

Evidence of Volcanic Collapse and Mass-Wasting Events in the Paleoproterozoic Toumodi Region (Côte d'Ivoire)

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How to cite this paper: Yao, A.K., Tegan, E.S.N., Koffi, B.G. and Kouamelan, A.N. (2025) Evidence of Volcanic Collapse and Mass-Wasting Events in the Paleoproterozoic Toumodi Region (Côte d'Ivoire). *Open Journal of Geology*, 15, 627-644.
<https://doi.org/10.4236/ojg.2025.1510031>

Received: July 21, 2025

Accepted: October 8, 2025

Published: October 11, 2025

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Abstract

The Toumodi-Fetékro region, located in the heart of the Ivorian Paleoproterozoic domain, has been the subject of numerous petrographic, structural, and geochemical studies aimed at understanding its geological evolution. These studies, mainly conducted in the central part of the Fetékro greenstone belt, around the Toumodi region, have focused on localities such as Lomo Nord, Akakro N'zipri, Anikro-Kadjokro, Angoda, Gbonti, Loukou-Yaokro, Konan-Kokorékro, and Zaakro. The main goal of this study is to broaden the understanding of the mafic volcanoclastic deposits found in the central part of the Toumodi-Fetékro greenstone belt, with a specific focus on their depositional context while providing detailed volcanological insights. To achieve this, we conducted comprehensive fieldwork, including geological mapping, petrographic analysis, and sedimentological studies, complemented by thin-section analyses in the laboratory. The results obtained were carefully analyzed and interpreted from a volcanological perspective. Petrographic observations revealed the presence of various volcanoclastic deposits, including breccias (both monolithological and polyolithological), lapilli tuffs, and cinerites. Detailed sedimentological analysis uncovered several key structures, including cross-laminations at tight angles, large amplitude parallel laminations, and depositional features based on the Bouma and Lowe classification systems. These sedimentary structures allowed us to construct three stratigraphic logs at the Lomo Nord, Akakro N'zipri, and Anikro localities. Volcanological interpretations of these deposits suggest that they are the result of pyroclastic fallout, debris avalanche deposits, hyperconcentrated debris flow deposits, and riverine deposits. These are all secondary deposits formed in a hydrovolcanic environment, reflecting the complex interactions between volcanic activity and water. The deposits are interpreted as originating from an avalanche phase

during a sectoral collapse of an unstable volcanic edifice, likely triggered by significant hydromagmatic events. This study highlights the role of volcanic instability and hydromagmatic processes in the formation of mafic volcaniclastic deposits in the central Toumodi-Fetékro region, offering new insights into the volcanic history and geological processes of the Birimian greenstone belt.

Keywords

Toumodi, Volcanic Instability, Debris Avalanches

1. Introduction

Volcanic regions worldwide are frequently affected by gravitational instabilities, which can trigger rapid, large-scale movements of rock and debris known as debris avalanches [1]. These events, remarkable for their speed, scale, and unpredictability, are among the most catastrophic processes shaping volcanic landscapes. Despite their prevalence, debris avalanche deposits are often misidentified as moraines or pyroclastic flow deposits [2], necessitating careful field and petrological analysis for accurate recognition. In the Toumodi region of Ivory Coast, situated within the West African craton, the Birimian stratigraphy comprises a complex sequence of volcanic, volcanosedimentary, and sedimentary formations [3]-[6]. Extensive metamorphism under greenstone facies conditions and subsequent intrusive events, dated between 2.2 and 2.0 Ga [7]-[9], have significantly altered the original volcanic structures. These processes obscure the primary signatures of gravitational collapse, complicating the reconstruction of the region's volcanic evolution. Accurate identification and characterization of debris avalanche deposits are therefore critical for understanding volcanic collapse dynamics and the evolution of volcanic terrains. These deposits, typically highly fragmented and exhibiting distinctive morphological features, provide valuable insights into the processes leading to edifice failure. This study investigates the origin, transport mechanisms, and depositional dynamics of debris avalanche deposits in the Toumodi region, with emphasis on the role of volcanic instability. Our approach integrates detailed field observations, structural mapping, and petrological analyses to examine facies, clast morphology, fragmentation patterns, and the presence of jigsaw fractures. These data allow reconstruction of collapse dynamics, including disintegration during transport, interactions between magma and external fluids, and the broader processes of gravitational instability. The results offer new perspectives on the Birimian volcanic history and contribute to a refined understanding of debris avalanche formation and emplacement in Precambrian volcanic terrains. Beyond reconstructing past events, these insights have practical implications for hazard assessment and risk mitigation in regions prone to large-scale volcanic collapses.

2. Geological Setting

The Ivory Coast is part of the West African Craton, specifically located on the Man Ridge, which constitutes the southern segment of this cratonic block [10]. This region holds significant geological value, characterized by two major domains, separated by the transcurrent Sassandra fault: the Baoulé-Mossi domain and the Kénéma-Man domain. These domains are essential for understanding the regional tectonics and geological history of the area. The study area is located within the Baoulé-Mossi domain, with a specific focus on the Toumodi region, situated in the central part of Ivory Coast. This region is renowned for its Paleoproterozoic geological formations, commonly referred to as the Birimian formations [10] [11]. These formations are key to reconstructing the tectonic and volcanic history of the Toumodi region, providing crucial insights into the magmatic processes and volcanic activity that have shaped the area over billions of years. The Baoulé-Mossi domain, including the Toumodi region, is particularly important for its volcanic activity during the Paleoproterozoic era. The volcanic rocks in this domain are primarily of intermediate to felsic composition, reflecting a wide range of magmatic processes that occurred over an extended period [12]-[14]. These volcanic rocks, including those in the Toumodi region, help improve our understanding of the geodynamic evolution of the West African Craton, shaped by a combination of tectonic, magmatic, and volcanic events during this period. In contrast, the Kénéma-Man domain, located in the western part of the Man Ridge, represents another significant geological entity in the region (Figure 1). This domain is primarily known for its Archean volcanic activity, characterized by basic to ultrabasic compositions [15]. However, the Toumodi region is mainly focused on Paleoproterozoic volcanic activity, particularly within the Baoulé-Mossi domain, which is part of the Eburnean orogenic belt. This tectonic zone formed during the Eburnean orogeny, approximately between 2.1 and 2.0 billion years ago [10]. As part of the Baoulé-Mossi domain, the Toumodi region underwent significant magmatic and structural transformations during the Eburnean orogeny, leading to the deformation of earlier rock units and the intrusion of granitic and basaltic magmas. The volcanic formations in the Toumodi region are important not only for their tectonic implications but also for their potential as natural resources. The region's volcanic rocks are often associated with mineralization processes, such as gold and other ore deposits, which are of economic interest in Ivory Coast. Studying these formations, especially in the context of volcanic hazards like debris avalanches, is critical for understanding the geological dynamics of the Toumodi region (Figure 2). Moreover, these formations are vital for assessing mining potential, as they are frequently linked to ore-bearing systems in the region.

3. Methodology

The methodology for this study is multidisciplinary, relying exclusively on field observations to ensure a comprehensive understanding of the debris avalanche

deposits in the Birimian region. This approach integrates geological mapping, structural analysis, and sedimentological techniques to accurately describe and

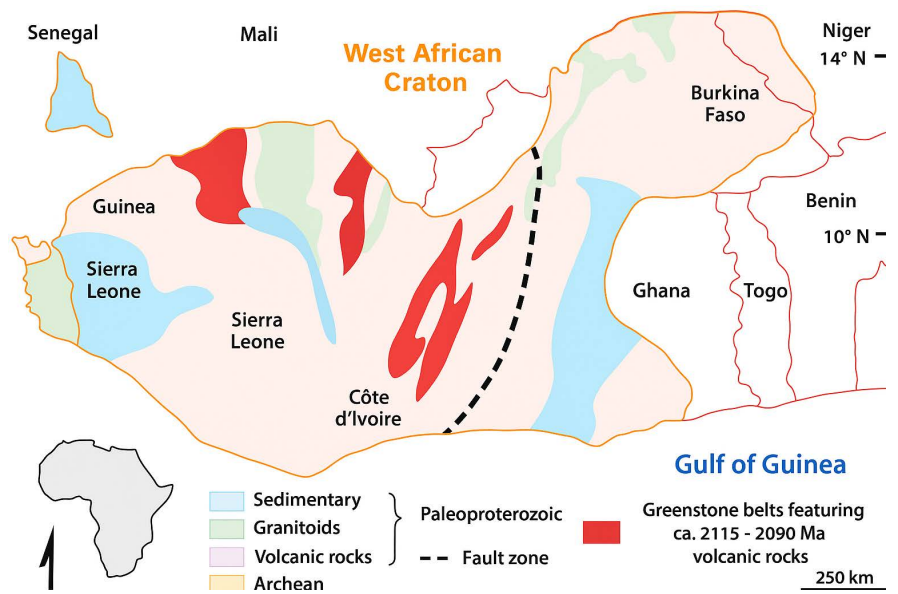
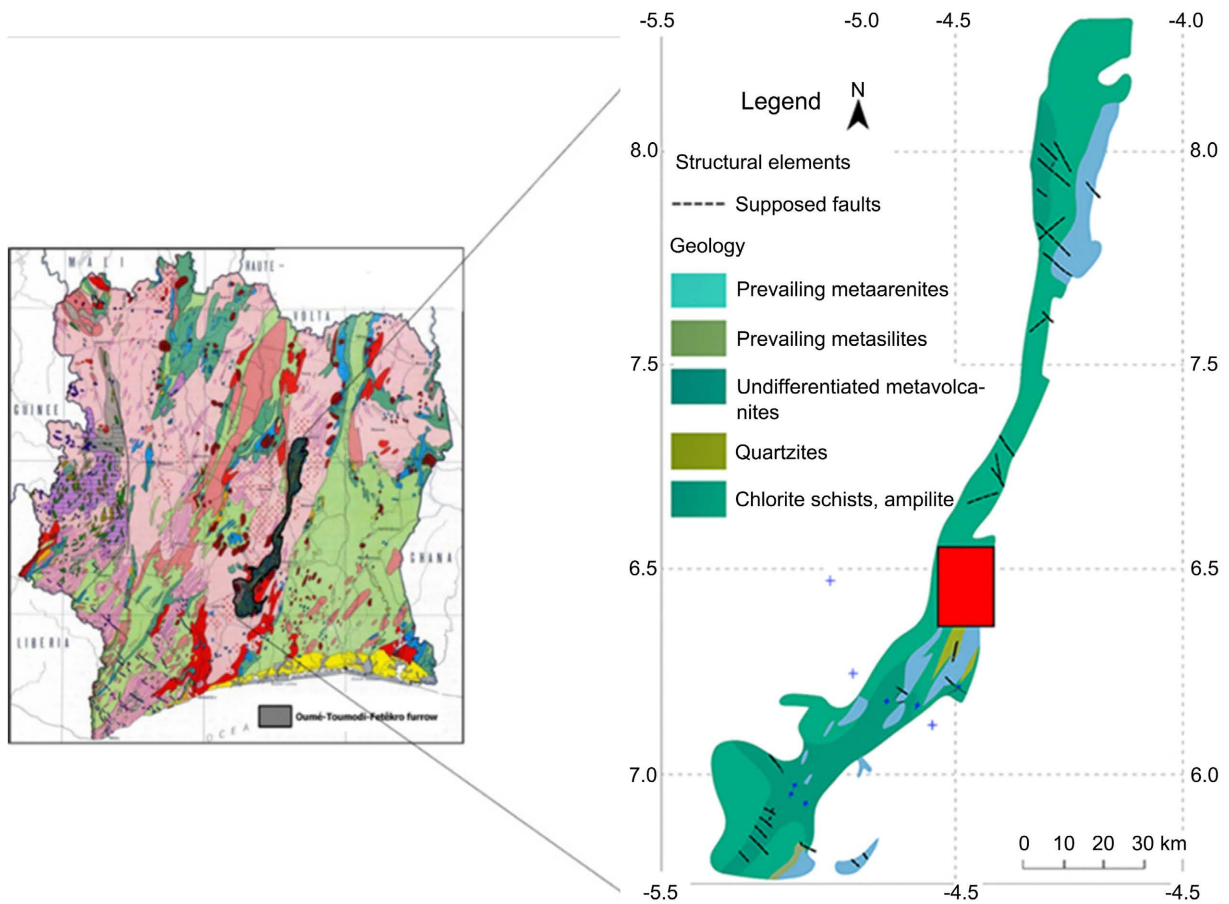


Figure 1. Geological map of Man-Leo Ridge and Kedougou-Kenieba (KKI) and Kayes (KI) inliers [16].



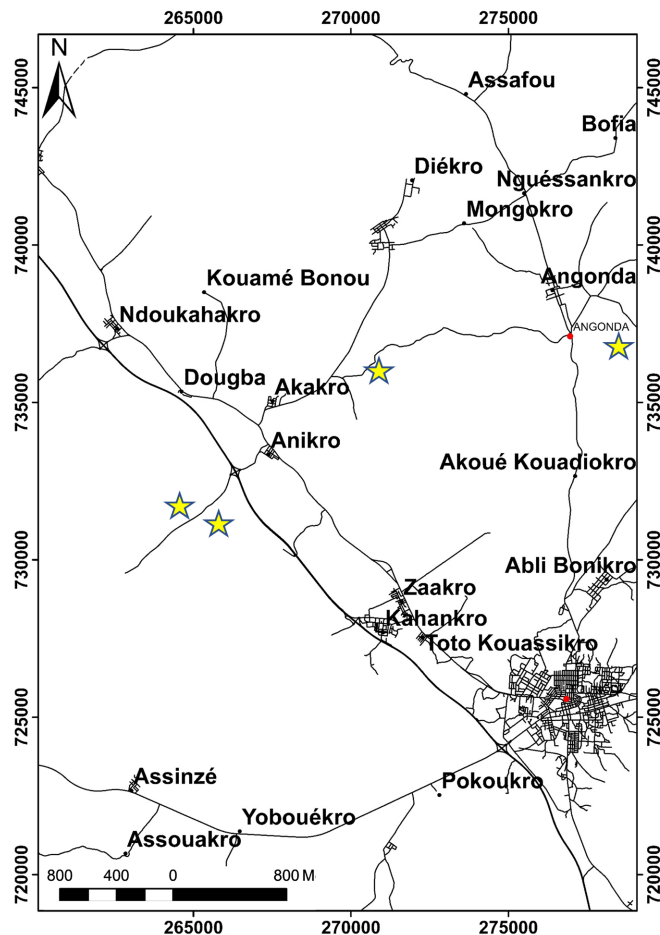


Figure 2. Localisation in Ivory Coast and geological map of the Toumodi-Fetekro-Oume greenstone belt (extract from geological map of Ivory Coast to 1/4,000,000) [17].

interpret the characteristics of these deposits. To begin with, we adopt the terminology recommended by the International Union of Geological Sciences (IUGS) for clastic formations [18], which provides a standardized framework for classifying and describing clastic materials. This ensures consistency and comparability with existing literature on clastic deposits, facilitating a more coherent understanding of the deposits' nature and origins. All field observations, particularly those related to the appearance and physical properties of the deposits, will be analyzed through the concept of facies. Facies represent distinct sedimentary environments, and by focusing on their intrinsic characteristics, we can gain insights into the depositional processes and environments that shaped these deposits. This study will place particular emphasis on the composition, grain size, and structural features of the deposits. These properties are crucial for understanding the transport and emplacement mechanisms of debris avalanche material. Grain size distribution, for example, provides valuable information on the energy of the flow, while the composition helps to infer the source of the material and the extent of fragmentation during transport. Structural features such as bedding, grading, and clast alignment will also be examined to interpret the dynamics of the flow and

the conditions under which the deposits were emplaced. Previous studies have significantly expanded the range of facies identified in clastic deposits, leading to a more detailed understanding of their formation processes. Building on these contributions, our approach will utilize the most widely recognized and precise criteria for classifying these facies, particularly regarding composition, grain size, and structure. This enables a more refined analysis and comparison with existing classifications, providing a solid foundation for interpreting the specific characteristics of the debris avalanche deposits in the study area. Overall, the methodology emphasizes a rigorous, field-based approach grounded in well-established sedimentological principles. By focusing on facies analysis and incorporating a multidisciplinary perspective, this study aims to contribute to the broader understanding of debris avalanche dynamics, particularly in the context of volcanic regions with complex geological histories.

4. Results

Debris avalanche deposits can be vast, with numerous facies and complex structures. The size and shape of these deposits vary greatly from one example to another. Below, we present some characteristics of the units found in the Toumodi region.

4.1. Description of Toumodi Deposits

4.1.1. Anikro Deposits

Unit 1 is approximately 100 m thick and extends over an area of about 700 m, forming a prominent volcanic exposure located ~3 km southwest of Anikro village, near the summit of a hill. The unit consists of highly indurated deposits, recognizable by their light green coloration and the predominance of a massive, matrix-supported facies. The embedded blocks are sub-angular to angular, ranging from a few centimeters to several meters, and are dominantly tuffaceous with a scoriaceous texture, indicative of pyroclastic processes. Many blocks consist of pyroclastic fallout fragments enriched in amphibole and/or pyroxene crystals, reflecting a high-temperature magmatic environment (**Figure 3(A)**). Petrological observations include rare microdiorite xenoliths and secondary zeolite minerals in the matrix (**Figure 3(B)**), documenting the incorporation of country rock fragments during eruption. Brittle fragmentation features, including jigsaw cracks (**Figure 3(C)**) and comet-tail stretching structures (**Figure 3(D)**) oriented N55°, are widespread. Jigsaw fractures indicate rapid cooling and brittle disintegration during or shortly after deposition, whereas comet-tail structures record directed stresses associated with emplacement dynamics. Newly formed clasts are poorly dispersed, and the relatively large interstitial voids suggest a viscous matrix that solidified quickly. The matrix is predominantly tuffaceous, composed of fine volcanic ash mixed with crystalline fragments, including subangular amphibole and pyroxene grains. At the base, rare tuffaceous mega-blocks up to 1 m in size likely result from gravitational sorting and fragmentation during emplacement. The

overall chaotic fabric and absence of grading indicate rapid deposition under high-energy conditions, typical of pyroclastic flows and surges. At the foot of the hill, minor sedimentary traction structures, including parallel lamination and cross-stratification, suggest limited reworking by secondary pyroclastic surges or debris flows while the deposits remained unconsolidated.



Figure 3. Different structures in Toumodi's volcanoclastic rocks. (A) amphibole scoria, (B) xenoliths fragments, (C) Jigsaw structure, (D) comet tail structure in volcanoclastic rocks.

Unit 2 develops within a basin emplaced in intermediate to acidic volcanic formations. It exhibits a thickness ranging from 100 to 500 m and extends over nearly 2 km. This unit is characterized by strong vertical and lateral variability, reflecting the influence of multiple depositional processes within a dynamic volcanic basin setting. The coarse fraction is dominated by poorly sorted pebbles (4 - 30 cm), generally rounded to sub-rounded. The degree of rounding increases and pebble size slightly decreases toward the southwest (**Figure 4(A)**), suggesting moderate transport or local reworking by hydraulic currents or gravity-driven flows, including debris avalanches. The irregular grain size distribution and poor sorting reflect episodic, high-energy deposits in spatially restricted zones. The composition of the pebbles is highly heterogeneous, including fragments of granitoids, quartz, and various sedimentary rocks, often preserving relict stratification or foliation. Mafic volcanoclastic material is rare, whereas rhyolitic fragments dominate, indicating multiple sedimentary sources derived both from proximal volcanic edifices and from older crustal rocks within the basin. The contact between the coarse deposits and the underlying fine sediments is non-erosive, pointing to continuous sedimentation without major interruptions. The upper portion of Unit 2 is composed of tabular sandy sediments showing well-defined parallel laminations (**Fig-**

ure 4(B)), typical of uniform sedimentation under low-energy conditions. Locally, cross-laminations (Figure 4(C)) record transient changes in current direction or pulsating sediment supply.



Figure 4. Sedimentary structures recording gravity-driven chaotic deposits within a polygenic conglomerate from the Toumodi region (Côte d'Ivoire): (A): Chaotic deposit characterized by large vesiculated blocks; (B): Poorly sorted mass-flow deposit displaying parallel bedding; (C): Reworked or decantation horizon showing cross-stratification.

4.1.2. Akakro N'Zipri Unit

The breccia deposit observed along the road leading to Konan-Kokorekro, approximately 1500 meters after the village of Akakro N'Zipri, belongs to the group of lapilli tuffs. This deposit contains very large clasts embedded within a matrix that ranges from tuffaceous to cineritic in composition. Notably, the matrix of this deposit is not zeolitized, which differentiates it from the deposit studied in the Anikro-Ferme unit, where zeolitization is observed. The absence of zeolite alteration suggests a difference in post-depositional processes between the two units. The large, multi-centimeter clasts, or mega-clasts, are predominantly concentrated near the top of each stratigraphic level that forms the outcrop. These clasts are of tuffaceous composition and display slight parallel stratifications at their base, with orientations primarily in the N60° direction. The presence of these parallel stratifications may indicate deposition in a pyroclastic surge or flow environment, where fine volcanic material settled in layered patterns. The mega-clasts themselves are highly fractured, with the fractures becoming more intense towards the base of the deposit, where breccia is more pronounced (Figure 5(A)). This suggests that the breccia formation was likely driven by intense fragmentation and rapid cooling or deposition. Ubiquitous jigsaw fracture structures (Figure 5(B)).

are present throughout the deposit, indicative of brittle fragmentation during or after emplacement. These fractures are characteristic of volcanic rocks that have undergone rapid cooling or stress-induced fragmentation, typical of pyroclastic flows or explosive eruptions. While there is some separation of the fractures between the newly formed clasts, there is no matrix injection between these fractured clasts, which further supports the idea of rapid deposition and minimal post-depositional alteration. The clast banks within this breccia deposit are approximately 50 to 70 centimeters in thickness and exhibit distinct stratification, with an inverse grading pattern observed throughout the deposit. Inverse grading refers to the phenomenon where the coarser clasts are found at the top of each layer, with finer material concentrated towards the base. As one moves towards the top of the deposit, the inverse grading becomes more pronounced, suggesting a progressive increase in the settling or sorting of the clasts during deposition (**Figure 5(C)**). This pattern may reflect fluctuations in the energy of the depositional environment, possibly driven by variations in the intensity or flow characteristics of the pyroclastic surge or flow that deposited the material.

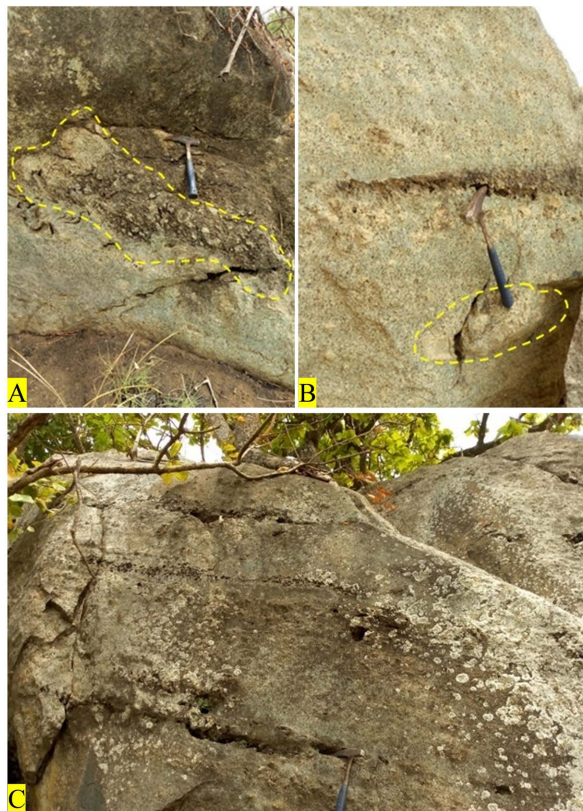


Figure 5. Debris Avalanche Deposits (DADs) of Akakro N'zikpri. (A): Elongated lithic block poorly integrated within a volcaniclastic matrix, illustrating the chaotic fabric of the deposit. (B): Large angular block embedded in a coarse-grained matrix, showing jigsaw-fit structures that record the abrupt detachment and incorporation of fragments during avalanche emplacement. (C): General view of a massive outcrop characterized by discontinuous alignments of blocks and fragments, together with a certain rhythmicity of deposition, reflecting successive phases of gravitational accumulation.

4.1.3. Angoda Unit

The breccified tuffs of Angoda are located in the hills approximately 2.5 km north-east of the Angoda locality. These deposits have a thickness that rarely exceeds 3 meters, covering an area of about 20 meters. The deposit exhibits a bimodal granulometry, displaying distinct internal organization that reflects variations in depositional processes. Notably, there is an absence of mega-blocks and jigsaw crack structures, which are commonly observed in more fragmented breccias, indicating a different mode of deposition. Instead, the deposit is dominated by mixed facies, suggesting a combination of pyroclastic and other volcanic processes during its formation. The larger clasts, with particle sizes ranging from 5 to 30 mm (**Figure 6(A)**), are generally disorganized and poorly graded. This lack of sorting suggests a high-energy depositional environment, possibly due to the dynamics of pyroclastic flows or surges, where clasts are deposited rapidly with little separation by size. The clasts themselves, which make up about 15% of the deposit, are characterized by a Belgian color (a reddish-brown hue), and most of them are sub-angular in shape, indicating that they have undergone limited transportation before deposition. These clasts are primarily tuffaceous in composition, with rounded porphyry fragments embedded in a cineritic matrix. The rounded nature of some clasts suggests that they may have been transported over short distances, while the porphyry content indicates that these fragments could have originated from more felsic volcanic sources. As you move closer to the top of the deposit, there is a noticeable concentration of coarser elements, indicating a possible shift in the energy conditions during deposition, with higher-energy processes contributing to the accumulation of larger clasts near the top. The smaller fraction, with clasts measuring less than 5 mm (**Figure 6(B)**), exhibits well-developed bedding, with distinct lamination patterns. The beds within this finer fraction have a maximum thickness of about 5 cm and show reverse grading, with perfectly rounded clasts at the base of each bed. Reverse grading is typically a feature of sedimentary processes where finer material is deposited on top of coarser material, often a result of settling in a dynamic depositional environment, such as a pyroclastic surge or fallout from a turbulent volcanic plume. These two fractions—coarse clasts and fine particles—are interbedded with layers of very fine-grained material, which imparts a silty texture to the deposit. The presence of these fine-grained layers suggests a transition in the depositional energy, from higher energy conditions favoring the deposition of coarser material to lower energy conditions, where finer sediment could settle more slowly.

4.2. Fragmentation and Paleoenvironmental Interpretation of the Toumodi Volcanic Deposits

Anikro Unit 1 (~100 m thick) forms a prominent exposure of highly indurated, light green, matrix-supported tuffaceous deposits. It contains sub-angular to angular blocks, amphibole and pyroxene crystals, and brittle fragmentation features such as jigsaw cracks and comet-tail structures, reflecting rapid emplacement,

high-energy pyroclastic flows, partial fluidization, and limited post-depositional reworking. Unit 2 (100 - 500 m thick) develops within an intermediate to acidic volcanic basin and exhibits pronounced vertical and lateral variability. It is dominated by poorly sorted pebbles (4 - 30 cm), mainly rhyolitic, with increasing roundness and decreasing size southwestward. These coarse deposits are overlain by sand-sized tabular sediments with parallel and cross-laminations. Thin-section analyses reveal volcanic breccias, lapilli tuffs, and fine vitric tuffs, reflecting a transition from high-energy coarse deposition to low-energy fine sediment accumulation influenced by both gravity-driven and water-mediated processes.



Figure 6. Laminated structures and internal stratification of volcanosedimentary deposits of Angoda. (A): Outcrop showing subhorizontal bedding with alternating coarse- and fine-grained layers, highlighting rhythmic deposition related to successive phases of settling and volcanoclastic reworking. (B): Well-developed stratification characterized by millimetric to centimetric-scale laminae and color variations (brownish-yellow to grey-green), reflecting pulsatory sedimentation within a gravity-driven volcanoclastic environment.

Unit of Akakro N'Zipri consists of lapilli tuff breccias with mega-clasts embedded in a tuffaceous to cineritic matrix lacking zeolitization. Clasts display parallel stratification ($N60^\circ$), intense fracturing, ubiquitous jigsaw structures, and inverse grading within 50 - 70 cm thick clast banks, recording rapid deposition from pyroclastic surges or flows under fluctuating energy conditions.

Unit of Angoda comprises thin (~3 m) breccified tuffs with a bimodal grain size distribution (coarse 5 - 30 mm, fine <5 mm). Coarse sub-angular clasts contain rounded porphyry fragments, whereas fine fractions exhibit well-developed lamination, reverse grading, and interbedded silty layers, reflecting moderately high-energy pyroclastic deposition with transitions to lower-energy settling.

Collectively, these units illustrate the interplay of explosive volcanism, pyroclastic fragmentation, gravity-driven transport, and sedimentary processes, capturing the progressive evolution from high-energy emplacement to calmer volcanic-basin sedimentation within an active Paleoproterozoic landscape (**Figure 7**).

The studied deposits are interpreted as resulting from the partial or total collapse of a Paleoproterozoic volcanic edifice. The presence of angular to sub-angular blocks, mega-clasts, and tuffaceous fragments within variable matrices indicates rapid gravity-driven transport, characteristics of debris avalanches and mas-

sive pyroclastic flows. Jigsaw fractures, intense clast breakage, and preferred fragment orientations reflect dynamic fragmentation and mechanical instability of the edifice during collapse. Bimodal grain-size deposits, with laminated fine layers interbedded with coarser sediments, record variations in flow energy, suggesting hyperconcentrated flows and pyroclastic surges modulated by topography and flow velocity. Limited post-depositional reworking further supports rapid emplacement under catastrophic gravity-driven processes. Together, these lithological and structural features document a volcanic landscape shaped by edifice instability, gravitational collapse, and rapid redistribution of pyroclastic and volcanic materials into the surrounding basin (Figure 8).

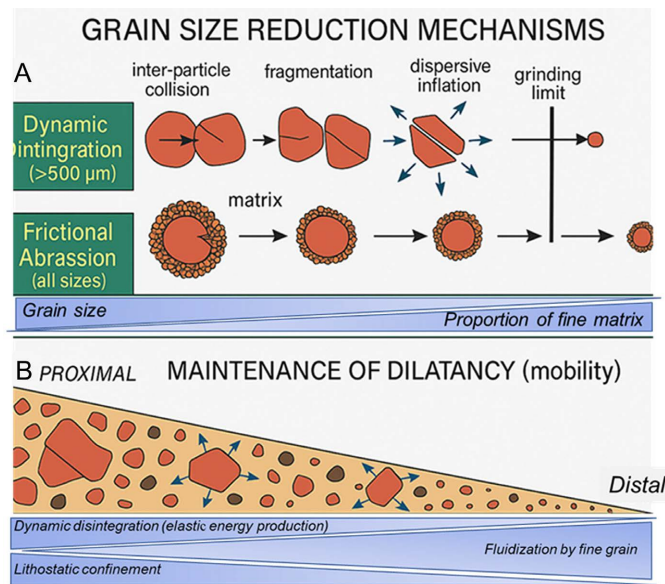


Figure 7. Schematic model illustrating the evolution of lithic particles in an avalanche of debris during transport. (A) The successive stages of the dynamic decay mechanism. (B) The mechanisms for maintaining the dilatancy of the granular mass during transport are dynamic disintegration (white arrows) and thin matrix thinning (black arrows) [1].

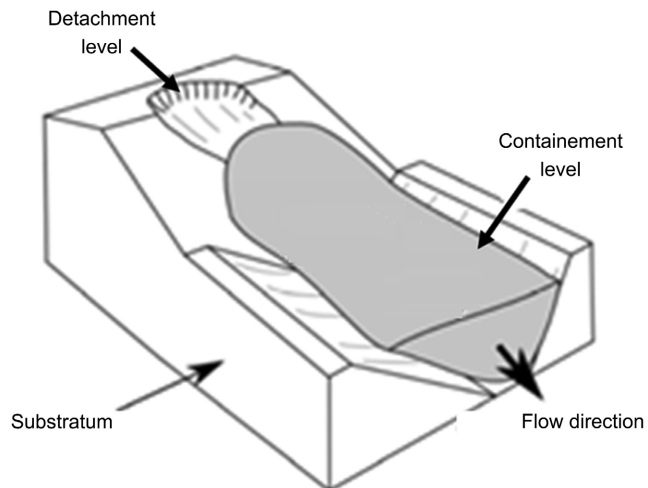


Figure 8. Schematic sketch of sectorial collapse illustrating a confined flow.

5. Discussion

The deposits identified in the Toumodi region record a complex volcanoclastic dynamic, dominated by debris avalanches (Debris Avalanche Deposits, DADs) and associated mass flows. Their architecture and textural organization reflect a series of catastrophic events linked to volcanic flank collapses, comparable to those observed in modern edifices such as Mount St. Helens [19] [20] or Shiveluch [21]. The Anikro-Ferme unit illustrates typical proximal facies, characterized by large angular to subangular blocks, ranging from decimeters to several meters, embedded in a fine volcanoclastic matrix. The absence of internal sedimentary structures and poor grain-size organization indicate a rapid, gravity-driven, unsorted deposit, generally associated with sudden flank failure or collapse [22] [23]. This type of facies corresponds to deposits directly produced by the rapid disintegration of the volcanic edifice, with limited transport and reduced fragmentation [24]. In contrast, the Akakro N'Zipri and Angoda units display finer grain sizes, often interrupted by laminations and discontinuous bedding. These features indicate prolonged transport and progressive settling of remobilized material, suggesting the involvement of hydrosedimentary processes in a more distal environment [25] [26]. This granulometric and structural evolution reflects a transition toward water-affected deposits, such as hyperconcentrated debris flows, lahars, or fluid-supported deposits [27]. The juxtaposition of proximal facies (Anikro-Ferme) and distal facies (Akakro N'Zipri, Angoda) illustrates a continuum of deposits, from the initial dry avalanche to secondary hydrosedimentary remobilization—commonly observed in volcanic systems affected by sector collapses followed by sedimentary reworking [28] [29]. The absence of internal sedimentary structures (e.g., cross-bedding, laminations, or graded bedding) in the proximal deposits of Toumodi units suggests dry deposition, dominated by debris avalanches undersaturated in water, typical of sudden sector collapses. Such massive deposits, without immediate post-depositional reorganization, are generally interpreted as the product of high-density, high-viscosity flows in a non-fluid or hydraulically unconfined environment [21] [23] [28]. By contrast, the more distal facies display greater textural diversity, including stratification, fine laminations, and evidence of reworking. This transition reflects increasing hydrosedimentary influence, involving fluvio-lacustrine or laharc reworking processes [25] [26]. The alternation of massive coarse beds and fine laminated intervals may record a rhythmic dynamic, with successive eruptive pulses or sedimentary remobilization phases triggered by intense rainfall, floods, or sudden drainage of volcanic lakes [29] [30]. Such composite stratification is well documented in both modern and ancient collapse settings, where primary debris avalanche deposits are commonly overlain or reworked by secondary hydraulic or gravitational processes [22] [27] [31] [32]. Thus, the sedimentary signature of the Toumodi deposits reflects a spatial and temporal transition between an initial dry collapse event and subsequent wet processes in topographically low or poorly drained areas.

The preferential orientation of internal structures within the deposits (N55° -

N60°) closely matches the regional directions of Birimian shear zones [33]-[35]. This correspondence suggests that pre-existing tectonic fracturing played a major role in preconditioning volcanic edifice instability, by controlling the weak planes that favored sector collapses and the directional dispersal of volcanic debris [36]-[38]. Within this context, the Paleoproterozoic corresponds to an active margin, characterized by oblique subduction and the development of calc-alkaline magmatic arcs, providing a geodynamic framework conducive to the construction of large, unstable volcanic edifices prone to repeated collapse [34] [39] [40]. The combination of tectonic stress and internal magmatic overpressure in such a setting would have favored gravitational destabilization of volcanic flanks, as observed in other comparable orogenic belts [21].

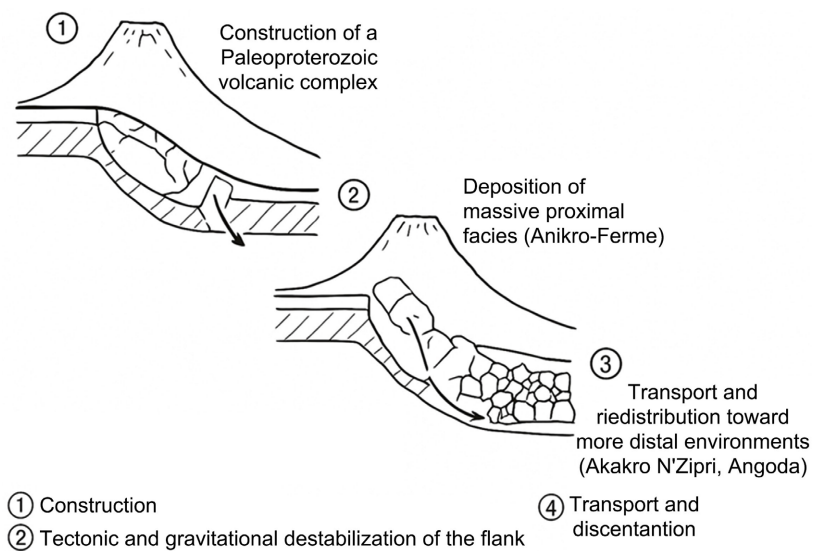


Figure 9. Schematic model illustrating the collapse of a volcanic edifice and the emplacement of debris avalanche deposits.

These observations allow us to propose an evolutionary model (**Figure 9**):

- 1) Construction of a Paleoproterozoic volcanic complex.
- 2) Tectonic and gravitational destabilization of the flank.
- 3) Deposition of massive proximal facies (Anikro-Ferme).
- 4) Transport and redistribution toward more distal environments (Akakro N'Zipri, Angoda).

5) Secondary water-driven remobilization and formation of stratified deposits.

These deposits therefore testify to the occurrence of a major volcanic collapse during the Paleoproterozoic in the Toumodi-Fêtékro belt. Their study provides a unique window into ancient volcanic processes and demonstrates that the destabilization and transport mechanisms documented in modern arcs were already active more than two billion years ago.

6. Conclusion

This study focused on the analysis of debris avalanches within the Birimian region,

a significant subject in volcanology as it enhances our understanding of the processes involved in the transport and deposition of volcanic materials following the collapse of volcanic edifices. The primary goal of this research was to identify the mechanisms driving the formation of these avalanches and to characterize the deposits formed during the event, enabling us to reconstruct the dynamics of debris transport and deposition. To address this, a comprehensive methodology was applied, combining field observations with detailed analyses of block morphology, fracture structures (particularly jigsaw fractures and comet-tail features), and the characteristics of the deposits themselves. Additionally, we examined the distribution of block sizes and their degree of maturation, which allowed us to estimate transport distances and gain insights into the conditions of confinement during the movement of debris. The findings from this study demonstrate that the transport of volcanic materials during the debris avalanches was primarily influenced by dynamic fragmentation, as indicated by the presence of jigsaw fractures and comet-tail structures. These features suggest that the debris flows were governed by environments of varying confinement, revealing significant differences between the units studied. Specifically, the Anikro-Ferme, Akakro N'zipri, and Angoda units exhibited distinct transport distances, with notable increases in fragmentation and flow dilution as the debris moved toward more distal regions. These observations highlight the role of dynamic disintegration as a key mechanism in the formation of debris avalanche deposits within the Birimian region. Furthermore, our analysis pointed to the collapse of the volcanic edifice as the triggering event for these debris avalanches, with magmatic and tectonic processes emerging as the primary drivers. This aligns with the Bezymianny-type collapse mechanism, which best explains the volcanic collapse observed in this study. While climatic factors or purely gravitational forces may have contributed to the edifice destabilization, the evidence supports the conclusion that magmatic instability, likely driven by tectonic processes and magma-water interactions, was the main factor leading to the collapse and subsequent formation of debris avalanches. This study thus contributes valuable insights into the complex interplay between volcanic processes and the dynamics of debris avalanches in the Birimian region.

Conflicts of Interest

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

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