Vol. 15(3), pp. 39-49, October-December, 2023
DOI: 10.5897/JGMR2023.0384
Article Number: 57D966D71561
ISSN: 2006-9766

http://www.academicjournals.org/JGMR

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Journal of Geology and Mining Research

Full Length Research Paper

Direction of material creep during the deformation phase in shear zones, role in mining prospecting: A case of the Nassara-Torkera gold deposits in the Gaoua region, Burkina Faso, West Africa

Pascal Ouiya[1,2]*, Gounwendmanaghré Hubert Zongo[2,3], Adama Ouédraogo Yaméogo[2,4] and Séta Naba[2]

[1]Ecole Normale Supérieure (ENS), Institute of Science and Technology (IST), Ouagadougou, Burkina Faso.
[2]Geosciences and Environment Laboratory (LaGe), Department of Earth Sciences, Ouagadougou, Burkina Faso.
[3]University of Fada N'gourma (UFDG), Fada N'Gourma, Ouagadougou, Burkina Faso.
[4]Norbert ZONGO University (UNZ), Koudougou, Burkina Faso.

Received 21 September, 2023; Accepted 20 November, 2023

Mineralization at the Nassara and Torkera gold deposits is situated at the contact between volcanic rocks (basalt-andesite) and volcanosedimentary rocks (pyroclastite, black shale) within the echelon faults of the large West Batié shear zone (WBZ). Along the mineralized body, shear deformation is intense, accompanied by significant hydrothermal fluid circulation. The objective of this study is to determine the direction of hydrothermal fluid creep in the Nassara-Torkera shear zone. To achieve this, we have integrated direct field measurements with Anisotropy of Magnetic Susceptibility (AMS) measurements and microstructure analysis. Magnetic foliation data align with direct field measurements. Additionally, the lineation data indicate that, during the deformation phase, the material or mineralizing fluids exhibit a southeastward creep, following the contemporaneous structures of deformation. These structures are observed to govern the gold mineralization. Furthermore, the gold content increases in the vicinity of lamprophyre, dacite, and diorite dykes. This observation suggests that the mineralizing fluid and the dykes were emplaced along the same structures of deformation. The drainage of the mineralizing fluid to the southeast explains the occurrence of the seven gold deposits (Djikando, Poni, Nassara, Torkera, Wadaradoo, Konkera and Napelepera) identified along the shear corridor. Identifying the direction of material creep in shear zones serves as a potent prospecting guide for mining explorers, enabling them to strategically position various drill holes efficiently.

Key words: Nassara-Torkera, gold deposit, material creep direction, Anisotropy of Magnetic Susceptibility (AMS), dykes.

INTRODUCTION

Most studies indicate that metal resources are associated with the circulation of hydrothermal fluids within shear

*Corresponding author. E-mail: pascal.ouiya@gmail.com.

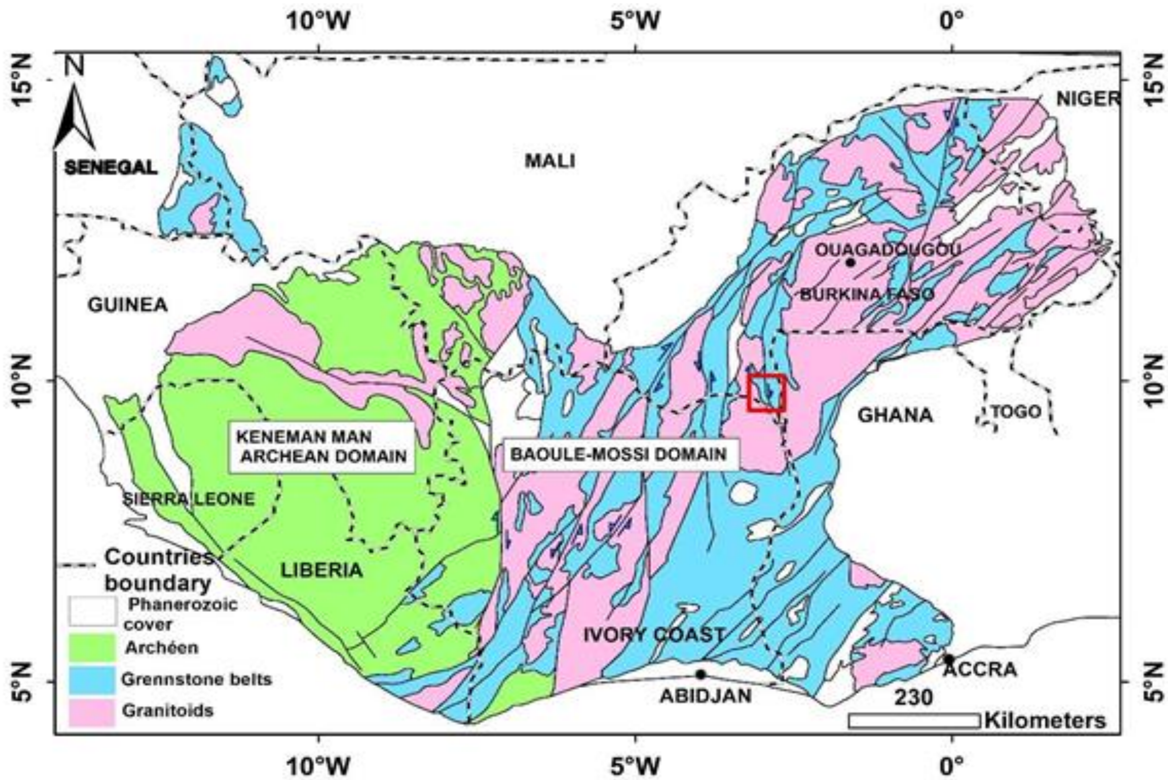

Figure 1. Synthetic geological map of the Man/Léo Ridge showing the position of the study area.

zones (Milési et al., 1992; Morey et al., 2007; Baratoux et al., 2011; Treloar et al., 2015; Robertson and Peters, 2016; Goldfarb et al., 2017). A comprehensive litho-structural mapping campaign can be instrumental in identifying shear zones, offering valuable guidance to mining explorers in selecting potential zones. Numerous works in this regard have identified shear corridors hosting different deposits or ore bodies by combining direct field measurements with various imaging techniques, including airborne photography, satellite imagery, radar imagery, and airborne geophysical images (magnetism, electromagnetism, radiometry, seismic, and gravimetry) (Baratoux et al., 2015; Ouiya et al., 2016; Markwitz et al., 2016; Sawadogo et al., 2018; Ouiya et al., 2020; Chardon et al., 2020).

In these shear zones, planar structures (schistosity, foliation) are evident, displaying variable deformation intensity. Four types of lineation are observed: intersection lineation, crenulation lineation, elongation lineation, and mineral lineation. Among these, the latter two serve as excellent indicators of the direction of material flow. The Anisotropy of Magnetic Susceptibility (AMS) method is employed in granitoids and massive volcanic rocks to identify planar structures and lineations (Naba et al., 2004; Traoré et al., 2011; Ilboudo et al., 2013; Sawadogo et al., 2018). In these formations, planar structures and lineations are not visible in the field. Lineations in granitoids primarily enable the proposal of a geodynamic emplacement model for the latter (Naba et al., 2004; Végas et al., 2008; Sawadogo et al., 2018; Yameogo et al., 2023).

Within shear zones, the absence of lineation may be attributed to the lack of marker minerals such as pebbles and phenocrysts (Brisson, 1998). This absence of lineation in the shear corridor in the field hinders mining explorers from determining the material's creep direction during deformation. Hence, the AMS method was applied in the Nassara-Torkera shear zone, an echelon fault located in the West Batié Shear Zone (WBSZ). The aim of this study is to constrain mineral lineation to offer guidance for mineral prospecting. The study utilizes direct field measurements in the Nassara-Torkera shear corridor and the magnetic susceptibility anisotropy method. The data are discussed to illustrate how they can inform and guide mining exploration.

Regional geological setting

The Man/Léo shield is composed of two domains. In the occidental domain, also called the Kenema-Man domain, the geological formations have Archean ages, while in the eastern part, also known as the Baoulé-Mossi domain, the geological formations have a Paleoproterozoic age (Figure 1). Formations of Paleoproterozoic age are referred to as Birimian formations (Bessole, 1977). These formations are organized into greenstone belts, bordered by vast batholiths of Tonalite, Trondhjemite, and Granodiorite (TTG), which are syn-tectonic granitoids (Pons et al., 1995; Gasquet et al., 2003).

The Boromo greenstone belt, located in southwest Burkina Faso, belongs to the Baoulé-Mossi domain. In terms of lithostratigraphic succession, the Boromo belt is composed of a volcanic and intrusive sequence consisting mainly of effusive volcanics (basalt, andesite, rhyodacite, rhyolite) and pyroclastites (Ouédraogo and Pros, 1986; Baratoux et al., 2011, 2015; Metelka et al., 2011). This volcanic sequence is surmounted by a volcanosedimentary sequence composed of tuffs, epiclastites, pelites, and greywackes. Basic to intermediate volcanic dykes with calc-alkaline affinity (dacite, rhyodacite, rhyolite), intercalated with sediments, are topped by a thick detrital layer of sediments and carbonaceous rocks (Leube et al., 1990; Hirdes et al., 1996; Vidal et al., 1996; Pouclet et al., 1996; Feybesse et al., 2006; Baratoux et al., 2011, Baratoux et al., 2015). These two sequences are intersected by several phases of granitization.

The Nassara and Torkéra gold deposits are located in the Boromo greenstone belt, south of Gaoua, where the main lithologies are volcanic, volcanosedimentary, and sedimentary rocks (Figure 2). Specifically, both deposits contain basalts, andesites, dacites, rhyodacites, and granitoids. This ensemble is intersected by circumscribed intrusives of diorite and lamprophyre dykes (Ouiya et al., 2016). All of these lithologies except from the late dykes are affected by at least four phases of deformations namely $D1_{GA}$, $D2_{GA}$, $D3_{GA}$, and $D4_{Ga}$ (Baratoux et al., 2015).

METHODOLOGY

The deposits here studied have been a subject of diamond drill program undertaken by the mining company Volta Resources, which allow us to take some samples for our studies. These samples have been used to make fifty (50) polished thin sections for observations under polarization microscope using both transmitted and reflected light at the Geosciences and Environment Laboratory (LaGE) at Joseph Ki Zerbo University (Burkina Faso).

For the measurements of Anisotropy of Magnetic susceptibility (AMS), small oriented samples (2.5 cm in diameter and around 7 cm in height) have been cored on the field using portable drilling machine. At least two oriented cores are sampled by station. All the structures (foliations and lineations) which are evident at the field scale are directly measured using a compass and clinometer.

In the laboratory each core is cut in order to get the appropriate shape (d=2.5 cm and h=2.2 cm) for AMS measurements. At least two small samples are cut by core giving a minimum of four samples by sampling station. The measurements have been performed using the susceptometer kappabridge MFK1-FA of AGICO from the Geosciences and Environment Laboratory (LaGE) of the Joseph KI-ZERBO University (Ouagadougou, Burkina Faso). On one hand the AMS measurements allow to access to the scalar data such as the mean susceptibility (Km), Anistropy degree (P) and the shape factor (T) and on the other hand, it is allowed to access to the directional data (magnetic foliations and magnetic lineations). The data have been processed using the Anisoft software of AGICO. Scanning electron microscope analyses were carried out on pyrite crystals at the Geosciences Environnement Toulouse (GET) laboratory at Paul Sabatier University, France.

Characteristics of the orebody at the Nassara and Torkéra gold deposits

The mineralized body in the Nassara and Torkéra zones displays the same characteristics, that is mineralization is located at the contact between volcanic rocks (basalt and andesite) and volcano-sedimentary rocks (pyroclastites and black schists) in highly sheared zones. In these zones, the various host rocks are affected by a shearing deformation structure (S1) of mean orientation 145°E with strong to medium dip values to the southwest corresponding to the second deformation phase $D2_{Na}$ (Ouiya et al., 2016). This structure globally controls gold mineralization in both deposits. It is taken up by a crenulation or fracture schistosity whose mean direction is northeast (N50 to N80°E) corresponding to the third deformation phase $D3_{NA}$ (Ouiya et al., 2016). In the field, these two phases of deformation are visible through quartz veins that are parallel to subparallel to the shear structure, which is locally taken up by the S2 crenulation or fracture schistosity (Figure 3a and b).

On the cores, these structures are clearly visible with the S1 shear structure, which is also picked up by the S2 crenulation or fracture schistosity (Figure 3c and d). At regional scale, $D2_{NA}$ and $D3_{NA}$ correspond respectively to $D3_{GA}$ and $D4_{GA}$ proposed by Baratoux et al. (2015).

These shear zones are also strongly affected by two hydrothermal alteration event. Carbonate (ankerite)-chlorite-quartz ± albite is the first typical paragenesis in most host rocks (Figure 4a and b). The second alteration phase is superimposed on the first, and is marked by strong silicification accompanied by significant pyritization (Figure 4c and d). This quartz-sericite-pyrite paragenesis is mainly located between the white-mica-rich bands that run parallel to sub-parallel with the S1 shear structure (Figure 4e).

Indeed, the silicification that accompanies pyritization is strongly enhanced in contact with small felsic dykes (dacite, diorite) and lamprophyres (Figure 5a and b). Most sulfides (pyrrhotite, pyrite, chalcopyrite) are found in these zones. Among these sulfides, mineralization is associated with pyrite, regardless of the nature of the host rock. Gold grains either occupy micro-fractures (Figure 6a and b), or are found as inclusions in pyrite crystals (Figure 6c) (Ouiya et al., 2016). Gold is rarely found in minerals of the hydrothermal alteration paragenesis (Figure 6d). The various gold grains are xenomorphic in shape, with sizes not exceeding a few micrometers in pyrite crystals.

This gold mineralization is related to the second paragenesis of hydrothermal alteration that developed synchronously with S1 shear deformation. This D1 deformation underlined by S1 corresponding to $D2_{NA}$ at Nassara (Ouiya et al., 2016) and D3GA at the scale of the Gaoua region (Baratoux et al., 2015) (Figure 7a and b). This phase of deformation is taken up by the second phase of deformation highlighted by S2, but which does not significantly affect mineralization to the point of creating remobilization (Figure 7c and d).

Anisotropy of magnetic susceptibility (AMS) data

The AMS measurements allow access to scalar data and directional data (Table 1). For the present study, we use only the directional data (magnetic foliation and magnetic lineation) to complete the field measurements. A number of studies have established that the three axis of the ellipsoid of AMS are coaxial with the axis of the ellipsoid of deformation (Bouchez et al., 1997).

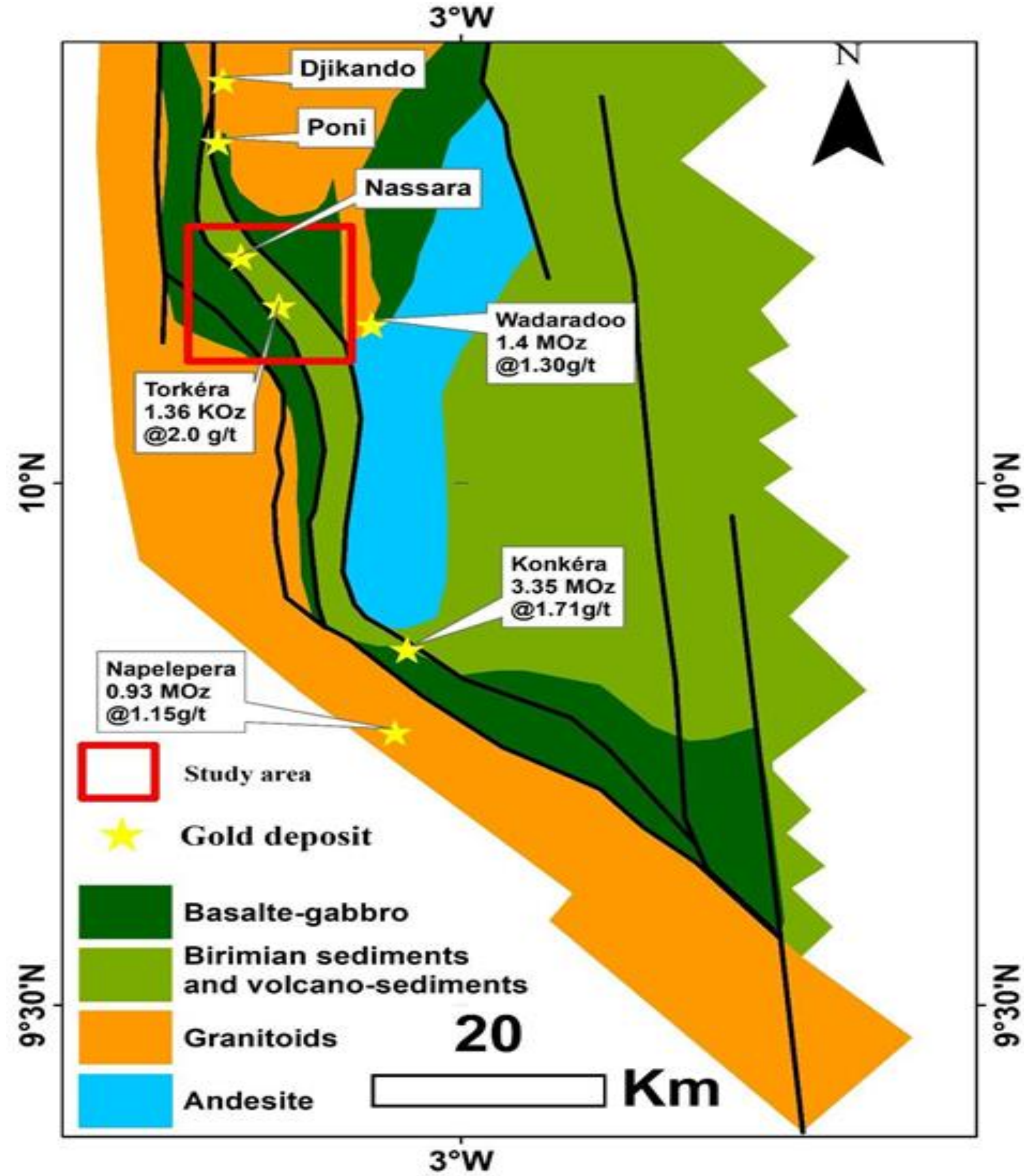

Figure 2. Geological map of the Gaoua region, showing the location of the Nassara and Torkéra gold deposits, as well as many others.

Magnetic foliation

The foliations data on five sampling stations are consistent with the field measurements with a mean NW to NNW trend and steeply dipping toward the NE (Figure 8). This suggests that the maximum flattening direction was NE to ENE directed.

Magnetic lineation

Stretching lineation markers are scarce, even in highly deformed zones. Given the importance of lineations in determining the direction and sense of material flow during deformation, employing the AMS method to highlight them was justified. The azimuth (NW-SE) of the lineation at the five sampling stations is consistently homogeneous, aligning with the mineralized body, and exhibits slight to moderate plunges toward the SE (Figure 9).

RESULTS AND DISCUSSION

The Nassara and Torkera gold deposits are situated within an echelon fault of the large western Batié shear zone. The alignment of magnetic foliation with direct field measurements unequivocally identifies the shear corridor hosting these two deposits. This S1 shear structure corresponds to the $D2_{Na}$ at the local scale of the Nassara

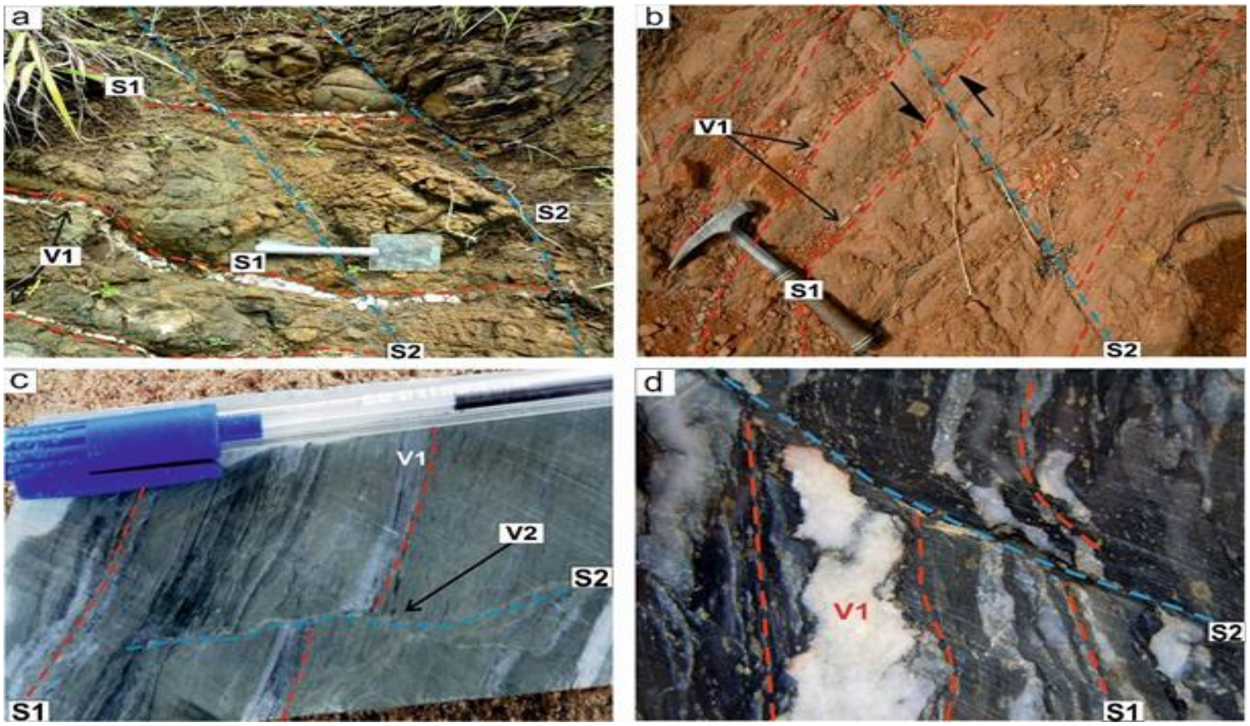

Figure 3. Photographs showing the various structures in the shear corridor. (a) Quartz vein parallel to subparallel to the shear plane (S1) in basalt-andesite and locally overprint by the crenulation cleavage (S2), (b) quartz veinlet concordant to S1 in basalt-andesite and overprint by a S2 fracture cleavage, (c) basalt-andesite crosscut by a quartz veinlet concordant with S1 and overprint by fracture cleavage (S2) with carbonate veinlets, (d) graphitic schist cut by sigmoidal quartz-albite veins and affected by S2 cleavage.

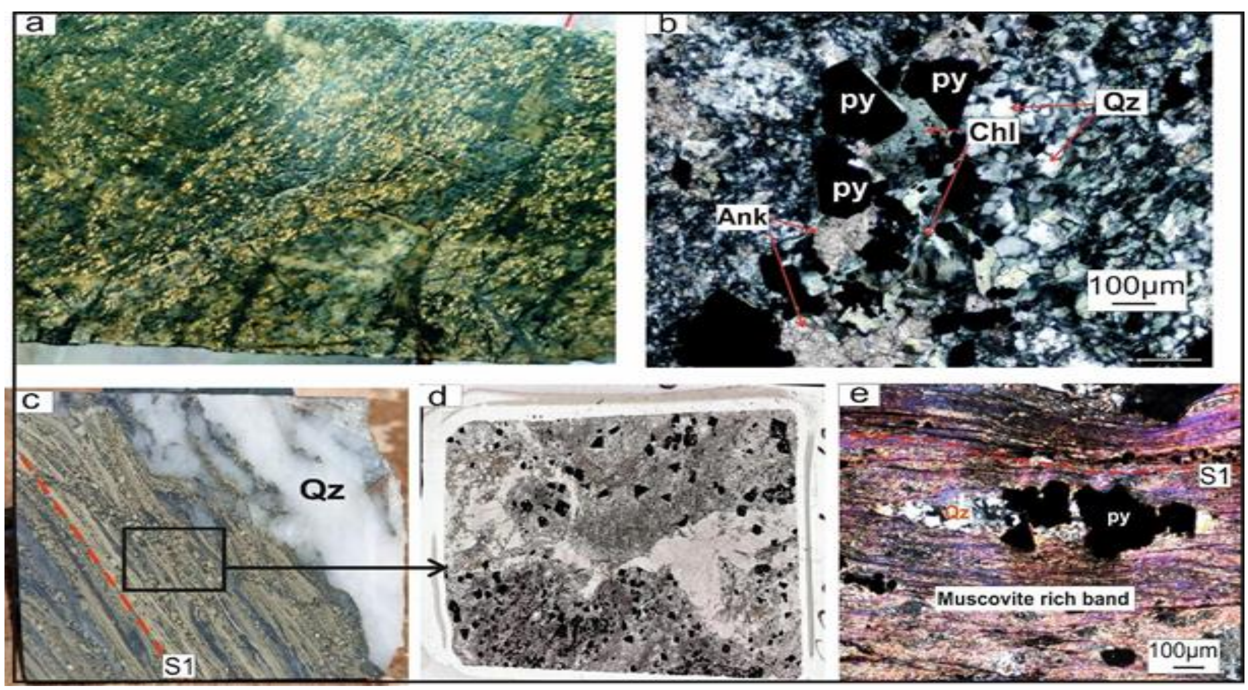

Figure 4. Hydrothermal alteration in host rocks of the gold deposits. a) Quartz-chlorite-ankerite veinlets as hydrothermal minerals in the andesite-basalt, b) Microphotograph of ankerite-quartz-chlorite ± pyrite, as first phase of hydrothermal alteration (analyzed and polarized light), c) quartz-pyrite in basalt-andesite highly hydrothermalized, d) scanned whole thin section showing various minerals and pyrite crystals synchronous of the second phase of deformation, e) microphotograph of pressure shadows infilled by quartz around the pyrite crystals.

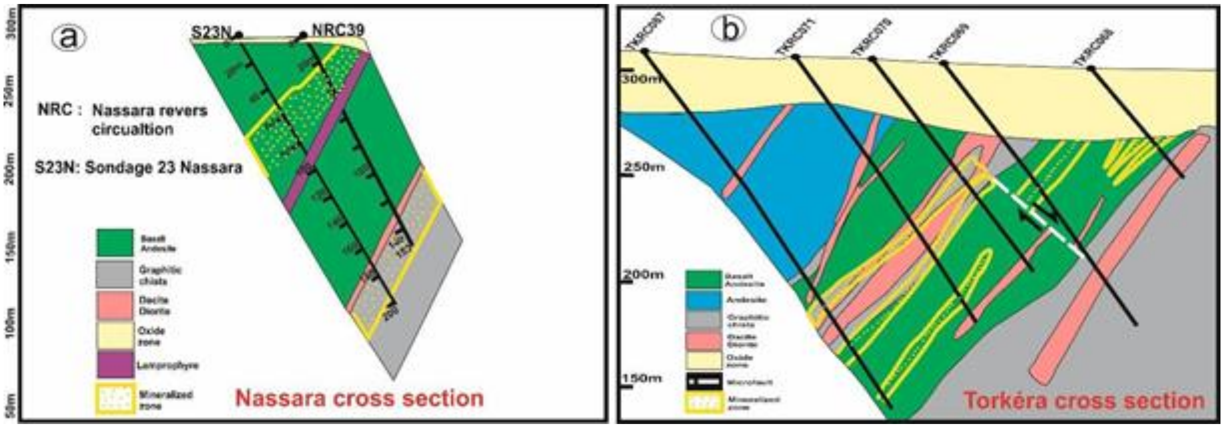

Figure 5. Sections showing the different rocks hosting the mineralization in the gold deposits. (a) Section of hole S23N in the Nassara zone intersecting the orebody rocks and mineralized zones; (b) Section of holes TKRC087, 71 and many others intersecting the orebody rocks with the mineralized levels.

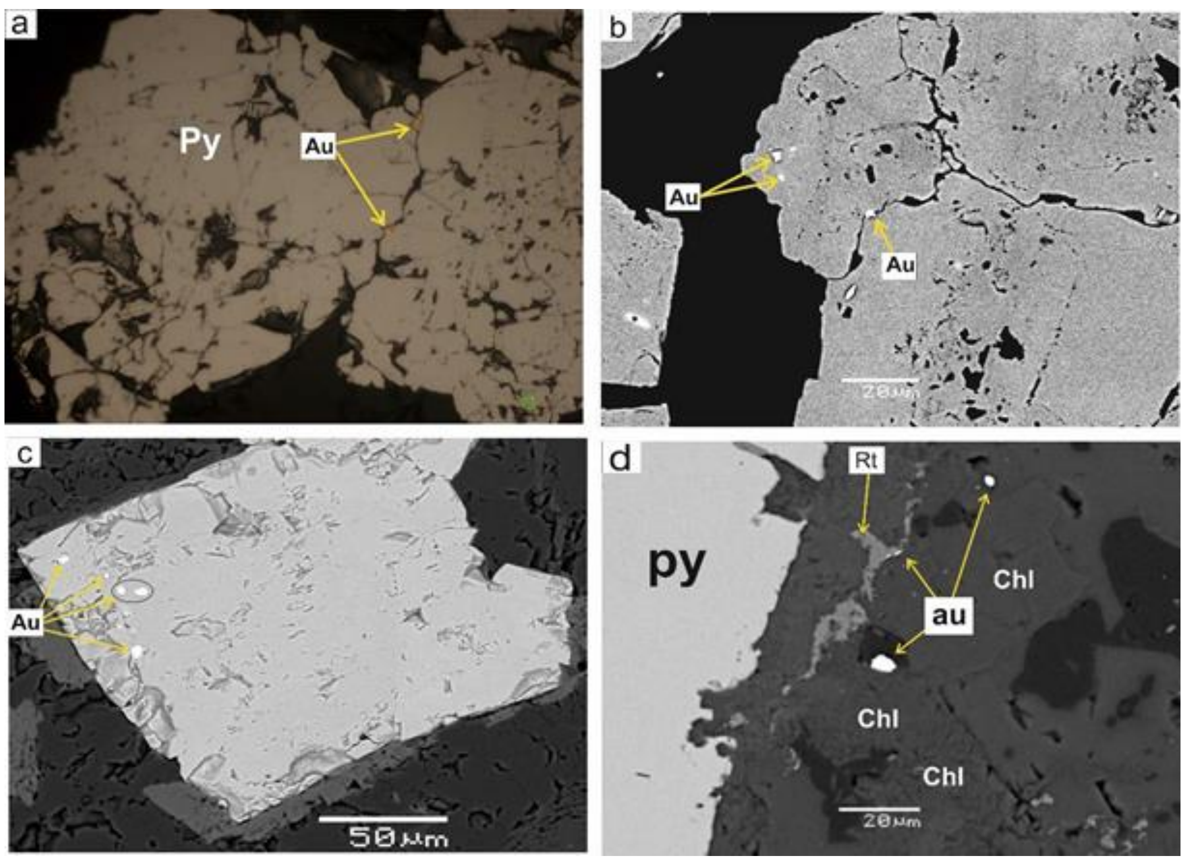

Figure 6. Relationship between pyrite crystals and gold grains. (a,b) Reflected-light and scanning electron microscope images, respectively, showing gold grains filling microfractures, (c) Scanning electron microscope image showing gold grains embedded in pyrite, d) Scanning electron microscope image showing the rare instances where gold grains are associated with minerals of the hydrothermal alteration paragenesis.

shear zone (Ouiya et al., 2016) and to the $D3_{Ga}$ at the regional scale (Baratoux et al., 2015). Globally, it governs gold mineralization at Nassara and Torkera. S1 is locally affected by crenulation or fracture S2, corresponding to $D3_{Na}$ and $D4_{Ga}$ on a regional scale.

Mineralization at Nassara and Torkera is distinctive in

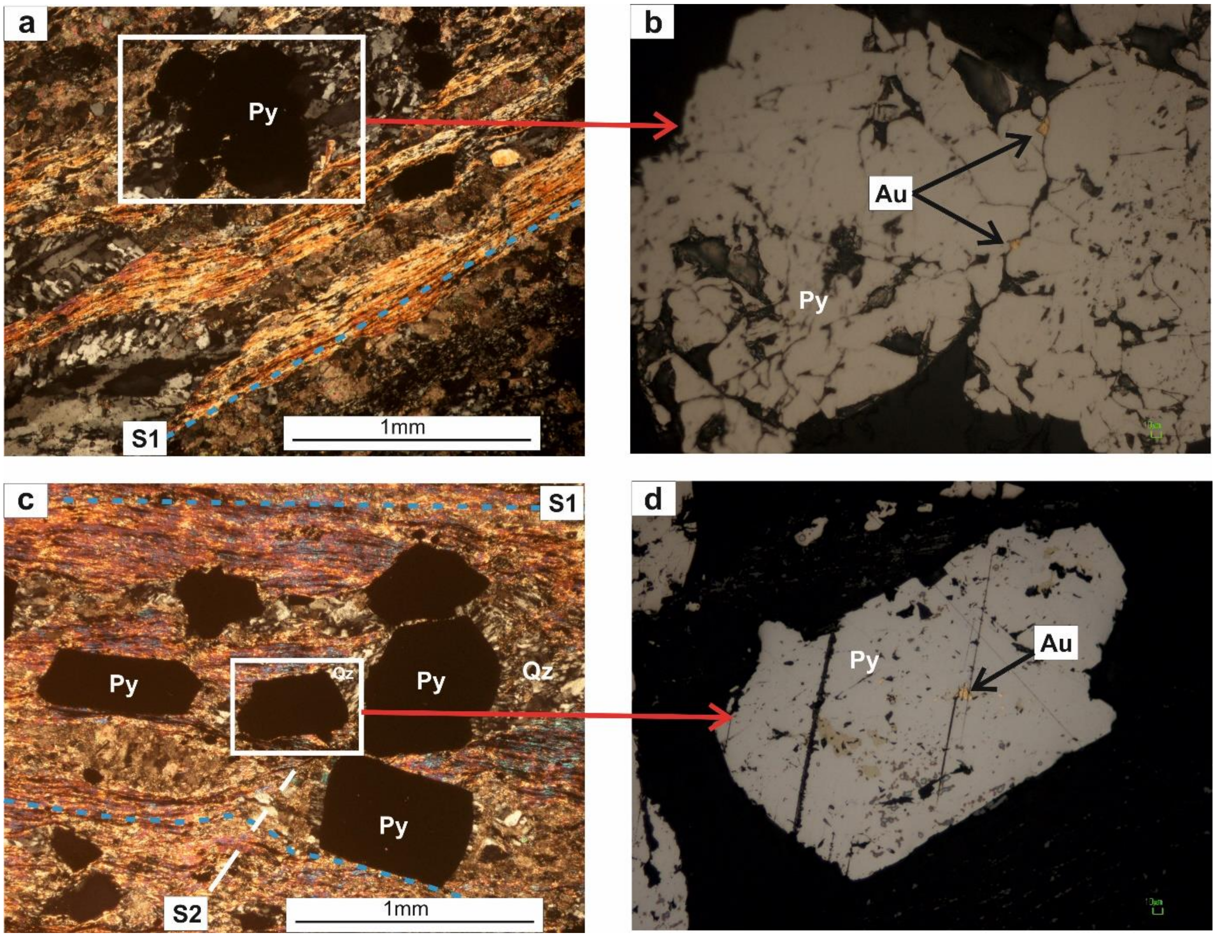

Figure 7. Microphotographs showing the relationship between hydrothermal alteration, deformation and gold mineralization. a) Polarized analyzed light image of a pyrite crystal caught in a white mica-rich S1 shear band highlighting the D1 deformation, b) Reflected light image of gold grains filling microfractures in pyrite, c) Polarized analyzed light image showing pyrite crystals arranged between white mica-rich bands highlighting the S1 locally taken up by the S2, d) Gold grain inclusion in pyrite seen in reflected light.

Table 1. Scalar and directional data for the Nassara-Torkera shear corridor. Km: Average susceptibility by site. P: Total anisotropy by site. T: Shape parameter by site.

Sampling station	Location (UTM, Zone 30P North)		Scalar data			Directional data	
ID	X (m)	Y (m)	Km (10^{-6} SI Unit)	T (en SI)	P (SI Unit)	Lineation	Foliation
NS01	481856	1128320	1026.3	0.1	1.08	96/35	146/42 NE
NS02	482118	1128590	462.4	-0.3	1.00	161/14	159/85 NE
NS03	482604	1127911	1009.1	0	1.03	133/60	141/83 NE
NS04	483843	1125489	1157.1	-0.2	1.08	122/44	152/63 NE
NS05	484521	1124758	1085	-0.3	1.05	153/20	172/48 NE

that the D2 deformation, intended to remobilize the early mineralization associated with D1, has only weakly remobilized it. This may explain why the Nassara and Torkera gold deposits have retained their status as deposits, as remobilization plays a crucial role in determining the economic viability of a deposit. Many economically profitable deposits owe their success to several successive phases of deformation occurring after the mineralization phase, facilitating the remobilization of the initial mineralization (Bourges et al., 1998; Traoré et al., 2016; Augustin et al., 2016; Fontaine et al., 2017; Woodman et al., 2016).

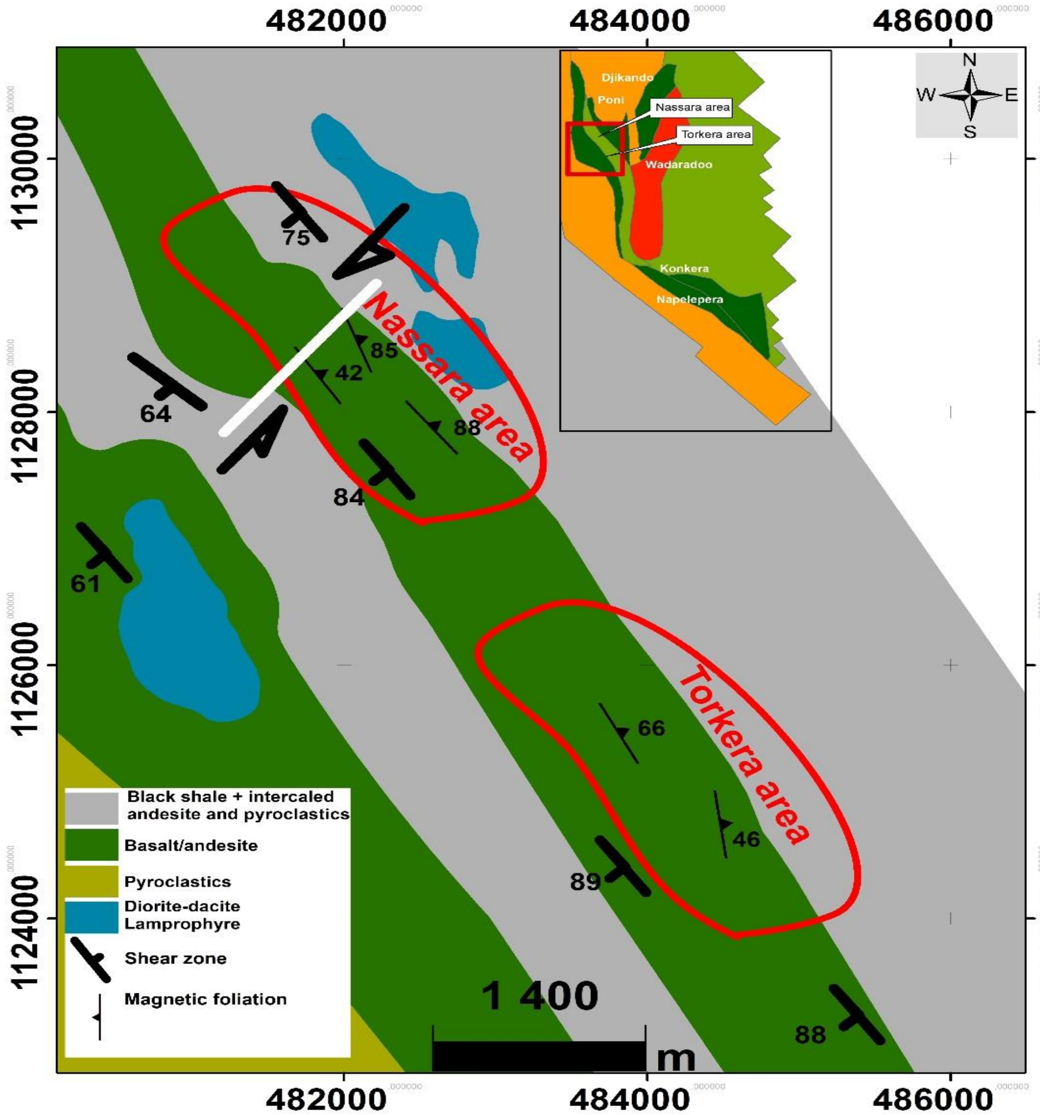

Figure 8. Litho-structural map of Nassara and Torkera. The magnetic foliations are oriented NW-SE with a NE dip, while the structures measured directly in the field have the same direction with a SW dip.

Furthermore, at Nassara and Torkera, mineralization is exclusively associated with pyrite crystals, whereas in other locations, it is linked to both pyrite and arsenopyrite, and sometimes to tourmaline (Béziat et al., 2008; Traoré et al., 2016; Salvi et al., 2016).

The direction of the material flow during the deformation is important information which may help to follow the path of hydrothermal circulation and therefore would be a major contribution for determining the extension of the mineralization. Since the AMS method allow getting information about lineation even is the cases the fabrics are discrete, we have used it. Strong plunge lineations (>60°) in the magmatic bodies indicate in many cases the magma feeding zones (Vigneresse and Bouchez, 1997; Améglio et al., 1997; Naba et al., 2004; Traoré et al., 2011; Sawadogo et al., 2018). However, slight to moderate plunging lineations would indicate the magma flow, perpendicularly or oblique to the maximum regional stress in the upper levels of the crust (Naba et al., 2004; Vegas et al., 2008). In the present case, along the ore body, the lineations have a NW-SE azimuth, with slightly to moderate plunging towards the SE.

This reflects creep of the material during the deformation phase towards the SE, as lineation is the finite stretch of deformation. This result presents prospecting leads for mining explorers in that the lineations indicate where mineralizing fluids have circulated. The link between mineralization and hydrothermal fluid circulation has been established in

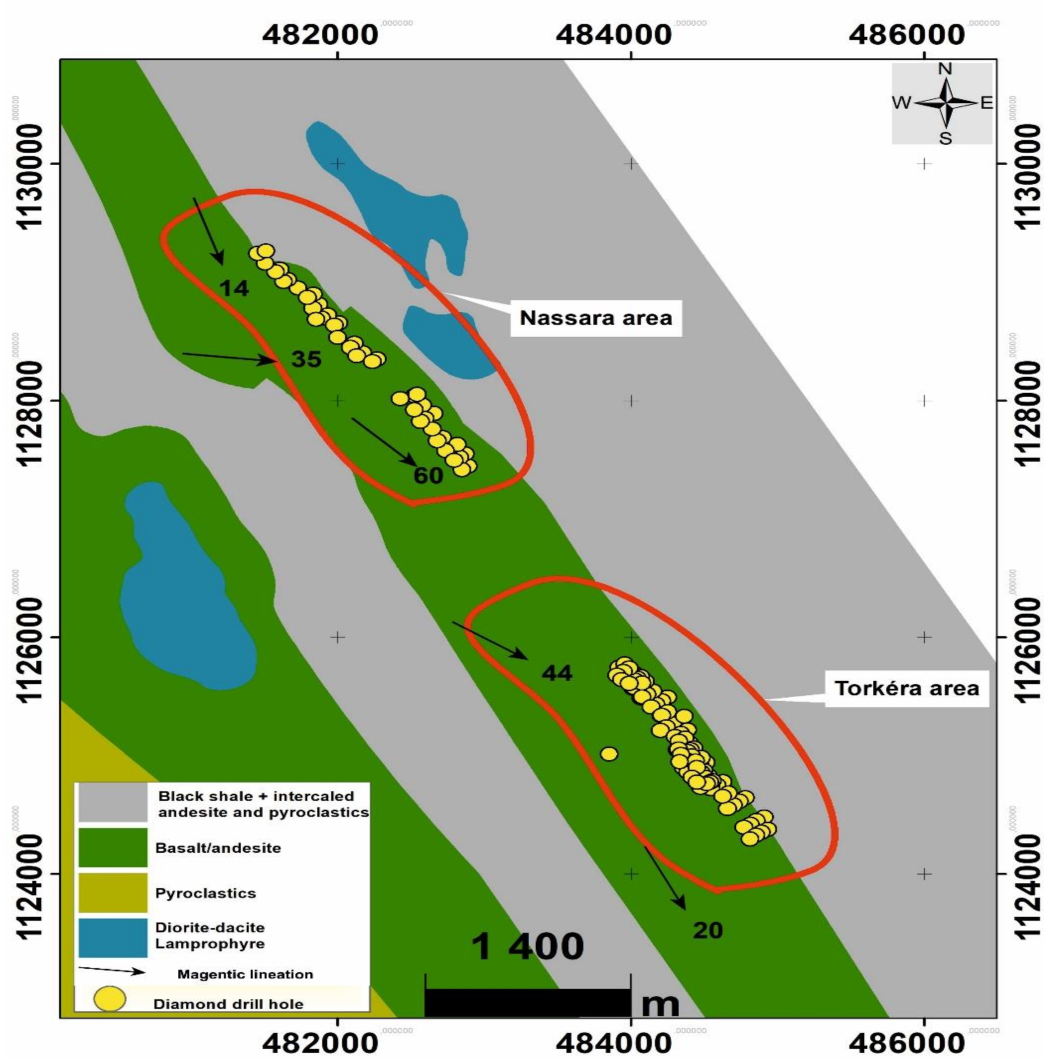

Figure 9. Litho-structural map showing magnetic lineation and Diamond drill hole positions for the Nassara and Torkéra gold deposits. The shallowly dipping magnetic lineations indicate that the mineralizing fluids flowed from NW to SE.

almost all shear zone work (Traoré et al., 2016, Augustin et al., 2016; Fontaine et al., 2016; Woodman et al., 2016). In the Nassar-Torkera gold deposits, the mineralizing fluid flowed from northwest to southeast. Here, prospectors can accentuate drilling in the south-eastern part of the exploration permit, with a greater chance of circumscribing the mineralized body.

Mineralization is much more concentrated in contact zones with felsic and lamprophyric dykes. Indeed, the close relationship between high gold grades and these dikes is not indicative of a genetic link with them. However, this spatial link between mineralization and the various dykes indicates that the mineralizing fluids follow the same structures with the dikes. Some authors (Muller et al., 1992; Taylor et al., 1994; Dubé et al., 2004) believe that there is no direct genetic link between lamprophyres and gold in the various deposits, but rather a spatial link. Some studies have demonstrated that the altered dikes are rich in gold due to mineralizing hydrothermal fluids (Kerrich and Wyman, 1994; Wyman et al., 1995). The presence of lamprophyre and felsic dikes, especially at the vicinity of highly mineralized zones, is therefore an indicator of crustal permeability capable of draining mineralizing hydrothermal fluids at the time of emplacement. It is along these structures that the stretching material or mineralizing hydrothermal fluids drained, the direction of which is indicated by the lineations to the SE in the case of the Nassara and Torkéra gold deposits. This channeling of mineralizing fluids during the deformation phase from northwest to southeast would have generated the various gold deposits from the Djikando, Poni, Nassara, Torkéra, Wadaradoo, Konkéra and Napelepra zones.

Thus, the AMS method, through its directional data, in particular lineation, applied in shear corridors, could be a powerful prospecting guide for mining explorers. This technique has been used to identify the Nassara corridor and its associated zones (Ouiya et al., 2020). The present study proposed that AMS be applied as an exploration technique not only to identify shear zones, but also to identify the direction of the creep of hydrothermal fluid at the time of the deformation.

Conclusion

Gold mineralization occurs at the contact between volcanic rocks (basalt-andesite) and volcanosedimentary rocks (pyroclastite, black shale) along a highly sheared ore body. The first phase of deformation, characterized by shear deformation, predominantly controls the gold mineralization and is locally overlaid by crenulation or fracture cleavage.

In the vicinity of lamprophyre, dacite, and diorite dykes, there is an increase in gold content. This is attributed to the mineralizing fluid circulating within the same structures as these dykes during their emplacement. The lineations gave a NW-SE azimuth with low to medium plunges to the SE, indicating that the fluid responsible for mineralization flowed from NW to SE.

Drainage of the mineralizing fluid to the SE explains the concentration of the seven gold deposits (Djikado, Poni, Nassara, Torkera, Wadaradoo, Konkera and Napelepera) in this part of the permit.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

ACKNOWLEDGEMENTS

The authors appreciate B2Gold, the mining company, and its chief geologist, Mr. NARE Athanase, for granting permission to sample various rocks for analysis. Special thanks are extended to the WAXI-2 project for providing funding for the fieldwork and geochemical analyses and Research Institute for Development for their logistical support.

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