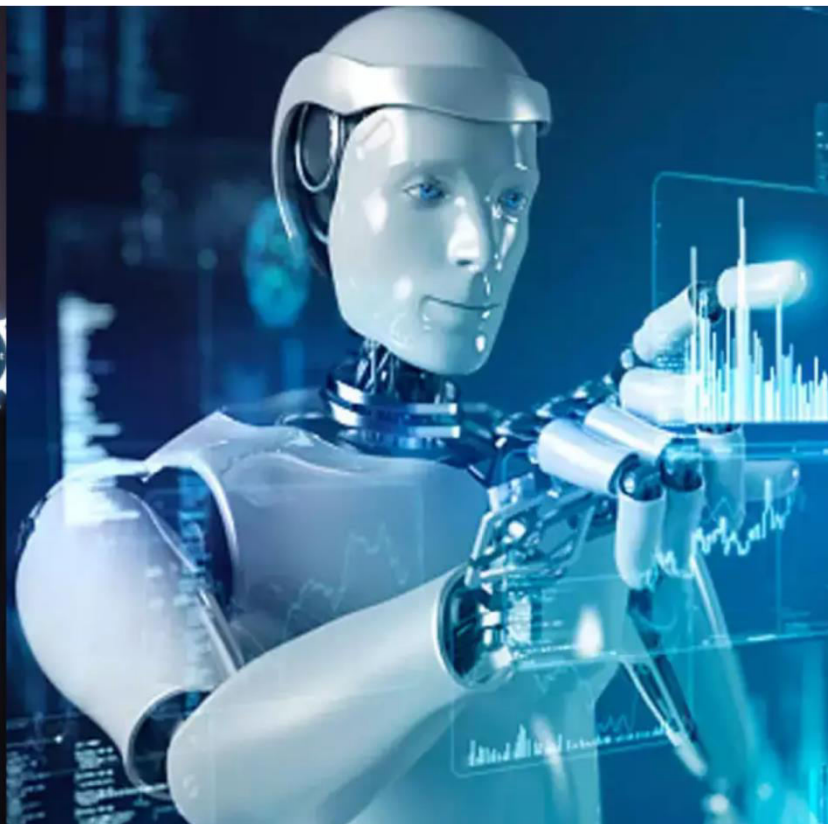




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Petrological and Structural Characteristics of Auriferous Mineralization in the Betsiaka Group, Northern Madagascar

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ABSTRACT: The Betsiaka region, located in northern Madagascar, is renowned for its significant gold mineralization. This study aims to characterize the gold mineralization using a petrostructural approach. In the Betsiaka Group, gold occurs both in free form and in association with various minerals. It formed within a mesothermal to epithermal context, favorable to the circulation of gold and precious metal rich hydrothermal fluids of magmatic origin. In the main gold-bearing zones namely Ankatoko, Ambilo, Mantalimaro, Betsiaka and Labaika gold is predominantly associated with quartz and barite, while galena and sphalerite occur locally. The host rocks are characterized by a variety of both dense and transparent minerals, including amphiboles, pyroxenes, muscovite, and biotite, which serve as favorable indicators for gold prospecting. The regional lithological assemblage comprises three major rock types: magmatic, sedimentary, and metamorphic. The diversity of these petrographic facies, combined with the area's complex tectonic architecture, largely explains for the high concentration and widespread distribution of gold mineralization. The study area exhibits intense structural deformation, marked by prominent shear zones, fault systems and fracture networks. Two principal generations of mineralized veins have been identified: auriferous quartz veins and barren barite veins. Gold mineralization is distributed between structurally controlled lode-type deposits and secondary placer accumulations, the latter resulting from the weathering and erosion of primary sources, particularly within the Permo-Triassic Andavakoera Sandstone Formation. The development of the current gold-bearing vein systems is attributed to two major metallogenic events associated with the Bemarivo orogeny: an initial strike-slip tectonic phase (D1) and a subsequent plutonic phase (D2), both of which played a critical role in controlling fluid migration and ore deposition.

KEYWORDS: Betsiaka, petrostructural, metallogeny, gold deposits, mineralization

I. INTRODUCTION

The Betsiaka Group, situated in the Ambilobe District at the transition zone between the sedimentary basin and the crystalline basement of northern Madagascar, is notable for hosting a significant gold deposit of considerable geological, economic and social importance. In this region, small-scale artisanal gold mining represents a vital livelihood for the local population, contributing substantially to the socio-economic fabric of the area. Although numerous geological studies have been conducted in northern Madagascar such as those by [1],[2],[3],[4],[5],[6],[7],[8], [9], [10],[11] geological data specifically concerning the genesis of gold mineralization within the Betsiaka Group remain scarce and are generally lacking in detailed analytical interpretation. The genesis and spatial distribution of these gold deposits are generally attributed to geological events spanning from the Neoproterozoic [11], [12] through to the late Permian. Despite

this temporal framework, the specific geological processes responsible for their formation and mineralization potential remain inadequately understood. A comprehensive understanding of the mechanisms governing gold emplacement in this region is critical, both for elucidating the geodynamic conditions conducive to gold concentration and for enhancing existing models of exploration and resource exploitation.

This study aims to address the central question: How do geological structures and petrographic features govern the genesis and spatial distribution of gold mineralization within the Betsiaka Group? Accordingly, the primary objective is to elucidate the petrostructural controls influencing gold mineralization in this region.

II. MATERIALS AND METHODS

This study involved an extensive literature review complemented by field investigations, which included systematic sampling and interviews with local artisanal miners. The integration of these methodologies enabled the comprehensive acquisition of data required for subsequent analysis.

GEOLOGICAL FRAMEWORK REGIONAL GEOLOGY

The Betsiaka Group is situated in the northwestern sector of the Neoproterozoic Bemarivo domain, with an estimated age of approximately 2477 Ma ^[10]. It constitutes a tectonic contact zone between the Neoproterozoic Bemarivo basement and the Permian-Triassic sedimentary succession of the Ambilobe basin. This boundary is marked by a normal fault, which developed in response to tectonic collision processes linked to the Mozambican rifting event. In the northern sector, the Betsiaka Group represents one of the oldest lithotectonic units within the Bemarivo domain, surpassed in age only by the Sahantaha Group to the south. The structural discontinuity observed between the Betsiaka and Sahantaha Groups is indicative of a subduction-related tectonic event within the region.

LOCAL GEOLOGY

The Betsiaka Group extends over an area approximately 6 km in width and 50 km in length ^[8], constituting the northernmost boundary of the Neoproterozoic Bemarivo block. It is geographically bounded to the north and northwest by the Permian-Triassic Andavakoera sandstone massif, to the southwest by the Milanoa sub-terrane and to the southeast by the Daraina sub-terrane. The group comprises three principal petrographic units: the Mantalimanera metasediments, amphibolite orthogneisses and calcsilicate formations ^[10]. The landscape is predominantly covered by lateritic soils and hardened sands, which obscure much of the original outcrop exposures. The occurrence of shales, conglomerates, sandstones and argillites reflects a lithological affinity with the post-orogenic Ambilobe sedimentary basin. Secondary gold mineralization observed within the lateritic soils is indicative of ancient erosion processes affecting the Permian-Triassic Andavakoera sandstone massif. The local tectono-magmatic evolution has produced a diverse assemblage of lithologies, including migmatites, pegmatitic intrusions, amphibolites, garnet-bearing amphibole orthogneisses, quartzites, quartz-feldspar gneisses, marbles, and biotite-rich micaschists. These rock units are closely associated with the emplacement of auriferous quartz and barite vein systems within the region. Mineralogical variations and the presence of stretching structures signify a pronounced degree of retrograde metamorphism, consistent with observations from other units within the Bemarivo domain. Outcrops of granitoids, paragneisses and volcanic rocks exhibit petrographic and geochemical affinities with the Archean Antongile sequence ^{[4], [13], [14], [10]}. Numerous hydrothermal veins oriented along NE-SW and NW-SE trends record the imprint of significant tectonic events that have shaped Madagascar. The regional geology is further characterized by dome-and-basin structural patterns resulting from large-scale tectonic processes.

2.2. EVOLUTION OF THE BETSIKA GROUP

The structural evolution of the Betsiaka Group is intimately associated with the closure of the Mozambique Ocean and the subsequent amalgamation of East Gondwana. The tectonic imprint of the group is primarily defined by brittle deformation features linked to Precambrian orogenic processes. Key structural elements include fractures, fault systems, folds, stretching lineations and shear zones, with dominant orientations along NE-SW and NW-SE trends ^[10]. Post-Triassic fracturing, predominantly oriented around N120°, locally displaces earlier structural alignments trending between N20° and N50°, and affects all lithological units up to the Upper Triassic strata. Pre-existing tectonic features contributed to the development of a shear zone characterized by the formation of thick silicified breccias along the contact between the basement complex and the Mantalimaro sandstone. Extensional fractures associated with this

tectonic evolution are frequently mineralized, serving as conduits for ore-bearing fluids. Recent isotopic analyses of zircon grains indicate that the Betsiaka Group developed within a juvenile arc-related tectonic environment.

2.2.1. GEOLOGICAL DATA AND SURVEYS

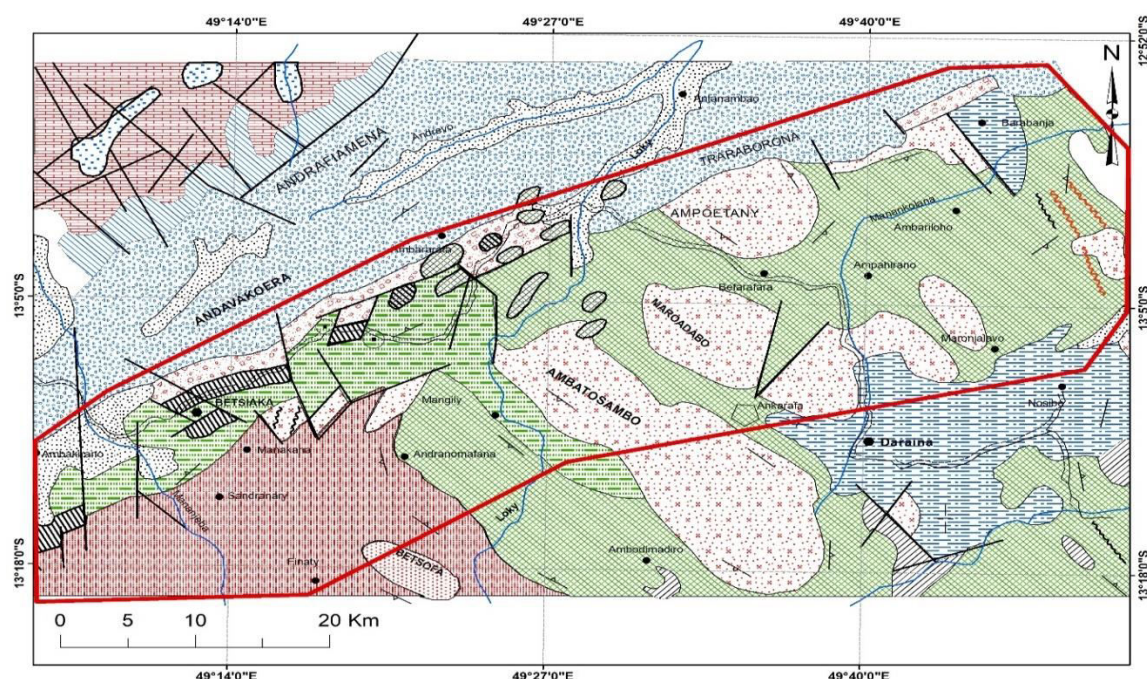
The primary data supporting this study were drawn from geological mapping undertaken by the Société Mine d'Or d'Andavakoera ^[15], along with the cartographic syntheses of ^[16] and the ^[17]. These foundational sources facilitated the identification and selection of key sites for detailed petrostructural characterization. The selected investigation areas include Betsiaka, Mantalimaro, Ankatoko, Ambilo, Korimalandy, Analamanga, Labaika and Ambatosolaitry. The selection of study sites was guided by the diversity of petrographic and structural features, as well as the presence of active artisanal gold mining operations. The majority of the selected sites are situated within zones of intense tectonic deformation. Field mapping and petrostructural analyses were conducted at 133 observation points distributed throughout the study area.

2.2.2. STRUCTURAL DATA

Structural data were collected from measurements performed at 133 field observation points, including outcrops, sub-outcropping rock exposures, and particularly the walls of artisanal gold mining shafts. This dataset provided the basis for a detailed structural analysis through the geometric processing of the orientation patterns of key structural features. These data formed the basis for interpreting the spatial distribution and structural organization of the geological features observed in the field. The resulting structural interpretation enabled the reconstruction of the tectonic history of the study area, allowing for the delineation of the successive stages of its structural evolution through time.

2.2.3. SURFACE AND SHAFT PROSPECTING

This approach allows for the direct observation of petrostructural variations in both surface outcrops and artisanal gold mining shafts within the Betsiaka area (Figure 1). It is applied to systematically collect detailed geological data on petrographic facies, structural heterogeneities, kinematic indicators and mineralogical characteristics at gold-bearing sites. A diverse suite of rock samples was collected from both the sedimentary cover and the underlying crystalline basement. Sampling was conducted at multiple sites located within or adjacent to artisanal gold mining shafts. The shales, sandstones, arkoses and conglomerates are attributed to the Andavakoera Sandstone Massif, whereas the quartz veins, barite mineralizations, amphibolites and various granitic lithologies are associated with the crystalline basement complex.



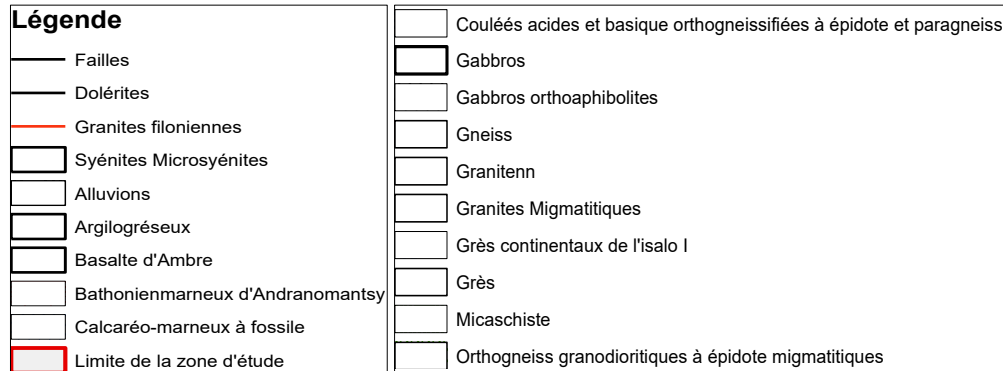


Figure 1: Location map of the study area superimposed on the geological background of Madagascar ^[16] digitized by Beny, 2025.

III. RESULTS

3.1 GOLD MINERAL ASSOCIATIONS IN THE BETSIKA GROUP

Gold mineralization within the Betsiaka Group occurs both as free particles and in association with a variety of accessory minerals. It formed in a mesothermal to epithermal geological setting conducive to the circulation of hydrothermal fluids along tectonic fractures. These auriferous fluids, of magmatic origin, are typically enriched in silica, sulfur and other precious metals. Gold precipitation is commonly attributed to geochemical interactions between these fluids and iron sulfides. Field observations at key gold extraction sites such as Mantalimaro, Ankatoko, Ambilo, Korimalandy, Analamanga, Labaika and Ambatosolaitry indicate that quartz and barite are the predominant gangue minerals associated with gold in the Betsiaka region. This interpretation is supported by the reddish coloration of the soils and the macroscopic characteristics of the host rocks. Galena and sphalerite are occasionally found in peripheral zones adjacent to gold deposits. The host lithologies typically comprise dense minerals such as amphiboles, orthopyroxenes, muscovite, biotite, garnet, tourmaline, magnetite, and ilmenite, alongside lighter mineral phases including calcite and potassium feldspar. Heavy metals and their associated minerals particularly iron, lead and magnetite commonly occur in association with gold mineralization. Moreover, the presence of ferruginous magnesium minerals, malachite, azurite and chalcopyrite constitutes important geochemical and mineralogical indicators for gold exploration within the Betsiaka Group.

3.2. PETROGRAPHIC CHARACTERIZATION

The petrographic facies associated with gold mineralization in the Betsiaka Group exhibit considerable variability. While the host rocks of the auriferous sites generally possess comparable mineralogical compositions, their metamorphic grades differ according to their specific outcrop locations. These lithologies can be categorized into three principal petrographic groups: igneous, sedimentary and metamorphic.

The igneous facies comprise a range of intrusive rocks, including hydrothermal quartzite, barite, amphibolite, pyroxenite, dolerite, syenite, pegmatite and granitoids. Pyroxenite and dolerite commonly occur as relict exposures manifesting as bedded units. The sedimentary facies are predominantly characterized by arkosic sandstones associated with the Andavakoera massif, in addition to marls, limestones and lateritic clay-rich formations, the latter often forming extensive surface cover over gold mining areas.

The metamorphic rocks including amphibole and garnet-bearing orthogneisses with or without biotite, migmatites, mylonites, schistose paragneisses and slates display a wide range of origins and metamorphic grades. Hydrothermal quartz and barite veins are commonly spatially associated with gold mineralization in the region (Fig. 2a). These veins often act as reliable indicators of gold deposits, as gold frequently occurs within quartzite-hosted structures (Fig. 2a). However, numerous quartz-barite veins exhibit minimal to no gold content, demonstrating that quartz alone is not a definitive indicator of auriferous potential (Fig. 2b).

Schist represents one of the predominant host lithologies for gold mineralization in the region. This metamorphic rock is characteristically fragile and friable, typically forming under conditions of elevated temperature and pressure (Fig. 2d). Its occurrence frequently marks zones of contact with the Earth's upper mantle. Dumortierite-bearing quartz develops within aluminum- and boron-enriched metamorphic environments, particularly in altered migmatites and quartzites (Fig. 2c). This mineral commonly originates from hydrothermal crystallization or metamorphic transformations affecting silica-rich protoliths. The coexistence and interaction of igneous, metamorphic and sedimentary rocks constitute fundamental factors contributing to the high gold mineralization potential observed in the Betsiaka region.

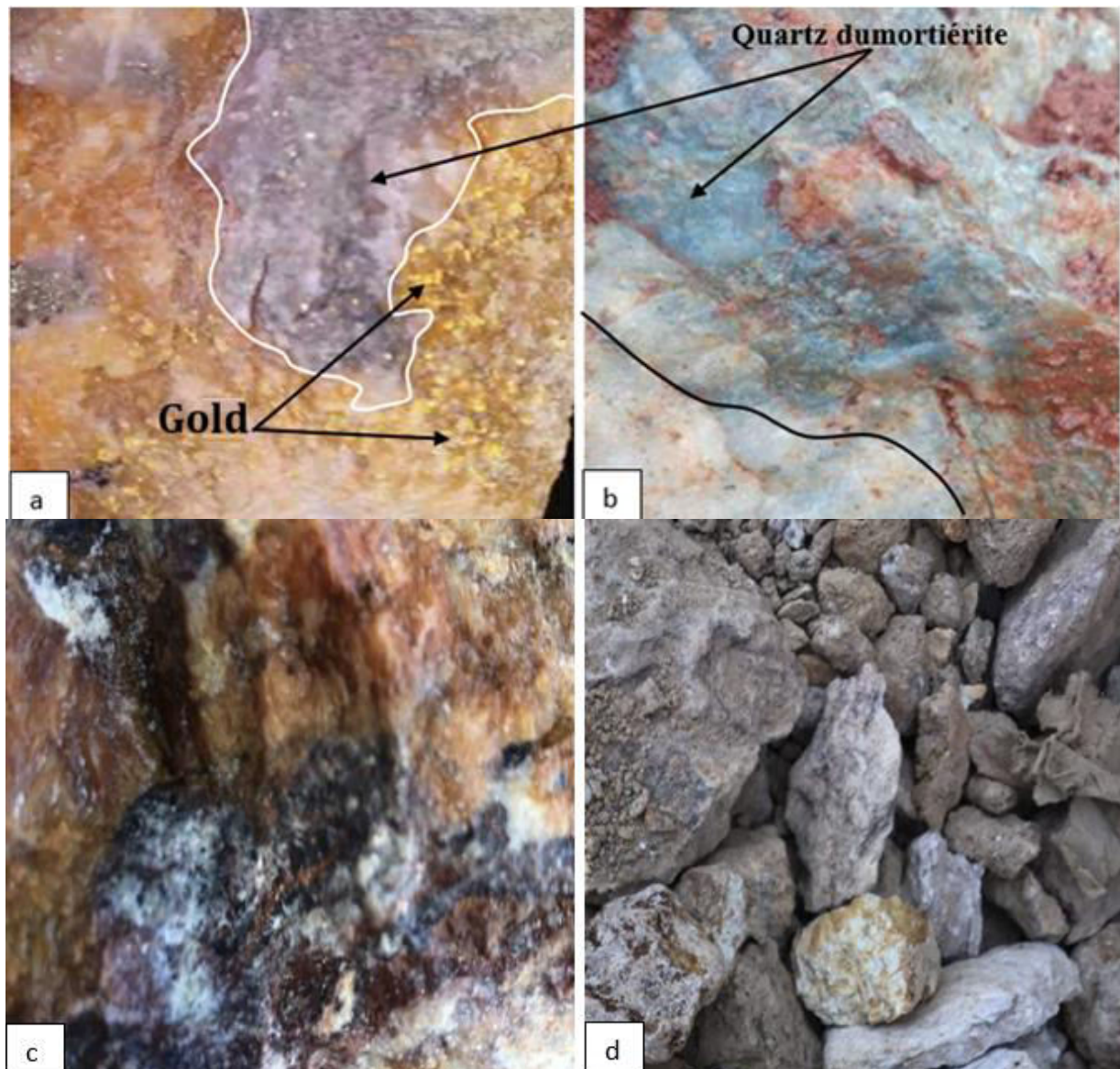


Figure 2: a) Auriferous hydrothermal quartzite; b) Dumortierite-bearing quartzite associated with gold mineralization; c) Migmatite; d) Schist serving as the host rock for gold deposits.

3.3. STRUCTURAL CHARACTERIZATION

The Betsiaka region is marked by intense deformation characterized by shearing, faulting, fracturing and folding (Fig. 3). Two distinct generations of veins have been documented within the auriferous mining galleries. The first generation comprises dark hydrothermal quartz veins formed during an early tectonic phase. These veins vary in thickness from 1 cm to 1.5 m and typically occur concordant with the foliation planes of the host gneissic rocks, frequently hosting gold mineralization. Subsequently, late-stage geodic quartz veinlets crosscut the sandstone facies (Fig. 3b). The second generation consists of lighter-colored, barren barite veins, which commonly infill voids created by earlier quartz veins. Both quartz and barite vein generations transect the principal structural features of the basement. The sequence is intermittently intruded by pegmatite dykes, although these occurrences are relatively rare. Within the Betsiaka Group, schists and quartzites display ductile deformation features intimately linked to gold mineralization processes. Arkosic sandstones are characterized by oblique stratification and a grain size distribution ranging from medium to coarse, interbedded with lenticular layers of black argillaceous silt enriched in pyrite and organic matter (Fig. 3c). These rocks bear the imprint of significant tectono-metamorphic events that have been instrumental in the orogenic evolution of the region and in exerting structural control over gold mineralization. The prevalence of hydrothermal veins indicates a fault-dominated structural setting (Fig. 3a), wherein these faults served as primary conduits for the circulation of metal-bearing hydrothermal fluids. Hydrothermal alteration processes played a critical role in the mobilization and precipitation of gold and associated elements. The Korimalandy sector, situated west of Betsiaka village, encompasses both Permian sedimentary formations and the underlying crystalline basement. The contact between the basement and the Permian sandstones is defined by a fault zone. Conversely, the Ambaliha area is predominantly underlain by crystalline basement rocks. These structural discontinuities have facilitated the formation of a series of horst and graben structures, with their expression diminishing progressively toward the northeast.

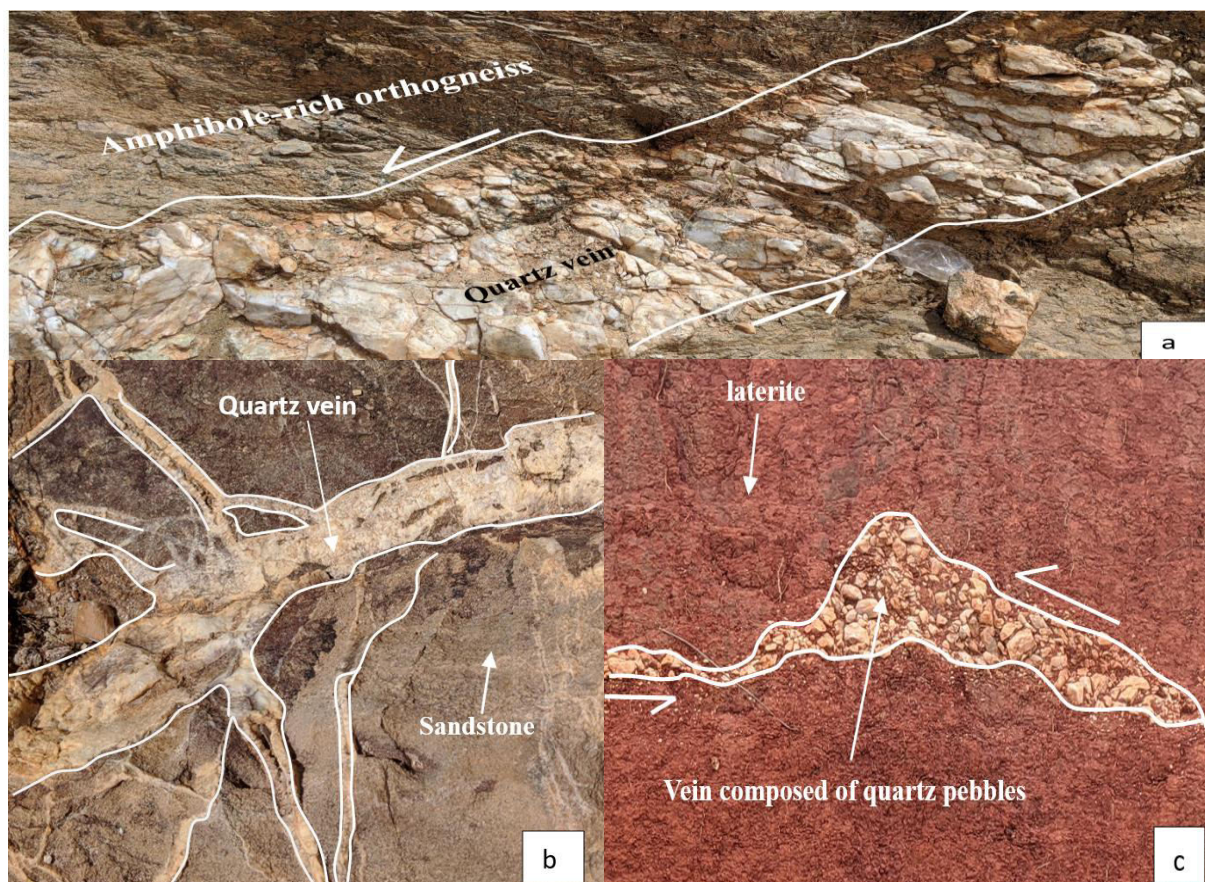


Figure 3: Tectonic Phases a) Primary hydrothermal quartz vein; b) and c) Late-stage quartz veinlets.

3.4. GENESIS OF GOLD MINERALIZATION IN THE BETSIKA GROUP

Gold mineralization within the Betsiaka Group is controlled by two primary processes: diagenetic and vein-related mechanisms. Accordingly, gold deposits occur both within alluvial and eluvial sediments and within hydrothermal vein networks. The area has experienced intense polyphase shear stress, which has played a pivotal role in the development of these vein systems. These shear structures act as structural controls, facilitating the migration and entrapment of hydrothermal fluids responsible for gold paragenesis. The enrichment of gold mineralization within the lateritic and eluvial soils of paleoplacer and alluvial deposits primarily composed of arkosic sandstones and conglomerates is attributed to the weathering and erosion of primary gold sources concentrated in the post-orogenic Permian-Triassic Andavakoera sandstone massif. Consequently, the genesis of gold mineralization in the Betsiaka Group, together with associated minerals such as galena, sphalerite, and pyrite, occurred within a hydrothermal environment related to the Bemarivo collisional orogeny. The parental magma was emplaced during the early stages of the tectonic evolution. Most gold-bearing chimneys are relatively shallow, except for the Tambo deposit southeast of Ambilo, which extends to an approximate depth of 41 meters. Gold is predominantly hosted within veinlets associated with quartz and barite veins, particularly along the principal Bereziy vein. At Ambilo, mineralization is chiefly localized along the hanging wall of the major vein. Gold occurs mainly within the quartz matrix and is rarely found within the surrounding host rocks, except in amphibole-bearing gneisses. Silicification features, exemplified by the rocky spur at Ambohidolo, occur at intersections where veins traverse diverse lithologies. The occurrence of galena within some veins, alongside the absence of volcanic rocks, does not adversely affect the gold potential of the region. It is plausible that gold mineralization was coeval with quartz crystallization, a proposition that warrants further confirmation through detailed analysis of mineral inclusions within the quartz.

3.5. MINERALIZATIONS RELATED TO TECTONIC STAGES

The Betsiaka Group underwent two principal metallogenic phases extending from the Neoproterozoic to the Permian-Triassic periods. The initial phase (D1), associated with the Bemarivo orogeny, was dominated by strike-slip tectonics and resulted in the formation of primary gold concentrations. The mineralization related to D1 is discordant and subsequently overprinted by brittle deformation during the late-orogenic phases D2 and D3. The second metallogenic phase encompasses a plutonic episode (D2) followed by a metamorphic overprint (D3). This phase was marked by the generation of hydrothermal fluids that facilitated the mobilization and redistribution of pre-existing mineral assemblages associated with earlier magmatic accretion events. These fluids were responsible for the transport and deposition of gold, which became concentrated in structural traps such as fault zones and lithological contacts. Quartz stockworks developed during this phase may also host polymetallic mineralization, including zinc, copper and silver. The auriferous mineralization is predominantly hosted within tectonic fractures associated with a transpressional tectonic regime, which promoted the circulation of mineralizing hydrothermal fluids. These structures generally align with the regional NW–SE oriented foliation. The main gold-bearing veins correspond to cross-cutting fractures, which are infilled with euhedral quartz, barite, and native gold. Gold mineralization occurs within host rocks that have experienced ductile deformation, particularly manifested through boudinage and folding structures. The principal lithologies hosting the mineralization are mica schists and banded gneisses. Tectonic processes facilitated the development of quartz veins within zones of extensional fracturing. The foliation exhibits orientations ranging from N05° to N170°, with dip angles between 55° and 60° toward the west and southwest. Brittle deformation structures such as joints, fissures and quartz veins exert a significant control on the physical and mineralogical characteristics of the host rocks. The geological formations generally display a submeridional strike, with orientations ranging from NNW–SSE to NNE–SSW.

IV. DISCUSSION

Globally, vein-type gold mineralizations predominantly formed during the Late Archean, between 3.0 and 2.5 Ga [18], and during the Proterozoic. In Madagascar, gold deposits are mainly orogenic in nature. The Betsiaka Group, located within the northern domain of the Neoproterozoic Bemarivo Belt dated between 1.6 and 0.57 Ga [10], is characterized by a predominance of vein-hosted deposits. The auriferous fluids are genetically linked to the Pan-African orogeny, during which subduction and collisional events played a critical role in the genesis of these deposits. Subduction processes generated auriferous systems analogous to Cordilleran-type mineralization. Gold mineralizations associated with greenstone facies and secondary placer deposits have been dated to the Permian–Triassic period. The subsequent tectonic collision event triggered an episode of intense and sustained plutonic magmatism, which induced multiple phases of fracturing and faulting. These structural disruptions facilitated the mobilization and ascent of magmatic fluids

originating from intrusive plutons ^[19], alongside metamorphic fluids produced through dehydration and decarbonation reactions ^[19], ^[20]. These fluid fluxes, particularly within the Andavakoera Massif, contributed to the development of significant vein-type gold mineralization zones in the Betsiaka region. The Andavakoera sandstone massif underwent significant tectonometamorphic events associated with subduction, continental collision, and high-grade metamorphism. The geochemical and structural evidence indicates that the interaction between mineralizing fluids and the paleo-oceanic sedimentary sequences within the massif points to a metamorphic origin of these fluids, primarily through dehydration reactions ^[21]. These processes triggered extensive fluid circulation, which in turn led to the formation of multiple generations of mineralized vein systems ^[21], ^[22]. Within the Betsiaka Group, gold mineralization is predominantly localized along the contact zones between the crystalline basement and overlying sedimentary sequences, particularly in the areas of Ambilo, Ranomafana, Tambo, Raphia, Beriziky, Andrafialava, and Mantalimaro. The rocks situated within the shear zones display advanced mylonitization, which significantly enhances the permeability and thus facilitates both the migration and entrapment of mineralizing fluids ^[23]. The transition from compressional to extensional tectonic regimes was marked by the development of a network of hydrothermal quartz veins, which defined a shear zone that enhanced the migration of late metamorphic fluids ^[23], ^[24] linked to the extensional event. The petrogenesis of gold deposits within the Betsiaka Group is intricately associated with magmatic activity, metamorphic transformations and subsequent mineralization processes ^[25], ^[26], ^[27]. Epithermal mineralizations are spatially correlated with Phanerozoic volcanic rocks and sedimentary cover sequences overlying the basement, occasionally linked to hydrothermal spring activity. Additionally, alluvial gold deposits occur within remnants of quartz veins hosted in Permian sandstone blocks as well as in ancient fluvial terraces. Moreover, the presence of extensive auriferous barite layers capping silicified sandstones supports a volcanogenic and epithermal genesis for these mineralizations.

V. CONCLUSION

The petrostructural analysis of the Betsiaka Group underscores the intimate relationship between tectonic dynamics, hydrothermal alteration, and the formation of gold mineralization. Gold predominantly occurs as native metal or enclosed within sulfide minerals, hosted within quartz and barite veins, and is associated with a range of lithologies including igneous, sedimentary, and metamorphic rocks subjected to complex tectonic deformation. The spatial distribution of mineralization is strongly controlled by NE–SW trending shear zones, which served as primary pathways for the circulation of mineralizing fluids. Two principal metallogenic phases associated with the Bemarivo orogeny controlled the gold enrichment: an initial transcurrent tectonic phase (D1) followed by a later plutonic phase (D2). These results highlight the critical importance of an integrated methodological framework—encompassing petrographic, structural, and geochemical analyses—to effectively delineate zones with elevated gold potential. An enhanced comprehension of this mineralized system constitutes a critical tool for guiding future exploration efforts and promoting the sustainable development of gold resources in northern Madagascar.

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