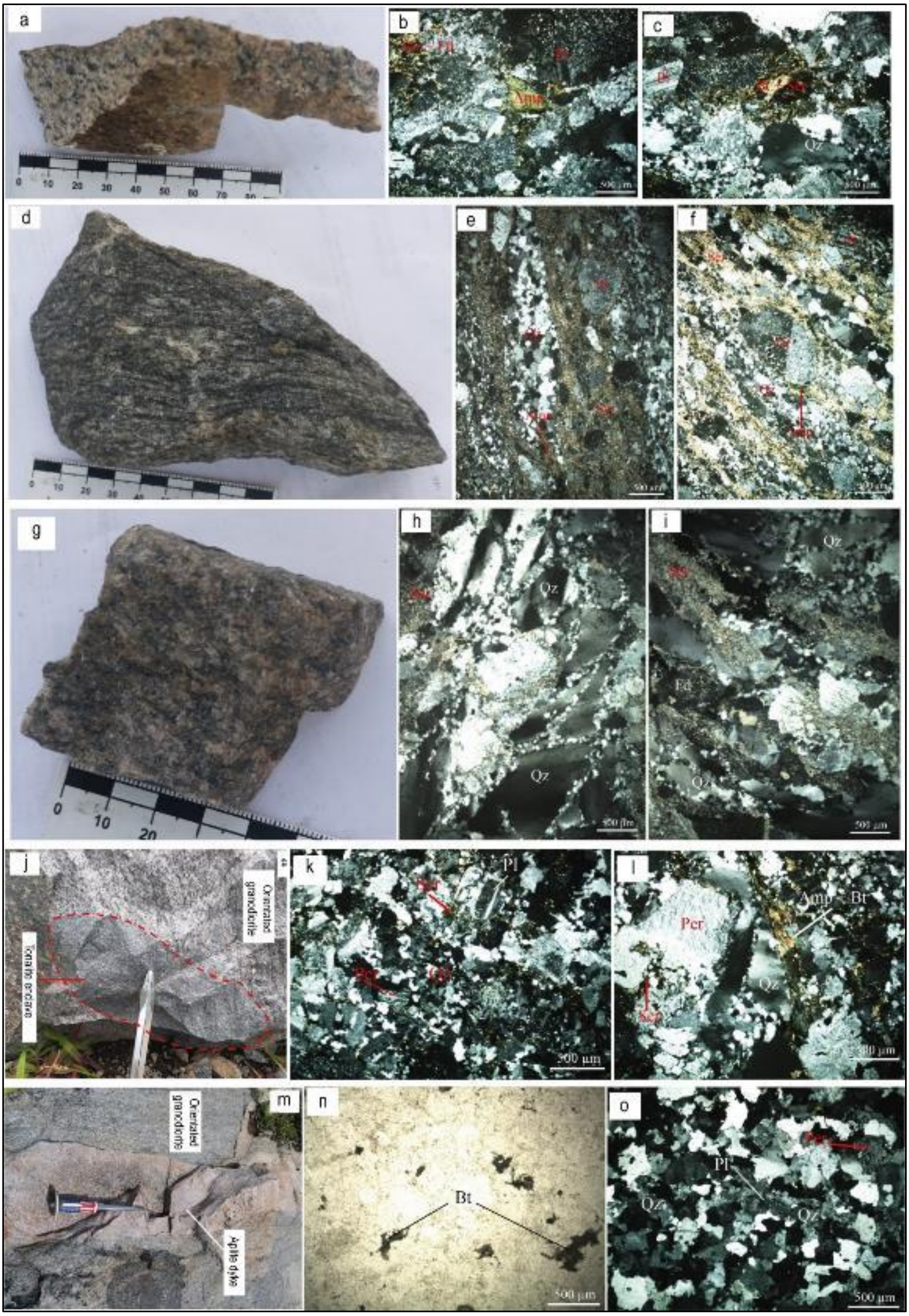

Figure 3 Photographs showing petrography of plutonic rocks. (a-c) granodiorite; (g-i) orientated granodiorite; (j-l) Tonalite enclave within orientated granodiorite; (m-o) aplite dyke within orientated granodiorite. Qz=quartz, Pl=plagioclase, Fd=felspar, Amp=amphibole, Ser= sericite, Or=orthoclase, Bt=Biotite, Per=perthite

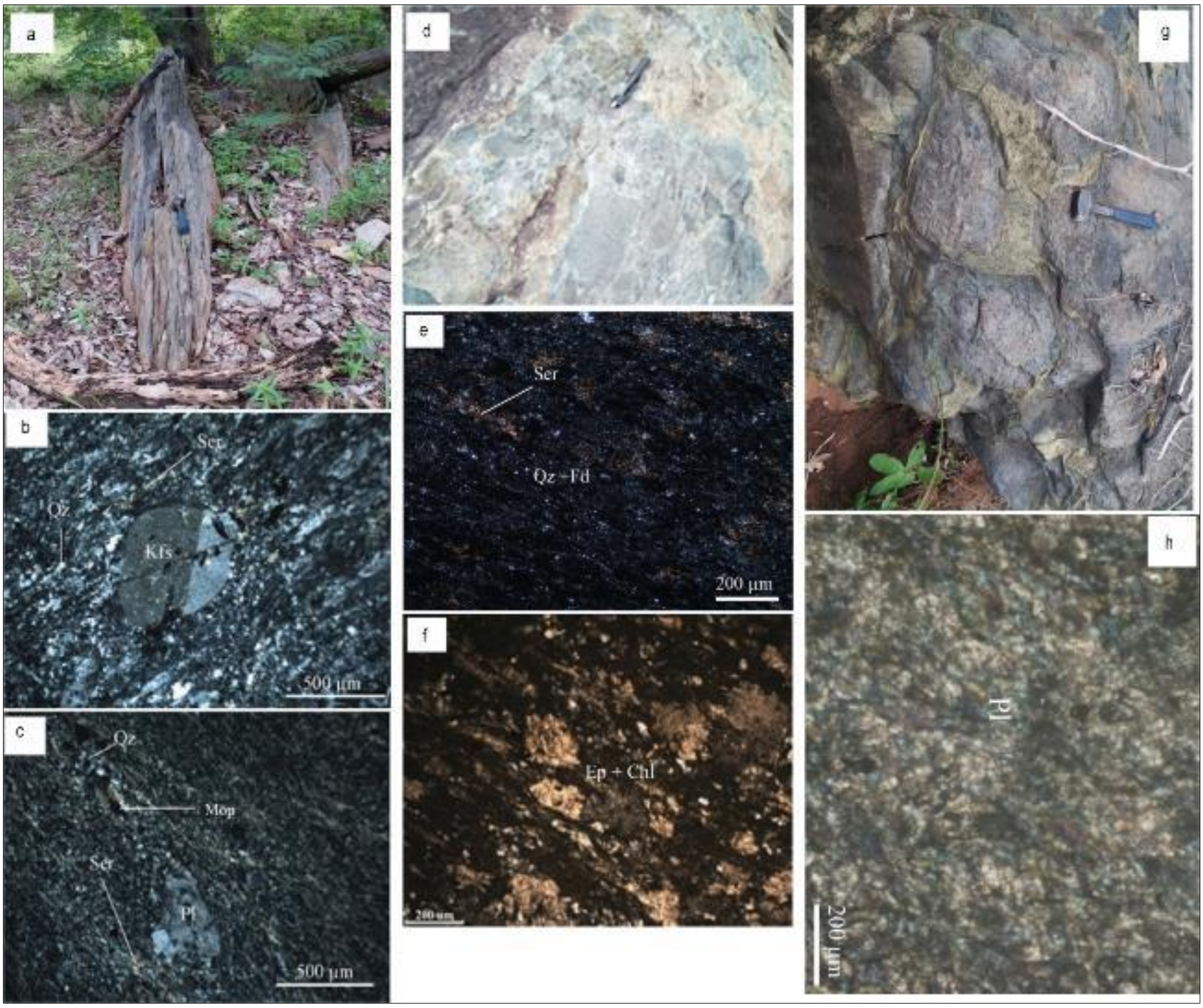

Figure 4 Photographs showing petrography of volcanic rocks. (a-c) rhyolite and rhyodacite; (d-f) pyroclastite; (g-h) basic lava. Qz=quartz, Pl=plagioclase, Kfs=K-felspar, Ser= sericite, Ep=epidote, Chl=chlorite, Mop=Oxide

4.3. Petrography of metamorphic rocks

4.3.1. Quartzite

Quartzites are relatively rare formations occurring as intercalations between the granitic zone and the volcano-sedimentary units, or within the volcano-sedimentary complex. They are gray to black, very fine-grained, and typically massive, though some show distinct banding (Figure 5a). The quartzites consist predominantly of quartz (Figures 5b–c). The quartz crystals are abundant, with grain sizes ranging from medium to coarse. The quartz porphyroblasts display pronounced undulatory extinction.

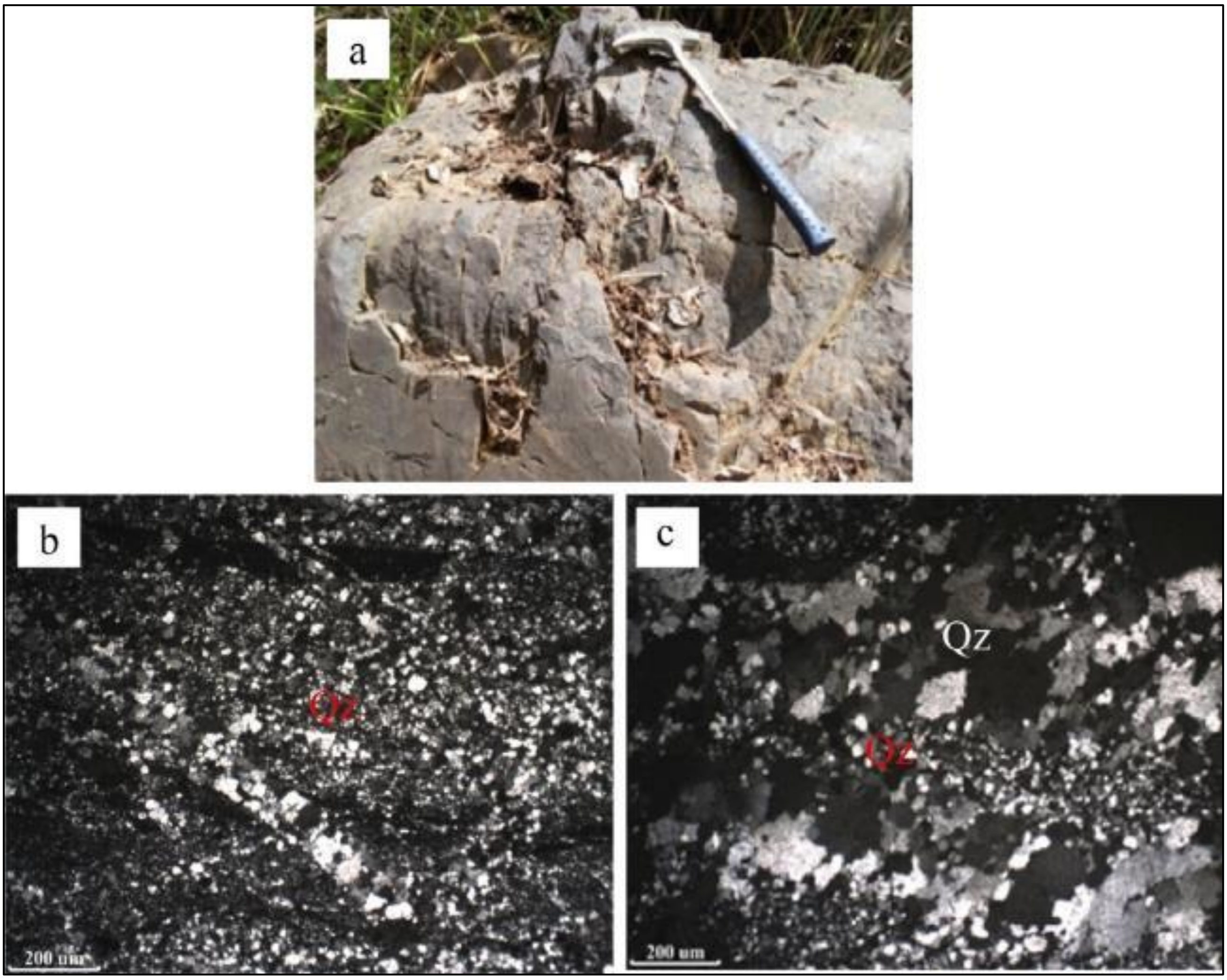

Figure 5 Photographs showing petrography of Quartzite, with quartz porphyroblasts display pronounced undulatory extinction. Qz=quartz

4.4. Structural characteristics of the Brobo area

4.4.1. Foliation

Planar fabric constitutes the dominant structural feature within the rocks of the study area, expressed through pervasive foliation (Figure 6). In the granitoids, the planar fabric is defined by an N020° foliation characterized by the alternation of millimeter- to centimeter-scale quartzofeldspathic layers and ferromagnesian bands composed mainly of biotite and amphibole (Figure 6a). This foliation reflects a flattening fabric associated with ductile deformation under regional compressive stress. The foliation is represented by a penetrative, generally subvertical foliation. Two main types are recognized: spaced and slaty cleavage (Figures 6b–c). The spaced cleavage, oriented N120°, occurs mainly within quartzitic units and consists of thin, open fractures lacking evidence of recrystallization (Figure 6b), suggesting deformation under brittle–ductile transitional conditions. The slaty cleavage, striking N010°–N040°, is defined by the preferred orientation and stretching of phyllitic minerals within the metarhyolites (Figure 6c). A structural rose diagram indicates a dominant NE–SW trend for the main foliation. The dip of the foliation is variable—locally directed toward the NW but predominantly toward the SE. In quartzitic formations, the foliation dips toward the SW.

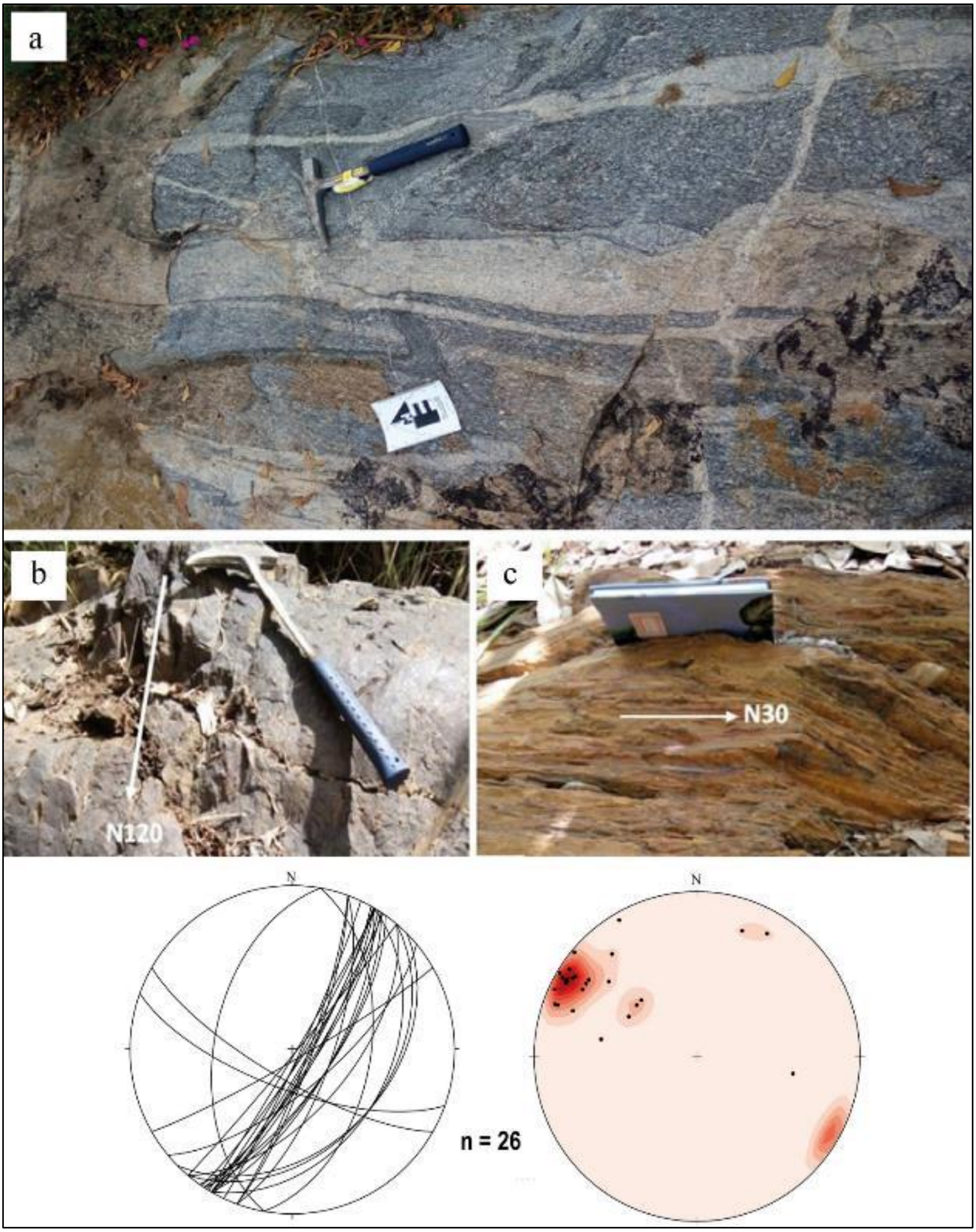

Figure 6 Photographs of planar structures observed in outcrop. (a) Alternating light quartz–feldspar bands and dark ferromagnesian bands (foliation); (b) Spaced cleavage developed in quartzites; (c) Slaty cleavage in acid lavas. Stereograms of planar structures

4.4.2. Shear zones, boudinage, and tension veins

Shearing is locally well developed and characterized by zones of high finite strain, evidenced by the displacement of passive markers. Shear zones striking N160° offset quartz veins trending N030° and exhibit a sinistral sense (Figure 7a). These structures likely correspond to localized ductile shear zones within the regional stress field. Boudinage structures are common and reflect extensional deformation of competent lithologies under differential stress parallel to the layering. Quartz-vein boudins trend N010° and indicate layer-parallel extension synchronous with ductile flattening (Figure 7b). En echelon tension veins are observed within foliated granodiorite and trend N100° (Figure 7c). Their geometry and orientation suggest formation under ductile shear conditions, consistent with progressive non-coaxial deformation within the same stress regime responsible for the shear zones.

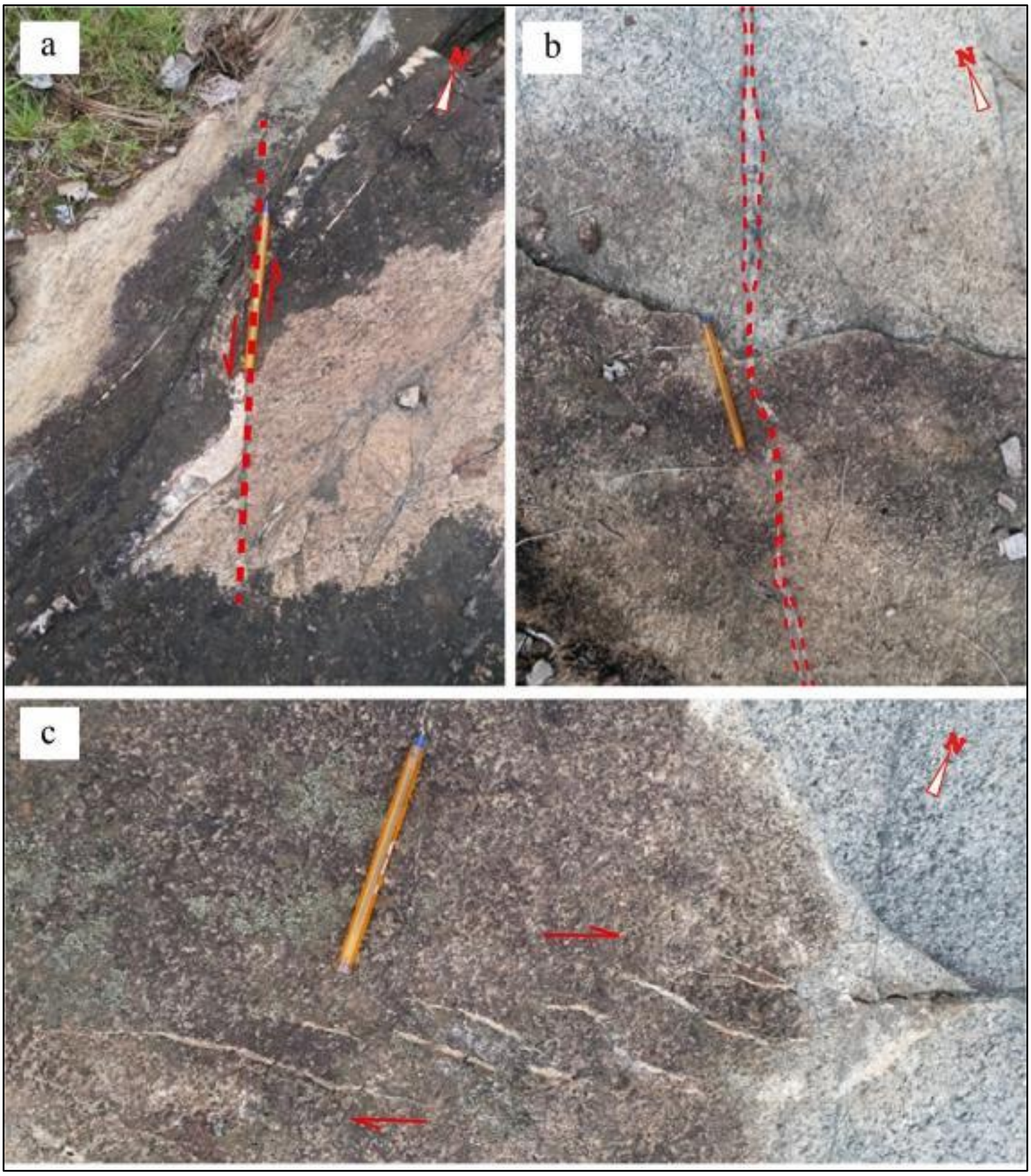

Figure 7 Photographs illustrating shear deformation: (a) sinistral shear; (b) boudinage structure; (c) dextral en-echelon tension veins

4.4.3. Strike-slip fault

Major brittle deformation in the study area is manifested by fracture systems affecting both the volcanic and plutonic formations. Two dominant strike-slip fault sets are recognized: sinistral faults trending N110° and dextral faults trending N070° (Figures 8a-b). These faults offset aplite dykes striking N020°, subparallel to the regional foliation, and mark a late-stage brittle deformation event overprinting earlier ductile fabrics.

Figure 8 Photographs of structures in study area: (a) sinistral strike-slip; (b) dextral strike-slip

5. Discussion

5.1. Pozzolanic formations and associated rocks

The center of the study area is dominated by volcanoclastic complexes composed predominantly of pyroclastic rocks. These formations, as documented by [14], exhibit lateral continuity and consist mainly of pyroclastic facies displaying both basaltic and rhyolitic affinities. Further south, in the Fétèkro Belt near Toumodi, [15] identified basic, intermediate, and acid volcanic rocks. According to these authors, most deposits consist of volcanoclastic debris accumulated in subaerial or shallow-marine environments, interbedded with true pyroclastic layers. They further demonstrated that the associated magmas are mainly basaltic to andesitic in composition, enriched in large-ion lithophile elements (LILE) and marked by negative anomalies in Nb, Ta, and Ti—geochemical features consistent with hydrous, subduction-related melting typical of arc settings. With regard to the pozzolanic potential of the pyroclastic units, geochemical data from[14] reveal chemical compositions broadly comparable to those of natural pozzolans of diverse origins (Table 1). [16–18] noted that pozzolans are generally dominated by silica (SiO_2), alumina (Al_2O_3), and ferric oxide (Fe_2O_3), with appreciable proportions of alkalis (Na_2O, K_2O) and alkaline-earth oxides (CaO, MgO). As emphasized by [4], the term pozzolan does not designate a specific lithology or mineralogy but rather encompasses a wide range of silico-aluminous materials. To exhibit pozzolanic reactivity, a rock must contain an amorphous phase rich in Si or Al capable of combining with Ca released from added lime. Notably, pozzolanic occurrences have been identified in the Brobo region, where LAFARGE HOLCIM has been exploiting such materials for approximately five years.

In addition to these volcanoclastic formations, the area also comprises orientated and massive granitoids, reflecting the coexistence of plutonic and volcanic lithologies. According to [19], plutonic rocks such as granites and granodiorites crystallize from acid or basic magmas at depths of several kilometers and are later exposed through erosion. Similar lithological associations have been described in the Dabakala region by [20]). The granitoids locally host mafic enclaves and aplite dykes (Figures 3m-o), attesting to complex magmatic processes. The occurrence of mafic tonalitic enclaves within granitoid intrusions indicates that (i) the tonalite predates its host intrusion and (ii) magma mixing or mingling processes occurred during emplacement [21]. These enclaves also record early stages of magma differentiation and represent fragments produced by fractional crystallization, some of which were subsequently entrained by residual magmatic liquids [19].

Table 1 Comparative table of the general composition of the pozzolans from Réunion Island and the study area

	Pozzolan general Composition [17]	**Pozzolan of Réunion [17]**		**Pyroclastite of Study area [14]**			
Sample		Tufs de Saint Pierre	Tufs de Saint-Louis	DB005	DBO65A	DBO65B	DBO68A
SiO_2	42-55	54.9	54.8	52.4	63.2	60.51	62.95
$Al2O_3$	12-24	16.2	16.1	13.5	14.46	14.36	13.25
Fe_2O_3	8-20	10.3	10.4	9.9	8.13	7.35	10.04
CaO	4-11	5.2	5.2	8.17	3.95	7.13	4.31
MgO	1-10	2.3	2.4	6.35	5.62	5.14	5.94
Na_2O	2.5-6	4.2	4.1	2.08	2.17	3.74	1.35
K_2O	0.8-4	2.34	2.29	3.64	1.24	0.45	0.97
MnO	0.1-0.2	0.2	0.21	0.16	0.09	0.19	0.1
TiO_2	0.5-2.5	1.96	1.96	1.03	0.89	0.91	0.84

5.2. Structural analysis

The N010–040° foliation trend is consistent with the dominant Birimian structural orientation. This foliation reflects a ductile deformation regime primarily associated with NW–SE–directed stresses, as documented across several regions of the West African Craton [22, 23]. Both ductile and brittle shear contributed to the development of a range of structural features. The structures observed within the study area—including shear zones, foliation, sigmoidal clasts, strike-slip faults, and quartz veins—collectively attest to the presence of a regional shear zone (e.g., [24]. A representative example is the N–S–trending ductile Brobo thrust fault, exposed in the western part of the M'Bahiakro. This structure, first described by [25] in its southern segment and by [26] in the north, affects granitoid formations and is locally characterized by well-developed C/S fabrics and foliations. The fault generally trends N–S but diverges NE–SW toward its southern extremity. These shear zones are of particular interest for mineral exploration, as their deformation fabrics often create favorable conditions for ore deposition [14, 20, 23]. In the northern part—and possibly throughout—the Fêtêkro Belt, [27] demonstrated that the lower series underwent reverse ductile shearing related to intraplate subduction. This major tectonometamorphic event, absent in other units, resulted in a pronounced regional unconformity at the base of the Birimian sequence.

6. Conclusion

Based on the results of this study, the following conclusions are reached:

- The investigated area is predominantly composed of acid to intermediate volcanic rocks, notably rhyolites, rhyodacites, and pyroclastic formations, which are spatially associated with granitoid intrusions (granodiorite and granite) and quartzites. The pyroclastic formations exhibit chemical compositions comparable to those of pozzolanic materials currently exploited worldwide.
- The Brobo region demonstrates significant potential for pozzolan resources, as evidenced by the ongoing operations conducted by LAFARGEHOLCIM. It is therefore recommended to extend exploration beyond the current study area to identify additional deposits and to provide a more comprehensive assessment of the pozzolan potential of Côte d'Ivoire.
- Two distinct deformation mechanisms have affected the study area. Ductile deformation is reflected by the development of foliation, en echelon tension veins, shear zone, and boudinage, whereas brittle deformation is characterized by the occurrence of faulting.

Compliance with ethical standards

Conflict of interest statement

No conflict of interest to be disclosed

Statement of ethical approval

As this study did not involve human participants or animals, no ethical approval was required.

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