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Review Article

Geological Approach to the Islands of the Union of the Comoros: Volcanic Structures, Mineral Resources, Geohazards, and Geological Heritage

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Abstract *- The Union of Comoros, a volcanic archipelago located in the Mozambique Channel, is characterized by geological formations dominated by alkaline basalts, reflecting a complex magmatic and tectonic history. This study presents an integrated approach to the geology of the islands, highlighting their volcanic structures, mineral potential, major geohazards, and geological heritage. The identified resources include construction materials, strategic minerals, and significant geothermal potential. The islands are exposed to various natural hazards, including volcanic eruptions, landslides, erosion, and flooding, emphasizing the need for appropriate prevention measures. Moreover, emblematic geosites such as «Lac Salé,» the Dragon's Back (le Dos du Dragon), and the Bambao Cirque (le cirque de Bambao) illustrate the scientific and touristic richness of the Comorian volcanic heritage. These findings provide a foundation for sustainable resource management and territorial valorization.*

Keywords *- Comoros, Basaltic volcanism, Mineral potential, Geohazards, Geosites.*

1. Introduction

The Union of the Comoros is a volcanic archipelago situated at the northern entrance to the Mozambique Channel, between Madagascar and the east coast of Africa (see Figure 1). [1] [2] [3] Its geological history has been determined in part by the breakup of Gondwana and regional tectonics, which was initiated in the Middle Jurassic (~250 Ma), representing a place to monitor intraplate volcanism and plate interactions almost directly, « in the open air » in this part of the Indian Ocean.

Nevertheless, despite years of experience in geology, petrology, and geophysics, the comprehensive function of the archipelago remains under discussion and controversy. [4] Models are in disagreement on the type of lithosphere that supports it (classical oceanic crust or ocean-continent transition zone), on how large deep structures affect the alignments of the islands, and on the interplay among magmatism, regional tectonics, and the building of volcanic edifices over time. [5] [6] [7] [8] [9] Much of the current literature is dedicated to evaluating geodynamics and mineral resources, as well as, in particular, geohazards and geological heritage, without considering these elements in a holistic sense at the scale of the archipelago.

This creates many grey areas. The first difficulty is that the lithosphere and the deep architecture of the Comoros are poorly identified, which impairs interpretations of the origin of basaltic volcanism and the alignments of the island. Second, the combination of lithology, geological structures, and mineralization has been limited to sporadic exploration, although the diversity of alkaline basalts and siliceous xenoliths indicates a variety of potentials and contexts conducive to a plethora of resources.

[10] [11] Geohazards are also infrequently surveyed systematically for volcanic, gravitational, and erosion-related hazards, relative to geology and climate, limiting the evaluation of a true human and infrastructure risk. Finally, geological heritage and emblematic geosites, while already mentioned in some studies, have not yet been the subject of a systematic inventory or concerted scientific support with tourists.

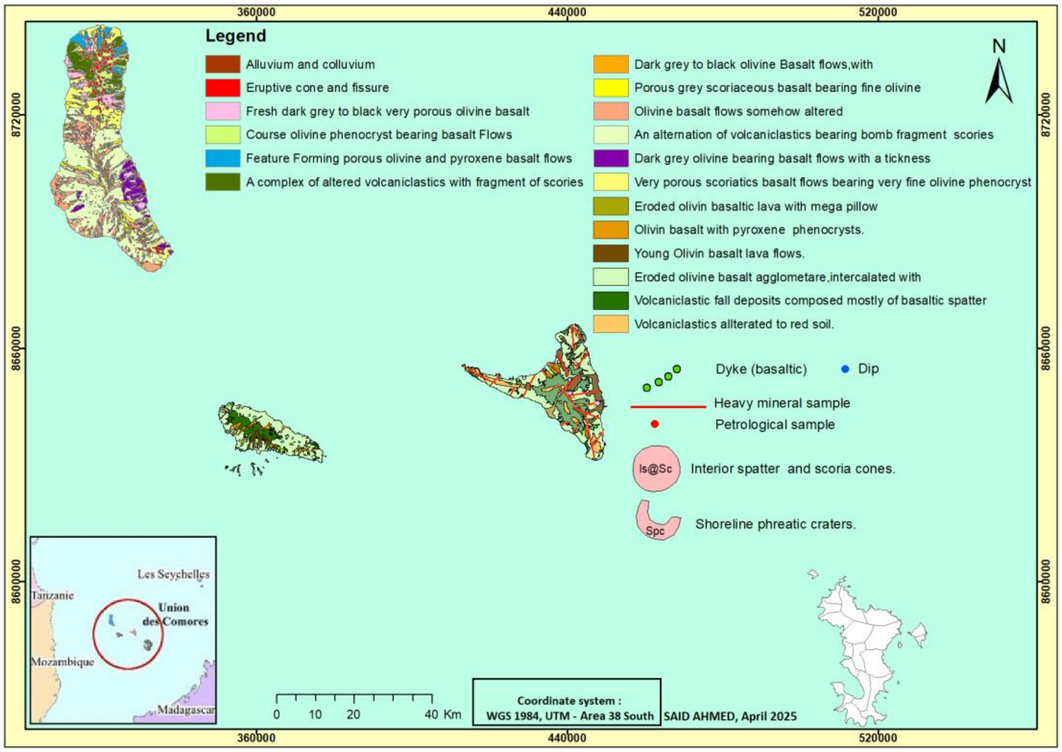

Fig. 1 Geological map of the three Comoro Islands and location of the archipelago in the Mozambique Channel

The article meets a twofold scientific challenge in this context. Its work intends to bridge the integrated geological synthesis of volcanic structures, lithospheric context, and mineral resources. Instead, it aims to address the lack of evaluation of geohazards and geological heritage at the archipelago level.

In order to alleviate this, the study makes the following geological contributions to the islands of the Union of the Comoros, namely: (i) situating the archipelago within its regional geodynamic background ; (ii) presenting the primary volcanic structures and lithologic formations ; (iii) outlining the associated mining potential ; (iv) delineating and describing the principal geohazards; and (v) listing key geosites of the geological heritage. The goal is to lay the scientific foundation for sustainable resource management and rational development of the Comoros territory.

2. Geological structures of Comoros

Observation of the geological formations of the Comoros archipelago is hampered by dense vegetation and surface weathering of volcanic rocks. This weathering generates red clay soils, particularly in Anjouan, Mohéli, and the Mbadjini massif in Ngazidja, and, besides vegetation cover, obscures the primary geological structures, complicating their study and mapping. [12] Recent volcanic flows, which have undergone little alteration in most of Grande Comore, maintain well-known geological features. Eruptive fissures, alignments of cones, pāhoehoe and ʻaʻā flows, and calderas are some of the features of basaltic volcanism uncovered by these outcrops. Their accessibility aids in a better geological comprehension of the island. [13, 14]

Geologically, it consists of volcanic rocks with a basaltic facies, generally massive and sometimes vacuolar, which were formed by successive effusive eruptions. [15] The presence of fractures and cooling joints in these rocks, which were formed very quickly, is the most frequent feature of such rocks. Anjouan has gabbro and mesocratic syenite veins or local intrusions and sedimentary enclaves of detrital siliceous sandstone associated with syenitic formations. [16] They suggest the large diversity of petrographic patterns and the complex magmatic history that formed them. On the structural level, the Comoros archipelago is defined by a complex web of faults and fractures in all volcanic edifices (see Figure 2). [17]

This network is particularly notable at the summit area of Karthala, where calderas and collapse escarpments are evidence of recent tectonic and volcanic activities. These are caused by regional stresses attributable to the dynamics of the East African Rift and the flexure of the oceanic crust. [18] Karthala's structural system is represented by a set of transform faults generally oriented northwest/southeast due to the combination of such regional tectonism and the internal volcanic dynamics. [18] Therefore, the geological structures in the Comorian archipelago depict those of a young oceanic volcanic system with basaltic magmatism, regional tectonics, and tropical weathering processes influencing the structure.

Their investigation is also critical, providing important information on the origin, differentiation, and morphology of volcanic islands in the Indian Ocean.

3. Mining Potential

The Comoros Islands consist largely of magmatic formations (see Figure 1). The formations of rocks vary from island to island, and their condition is highly affected by the age of the island. The mining potential of the Union of Comoros at present only lies in quarry materials, such as the production of sand and aggregates, cut stone, pozzolan, river sand, and sea sand. These all constitute construction materials. [2] This exploitation is artisanal, semi-mechanized, and industrial, with quarries in full operation on each of the three islands (see Figure 3). Besides these materials, the soil and subsoil of the Union of Comoros consist of rock formations that are mainly magmatic in nature and likely to be rich in substances such as precious metals, base metals, and strategic minerals.

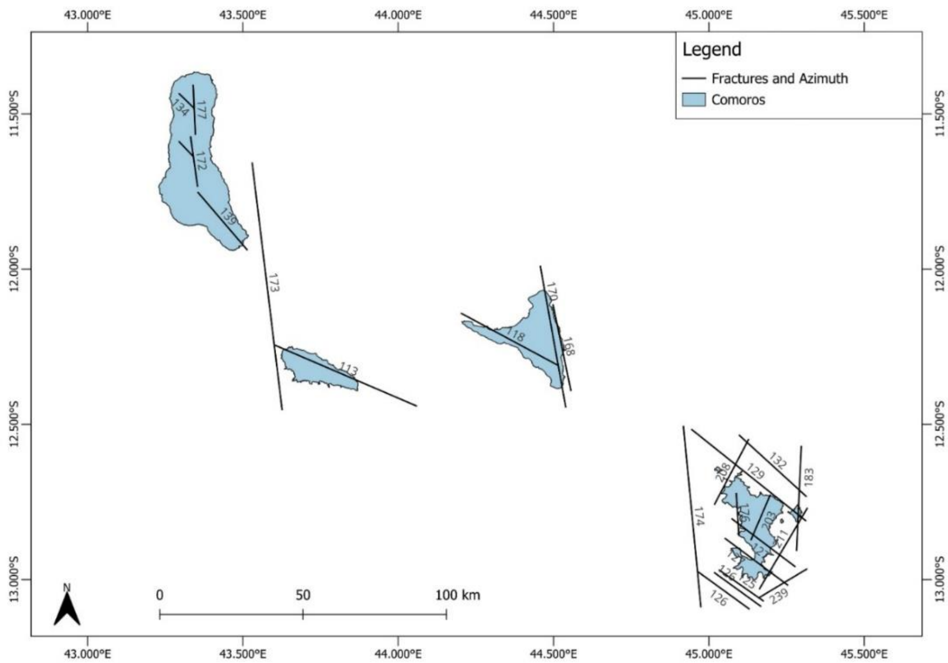

Fig. 2 Main directions of fractures in the Comoros Archipelago [19]

(a) (b)

Fig. 3 Deposits of construction materials: (a) crushed sand and (b) pozzolan

In 2009, Parkani [20] revealed in the report on the economic geology of Comoros that there are deposits of lateritic clays (see Figure 4a), ferruginous crusts, bauxite (see Figure 4b), and pozzolan, which are economically mined materials for the development of the Union of Comoros. Except for pozzolan, which can be found in limitless quantities within the country, the remaining materials are estimated to be tens of millions of tons. Heavy mineral deposits (gold, corundum, and spinel) throughout the country are highlighted in the same report. In Mohéli, corundum particles are much more prevalent in different parts of the island.

(a) (b)

Fig. 4 (a) Red soil deposit and (b) bauxite deposit

Beyond mining resources, the Union of Comoros has proactively conducted geothermal energy studies. During 2014-16, New Zealand company Jacos and the Bureau Géologique des Comores (BGC), with support from the African Union through the Geothermal Risk Mitigation Facility (GRMF), the New Zealand Government, and the United Nations Development Program (UNDP), undertook geological, geochemical, and geophysical investigations (80 MT stations and 200 gravimetric measurement stations) throughout the Karthala area. The final findings showed the potential of geothermal resources over an area of 4.1 km² north of Karthala.

The resource has been estimated at a temperature ranging from 150 to 190°C, which is ideal for exploitation. A conceptual model describing the presence of a geothermal system has been developed (see Figure 5). The geothermal potential is estimated at over 45 MWe. [21] [22] The location of the exploratory drilling sites is known, and a business plan for a 15 MWe power plant has been drawn up.

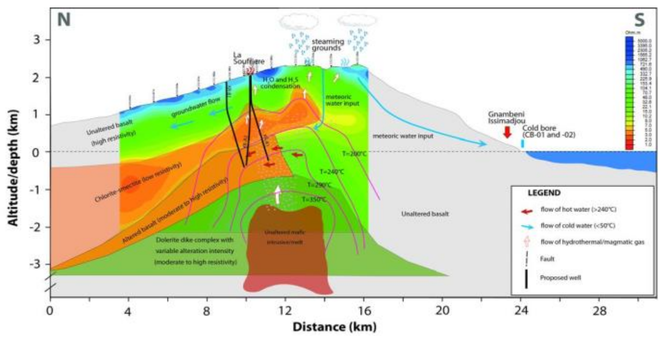

Fig. 5 Conceptual model of the geothermal system of Mount Karthala

4. Geohazards

Like any other country, the Comoros is exposed to geological hazards such as flooding and erosion, volcanic eruptions, landslides, and earthquakes. Since 2005, these geological hazards have been increasingly evident across the archipelago.

4.1. Floods

Despite the relatively recent formation, the Union of Comoros maintains a pedological structure and dynamics that have undergone geological changes over geological time. Geology varies in nature, and depending on the degree of rock weathering on each island, petrographic and pedological characteristics also differ. Comorian soils vary from island to island under the geological and pedological context.

Ngazidja (Grande Comore), characterized by highly porous and impermeable basaltic formations, is at high flood risk, while pedological formations are mainly clayey with a very low absorption capacity, including on Mohéli and Anjouan. [23] In 2012, the most severe flooding occurred in the Union of the Comoros (see Figure 6), [24] with close to 57,000 people (approximately 7% of the population) affected.

In the Union of Comoros, the causes of flooding can be classified into two main categories, namely (i) natural causes on account of climatic hazards associated with the evolution of meteorological phenomena, including precipitation and temperature and other natural events, which have an impact on the initial drainage systems (for example, volcanic deposits in Ngazidja), and (ii) human influences, mainly due to some agricultural practices (for example, in Anjouan and Mohéli). These are further aggravated by unbridled urban growth across the national territory, which increases surface runoff by limiting water infiltration.


Fig. 6 Impact Assessment of Flooding Before and After the Event

4.2. Erosional Processes

The Union of the Comoros is affected by two main types of erosion: continental erosion and coastal or marine erosion.

4.2.1. Continental Erosion

Continental erosion is one of the main ecological problems in the Comoros, particularly during the rainy season when heavy precipitation can increase the surface runoff and the movement of materials. This effect is highly intensified by deforestation and loss of vegetative cover, in addition to inappropriate agricultural practices on slopes, which weaken soils and increase the susceptibility to the effects of water. The effects of this erosion are numerous: gullies and deeply incised channels distort landscape morphology; loss of fertile topsoil layers lowers agricultural yield; and river silting (see Figure 7) predisposes areas to the risk of flooding and debris flows. Such combined impacts necessitate immediate action towards the need for soil conservation practices and sustainable land management systems to combat erosion and its adverse effects on the Comoros ecosystem and human activities.


Fig. 7 Observation of Stream Channels and the Impacts of Erosion on Forest Ecosystems

4.2.2. Coastal or Marine Erosion

In the Comoros, coastal erosion is driven by natural forces like waves, currents, and the volcanic nature of the islands, but also by human activities that quietly accelerate the process. One of the main pressures comes from the extraction of sand and other coastal sediments, widely practiced to supply the local construction sector. This loss of natural defenses is most evident in Anjouan Bay, the northern, southwestern, and eastern shorelines, as well as around the Nioumakélé and Sima peninsulas, where it exposes beaches and villages to the advancing sea (see Figure 8). [25]

To estimate how much sediment was being removed, the team counted the piles of aggregates such as fine and coarse sand, pebbles, and pieces of reef coral stacked along the shore. Each pile, according to the extractors interviewed, represents about 3 m^3, which is the load of a typical transport truck. The impact of this overexploitation is hard to ignore: landslides, sections of coastal roads collapsing, and beaches that seem to retreat year after year. By removing too much sediment, these practices disrupt the natural balance of beach dynamics, undermine the coastline's protective "buffer," cause slope failures more frequently, and make Comorian coastal zones more vulnerable to marine erosion and weather-related hazards.

Fig. 8 Coastal erosion processes along a Comorian shoreline and their impacts on road infrastructure

4.3. Volcanic Activity and Eruptive Events

The Comoros archipelago hosts an active volcano on Ngazidja Island, right in the heart of the island where most people live. This proximity means volcanic activity is not a distant phenomenon but a very real part of everyday life for many residents. The site of eruption known as Mount Karthala has been a frequent eruptor; its earliest documented eruption dates back to 1808, and the last one was in 2007. [26] According to a recent composite of events reported on the volcano, the only eruption on the flanks was in 1977, and all others occurred at the peak. [19] [27] All of these eruptions have caused earthquakes strong enough to be felt across the whole island of Ngazidja, periodically reminding communities of the volcano's presence beneath their feet.

The operation of Mount Karthala's eruptions closely resembles the great basaltic shield volcanoes of Hawaii, Réunion, and the Galápagos; the lavas are very loose, the eruptions are mostly effusive compared to explosive, and the volcano is designed as an elongated volcano, building broad, gently sloping flanks rather than steep cones. But even with this obvious similarity, the story of Karthala's eruptive life is only partly captured. Only a scattered array of accounts has survived; the earliest written data on how it erupted dates back merely to the early 20th century.

The first geological map of Grande Comore, which came from 1985 to 1993 and was published by Bachèlery and Coudray, [19] was one of the most significant advancements of that time, which provided a systematic approach to mapping lava flows, cones, and fissures throughout the island, beginning at Karthala and terminating at La Grille, while also aggregating all known eruptions at that time. The more recent summit eruptions of 2005, 2006, and 2007 exerted a much more direct hit on island life, devastating crops and infrastructure, with the 2005 event alone estimated to have impacted around 250,000 affected individuals. [28] The following table summarizes recent eruptions of the Karthala volcano.

Table 1

Year	Date	Location	Type of Eruption	Area Covered (10^6 m^2)	Damages
2007	13 Jan	Choungou–Chagnoumeni	Magmatic – summit	0.03	Yes, collapse after an earthquake
2006	28 May – 1 Jun	Choungou–Chahale	Magmatic – summit	0.2	No
2005	25 Nov – 8 Dec	Choungou–Chahale	Phreatomagmatic then magmatic – summit	>1/2 of the island is covered with ash	Yes
2005	16–20 Apr	Choungou–Chahale	Phreatomagmatic then magmatic – summit	2/3 of the island is covered with ash	Yes
1991	11 Jul	Choungou–Chahale	Phreatic – summit	–	Yes
1977	5–10 Apr	Southwest flank	Magmatic – eccentric	1.8	Yes, Singani and Hetsa destroyed

4.4. Landslide Phenomenon

In the Union of Comoros, landslides are rare, but if they happen, the impacts of a landslide can be severe. In April 2014, one such incident struck the Mahalé region on Anjouan (12°13′S / 44°29′54″E), a territory known for very steep slopes, strong erosion, and a dense and energetic drainage network. Here, the main regional road threads precariously along the contact between two contrasting landforms: a steep upslope hillside and a sharply incised plateau that hosts most of the coastal villages.

The landslide was triggered by the inherent instability of this hillside, resulting in the destruction of surrounding urban areas and sections of the road (see Figure 9a). The shock was so great that it affected Moheli for its entire extent, cracking road pavements and disturbing geological blocks along mountain slopes at Miringoni (see Figure 9b).

(a) (b)

Fig. 9(a) Mahalé Landslide and (b) Miringoni Landslide

5. Geological Heritage: Selected Attractive Geosites in the Comoros

The islands of the Union of Comoros are shaped by an outstanding geological heritage, forged by intense, almost uninterrupted volcanic activity since the Quaternary. This heritage is visible in the remarkable diversity of landforms and structures, which tell the story of how the volcanic edifices were built, transformed, and slowly sculpted over time.

5.1. Lac Salé: a natural and cultural landmark of Grande Comore

Nestled along the northern coast of Grande Comore, Lac Salé is an impressive phreatomagmatic maar, a crater formed from the explosive clash between rising basaltic magma and underground water. This roughly one-kilometer-wide collapse bowl maintains its crisp circular shape and is layered with well-preserved pyroclastic deposits that scream shallow explosive volcanism (see Figure 10a). A partial breach toward the Indian Ocean lets seawater rush in with the tides, turning it into a salty lake whose brininess ebbs and flows like the ocean itself. It is a vivid snapshot of how volcanic fury meets marine forces, capturing the island's recent eruptions alongside the relentless nibble of coastal erosion.

Yet Lac Salé (Salt Lake) is more than rock and water; it is a living heartbeat for local communities. Revered as a sacred site, it weaves into Comorian traditions through rituals and beliefs that safeguard the islands' intangible heritage. Picture dark basaltic cliffs framing turquoise waters amid scruffy coastal scrub: this dramatic scene makes it a geosite brimming with scientific intrigue, visual punch, and cultural depth. As a cornerstone of Comoros' geological legacy, it could anchor a future national geopark, spotlighting the archipelago's volcanic wonders and cultural tapestry.

5.2. The Dos du Dragon: a symbol of Comorian volcanic and cultural heritage

Located on the northeastern periphery of Grande Comore, the Dos du Dragon (Dragon's Back) is the rugged skeleton of a long-gone basaltic volcano cone constructed by piles of lava flows and pyroclastic blasts through the island's late effusive eruptions (see Figure 10b). It is being carved up by the relentless pounding of the ocean over the years, chiseling its deep ridges and rough basaltic boulders into a winding, scaly shape that alludes to a dragon's back, giving it its evocative local name. It is a front-row seat to the rise and fall of young oceanic volcanoes, which makes it a prime geosite for the decoding of recent basaltic activity and coastal erosion stretching across the Comoros.

But its appeal extends well beyond the rocks. The Dos du Dragon pulses with epic myths around nature's fierce and protective deities—woven into the Comorian storytelling. Its jaw-dropping contours and exposed volcanic bones make it a natural classroom for geoscience lessons and triggering public wonder, plus a geotourism gem waiting to be shown. That is to say, it is about the soul of the Comoros and how raw volcanism can come to life over a stunning landscape and evoke a sense of island identity.

(a) (b)

Fig. 10 (a) Salt Lake (b) Dragon's Back

5.3. Cirque de Bambao: a geological and cultural gem of Anjouan

Located within the heart of Anjouan Island, Bambao Cirque is an enormous collapse caldera that resulted from the severe destabilization of a prehistoric central volcano (see Figure 11a). The magma chamber partially drained, leaving this huge circular bowl, surrounded by sheer cliffs, and later filled with fresh lava flows, reworked pyroclastics, and dense tropical vegetation, a reminder that nature returns on weathered basaltic ground.

It is also a living testament to the evolution of island calderas, which provide a natural laboratory in the study of volcanism, erosion, and those wild rhythms of tropical scenery. But Bambao is more than a geology of magic. For locals, it has interwoven into founding myths and ancient fables that resonate like the rhythms of an Anjouan collective memory. With breathtaking vistas, leafy slopes, and scattered traditional villages, you have a geotourism paradise plus a local environmental storytelling class. With her well-rounded approach, unique culture, and the beauty that is an extraordinary wonder, Bambao Cirque emerges as a centerpiece of the Comoros' geological and natural heritage with volcanoes, wild places, and an entirely separate island economy.

5.4. Basalt Lava Desert

Gazing across Grande Comore, the lava fields of Mount Karthala's recent eruptions are one of the Comoros' most famous images of raw, active volcanism. These pāhoehoe and ʻaʻā flows originate from wave after wave of basaltic lava and demonstrate the extreme variety of how basalt cools, cracks, and hardens (see Figure 11b). Their fresh, almost pristine forms, unadorned black surfaces with no vegetation, and wildly different textures scream geological youth and document the pulsing heart of oceanic shield volcanoes.

This spot hits hard beyond science. It is a real-world lab for unpacking eruptions, basalt birth, and how volcanic islands change over time. Culturally, Karthala's blasts remain in our stories and memories and bind the land back to the people's soul. With jaw-dropping drama and a brainy sensibility, it is the perfect geotourism destination and a realistic way to show the natural and geological riches of the Comoros in a good way.

(a) **(b)**

Fig. 12 Bambao cirque and basaltic lava desert

6. Discussion

In comparison with the former works that focused on the Comoros and its related volcanic island systems, this research delivers a superior offering by adopting a comprehensive, multi-scale method across geological structures, geomorphology, erosion processes, and territorial dynamics. Previous attempts covered mainly volcanology, petrology, or geodynamics, applied more advanced means of analysis; coverage on surface processes was, in many instances, disjointed. The authors explicitly connect basaltic formations' lithology with topographic controls, tropical climate forcing, and man-made effects to present a more comprehensive picture of continental erosion as fundamental to landscapes, soil deterioration, sediment transfer, and hydrological hazards. Also, an evaluation of geological heritage is proposed as the primary thing being studied, as well as something that has been ignored in such studies in the Comoros.

In contrast to the imagery of other impressive sites described elsewhere, geosites are investigated within an internationally recognized geoheritage and geoconservation programmatic framework, including scientific, geomorphological, and cultural dimensions. Good results are due primarily to the integrated approach for robust local context that is used at the level at which we offer analytical solutions by taking into account substantial relationships between geology, erosion, and heritage. These are valuable results to develop an operational platform for sustainable land management and territorial valorization in volcanic island contexts.

7. Originality and Scientific Contribution of the Work

Unlike previous studies conducted in the Comoros, this work adopts an integrated and cross-cutting approach to studying the geology of the archipelago by combining, for the first time, volcanic structures, geological hazards, mining potential, and geopatrimony at the national level. Although other studies have been conducted on volcanology, the current literature focuses heavily on volcanology. [19] [26] [27]

This research is particularly original in that it introduces geoheritage as a scientific subject in the Comoros, as it had previously been overlooked. Here, these emblematic geosites are examined not only for their geological interest but also for their cultural, landscape, and sustainable development dimensions, opening up perspectives for geoconservation and geotourism.

In addition, continental erosion is placed at the heart of the study as a geological risk that shapes the Comorian landscape. The results, particularly on volcanic lithology, relief, humid tropical climate, and anthropogenic pressures, highlight the role of erosion in soil degradation, increased hydrological risks, and changes in landforms.

8. Conclusion

The Comoros group is composed of volcanic islands and a case study of how fledgling volcanism works. Such a system is subject to the forces of tectonic processes, basaltic magma, and tropical weathering. The islands have significant potential for mineral exploitation by mining, such as for construction materials, strategic minerals, geothermal energy, and more. Yet, natural events such as volcanic eruptions, landslides, erosion, and floods also make them more susceptible.

This also reinforces the need for sound management and countermeasures. Furthermore, the geological heritage of the Comoros, which is found among well-known places such as Lac Salé, Dos du Dragon, and Cirque de Bambao, is scientifically important and an important tourist site. It emphasizes that a holistic approach, balancing sustainable resource development and the protection of natural heritage and protection against geological hazards, is more relevant under such condition.

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