

Article

Manifestations of the 2023 Al Haouz Earthquake as Geoheritage: Geological Processes, Landscape Impacts, and Implications for Geoconservation in the Moroccan High Atlas

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Abstract

The 2023 Al Haouz earthquake (Mw 6.7–6.9) is the strongest quake ever recorded in modern Morocco and ranks among North Africa’s most significant seismic events of the century. It struck the High Atlas region, causing widespread land changes, thousands of landslides, destruction in remote mountain villages, and heavy losses of life and cultural heritage. The earthquake not only had immediate humanitarian and economic effects but also dramatically transformed the landscape, uncovered new geological features, and reshaped the region—providing a unique opportunity to study seismic activity as geoheritage. Researchers have begun systematically documenting how this earthquake affected perceptions of seismic hazards in the High Atlas area. Although often considered a dark geoheritage, the event holds valuable lessons that can inform programs to strengthen resilience to geohazards. This research places the 2023 Al Haouz earthquake in a geoheritage context, underscoring its scientific, educational, and cultural importance. By analyzing how the earthquake altered the terrain, exposed tectonic activity, and left lasting geological marks, this work aims to bridge the gap between the high scientific interest in seismic events and their limited roles in geoheritage, conservation, tourism, and education.

Keywords: geoheritage; geodiversity; tectonic; seismicity; earthquake; geohazard; resilience; geoconservation; geosite



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1. Introduction

Earthquakes are sudden, intense ground-shaking events caused by the rapid release of energy within the Earth’s crust, generating seismic waves that propagate across the surface. Throughout human history, seismic events have ranged from moderate to catastrophic, frequently causing profound damage to infrastructure, the environment, and human communities [1–5]. Recent examples include major earthquakes in Colombia (1999, Mw 6.2, ~2000 victims) [6]; Haiti (2010, Mw 7.0, 222,570 victims, USD 8 billion in losses); Indonesia—Aceh (2004, Mw 9.1, 165,708 victims, USD 4.4 billion); Iran—Bam (2003, Mw 6.6, 26,976 victims, USD 0.5 billion); Pakistan (2005, Mw 7.6, 73,338 victims, USD 5.2 billion) (UNDRR); Mexico—Gulf of Tehuantepec (2017, Mw 8.2, 98 victims) [7]; Peru—Chincha Alta (2007, Mw 8.0, 519 victims) [8]; China—Wenchuan (2008, Mw 7.9, 87,476 victims, USD 85 billion) [9]; Chile (2010, Mw 8.8, 521 victims, USD 30 billion) [10];

Japan—Tohoku (2012, Mw 9.0, ~15,000 victims, USD 411 billion); Nepal (2015, Mw 7.8, ~8000 victims) [11]; and the Turkey–Syria earthquake doublet (2023, Mw 7.8 & 7.5, ~59,000 victims, ~USD 118 billion in losses) [12].

Globally, earthquakes are among the most severe natural hazards and among the leading causes of disaster-related mortality. According to the United Nations Office for Disaster Risk Reduction (UNDRR), earthquakes caused the highest number of disaster-related deaths between 2000 and 2019, and in 2023 alone—following major events in Türkiye–Syria, Morocco, and Afghanistan—earthquakes accounted for the most fatalities worldwide. These impacts often extend beyond the immediate shaking, triggering secondary hazards such as landslides, ground failures, or, in coastal settings, tsunamis, further amplifying human and environmental vulnerability. For example, the 2018 Sulawesi earthquake in Indonesia generated a tsunami affecting Palu, Donggala, and Mamuju, and produced long-distance flow slides on gentle slopes, resulting in 2101 deaths, 4438 injuries, and 1373 missing persons [13–16]. Likewise, the 2008 Wenchuan earthquake in China triggered widespread landslides, rock avalanches, debris flows, and landslide-dammed lakes, with preliminary estimates indicating approximately 20,000 deaths from these secondary hazards [17–19].

Beyond physical destruction, earthquakes can disrupt essential services, including water supply, sanitation, healthcare, and housing, as well as critical lifelines, including energy grids, communication networks, and transportation systems. Overcrowded shelters, damaged infrastructure, and reduced access to clean water and other resources can increase the risk of disease outbreaks and long-term socioeconomic instability. These cascading effects underscore that earthquakes are not merely geophysical phenomena but complex events with profound human, cultural, and territorial consequences.

Although earthquakes are scientifically significant, they have seldom been studied from a geoheritage perspective, in part because seismic events are typically understood as sudden and destructive geological hazards rather than as legacy features of the landscape. Earthquakes often produce dramatic impacts that communities prioritize rebuilding and recovery for—especially where low-resistance building materials are used, populations are dense, or geoeducation and hazard resilience are limited—so physical traces of these events are quickly removed or obscured during reconstruction, reducing opportunities for their preservation as geoheritage elements [20,21]. In this sense, earthquakes can be considered a form of “dark geoheritage”, in which the tangible evidence of past disasters is neither preserved nor valorised, partly because societal responses focus on healing and rebuilding rather than on conserving the physical record of destruction [21]. This contrasts with other geological features that are more visibly appreciated and interpreted as heritage, illustrating a significant gap in how geoheritage frameworks account for hazardous, transient, and socially sensitive geological phenomena. Tectonic activity—such as faulting, folding, crustal uplift, and seismic deformation—is central to tectonic geoheritage, yet its heritage importance is often overlooked. Most previous geoheritage research associated with natural disasters has primarily focused on volcanic hazards [22–26], volcano tourism [27–34], tsunamis [35,36] and landslides [37–45], giving little attention to how seismic landscapes could contribute to geoconservation, education, risk awareness, and resilience-building. Characterisation of the volcanic geoheritage of Morocco is also an emerging subject that many researchers have explored recently [46–48]. This oversight is notable since earthquakes frequently produce, modify, or remove landforms and geosites, leaving lasting geological records that reveal the Earth’s ongoing changes.

Morocco offers a compelling context for examining seismic risk and its geoheritage implications. Although located south of the most active Mediterranean collision zones,

the country has been repeatedly struck by destructive earthquakes throughout its history, with documented events dating back to the 9th century [49–51]. In modern times, the Al Haouz earthquake is the third-deadliest seismic disaster of the past decades, following the 1960 Agadir earthquake (Mw 5.8), which caused more than 12,000 fatalities [52,53], and the 2004 Al Hoceima earthquake (Mw 6.4), which resulted in over 800 fatalities, 2539 destroyed and damaged houses, and 15,600 individuals being homeless [54–56]. Moroccan seismicity is primarily influenced by the complex interactions between the African and Eurasian plates, along with an extensive network of active faults—many characterized by strike-slip or reverse motion—resulting from lithospheric thinning, mantle uplift, and ongoing intraplate deformation within the Atlas orogenic belt. This geodynamic setting underscores the ongoing, and sometimes underestimated, risk of significant, potentially destructive earthquakes, emphasizing the need for a thorough understanding of seismic processes and their impacts on Morocco’s evolving landscapes.

Within this broader history, the 2023 Al Haouz earthquake (Mw 6.7–6.9) is the most powerful earthquake recorded in modern Moroccan history and among the most consequential seismic disasters of the 21st century in North Africa. Striking the High Atlas region, it caused extensive ground deformation, triggered thousands of landslides, devastated remote mountain settlements, and resulted in major loss of life and heritage. Beyond its immediate humanitarian and economic impacts, the earthquake profoundly altered landscapes, exposed previously unknown geological structures, and reshaped the region’s geomorphology—offering a rare opportunity to explore seismic phenomena as geoheritage.

This study situates the 2023 Al Haouz earthquake within a geoheritage framework, highlighting the scientific, educational, and cultural significance of seismic landscapes. By examining how the earthquake reshaped the terrain, revealed tectonic processes, and left enduring geological imprints, this work addresses the critical gap between the high scientific value of seismic events and their limited use in geoheritage, geoconservation, geotourism, and geoeducation. In doing so, it also contributes to broader discussions on disaster memory, risk awareness, and community resilience in Morocco and beyond.

2. Materials and Methods

This paper adopts an analytical narrative approach to examine the 2023 Al Haouz earthquake and its implications for geoheritage, geodiversity, and geoconservation in the Moroccan High Atlas. The study first outlines the High Atlas’s unique geotectonic setting, emphasizing the region’s intracontinental orogenic evolution, active fault systems, and ongoing intraplate deformation. This context is essential for understanding why seismic processes play such an important role in shaping both the physical landscape and the region’s geoheritage.

A narrative synthesis is then developed to reconstruct the seismic event of 8 September 2023, drawing on the current state of geophysical and geological knowledge. Because research on the earthquake is ongoing, information on rupture mechanisms, surface deformation, mass movements, and landscape impacts continues to evolve. In this dynamic scientific context, an expert, step-by-step analysis is provided to highlight the distinctive geological signatures and geomorphological consequences of the earthquake, with a focus on features with potential geoheritage relevance.

We used VOSviewer_1.6.20 and the Scopus database to map research outputs and identify major research clusters. Scopus is one of the major research output databases, primarily collecting English-language scientific literature appearing in globally significant research journals. Here, we consider this database a robust, relatively easy-to-use data source for examining global research trends, while noting that it does not list research outputs published in books, in grey literature (not listed in Scopus), or in languages

other than English. It has limitations. For identifying the general global trend, however, it is currently the best data source, and the results indeed demonstrate clustering and networking in global research output. We used search terms such as “(TITLE-ABS-KEY (geoheritage) AND TITLE-ABS-KEY (earthquake) OR TITLE-ABS-KEY (tectonic) OR TITLE-ABS-KEY (fault) OR TITLE-ABS-KEY (fold) OR TITLE-ABS-KEY (seismicity))” with a minimum number of 5 word co-occurrences within Abstract and Title of the located articles to identify global research output in the field of geoheritage and the most relevant structural geology markers. This search yielded 210 research papers, providing a good database for identifying global research trends (Figure 1).

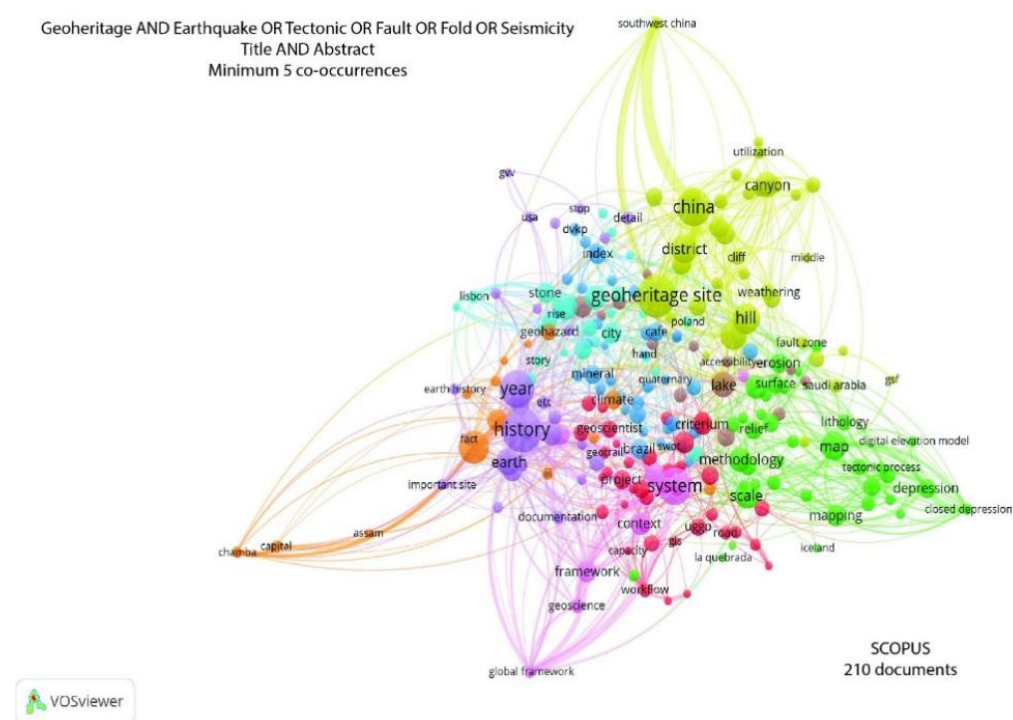


Figure 1. Co-occurrences network map generated based on 210 research outputs from search terms within Title, Abstract, and Keywords, such as Geoheritage AND Earthquake OR Tectonic OR Fault OR Fold OR Seismicity.

To identify relevant Moroccan research outputs, two sets of searches were performed: “(TITLE-ABS-KEY (geoheritage) AND TITLE-ABS-KEY (Morocco))” and “(TITLE-ABS-KEY (earthquake) AND TITLE-ABS-KEY (Morocco))”. The “earthquake” and “Morocco” search returned 415 papers, indicating vigorous research activity and interest in these subjects (Figure 2a). The geoheritage and Morocco searches returned only 50 research outputs, indicating that this field is emerging in Morocco (Figure 2b).

To situate the earthquake within a broader geoconservation and geoheritage context, the paper integrates insights from published studies of High Atlas geodiversity, including 42 research contributions identified through Scopus, ScienceDirect, and Google Scholar using the following search terms: “(TITLE-ABS-KEY (geoheritage) AND TITLE-ABS-KEY (High Atlas) AND TITLE-ABS-KEY (Morocco) OR TITLE-ABS-KEY (geodiversity) OR TITLE-ABS-KEY (geoconservation) OR TITLE-ABS-KEY (geotourisme) OR TITLE-ABS-KEY (geosite) OR TITLE-ABS-KEY (geomorphosite))”. Given the heterogeneity of available data and the rapid post-event landscape transformations, a conventional systematic review was deemed inappropriate. Instead, the study employs a comparative narrative that draws on analogous seismic events worldwide to contextualize the types of landforms and stratigraphic records that major earthquakes can imprint on the geomorphological and geological archive.



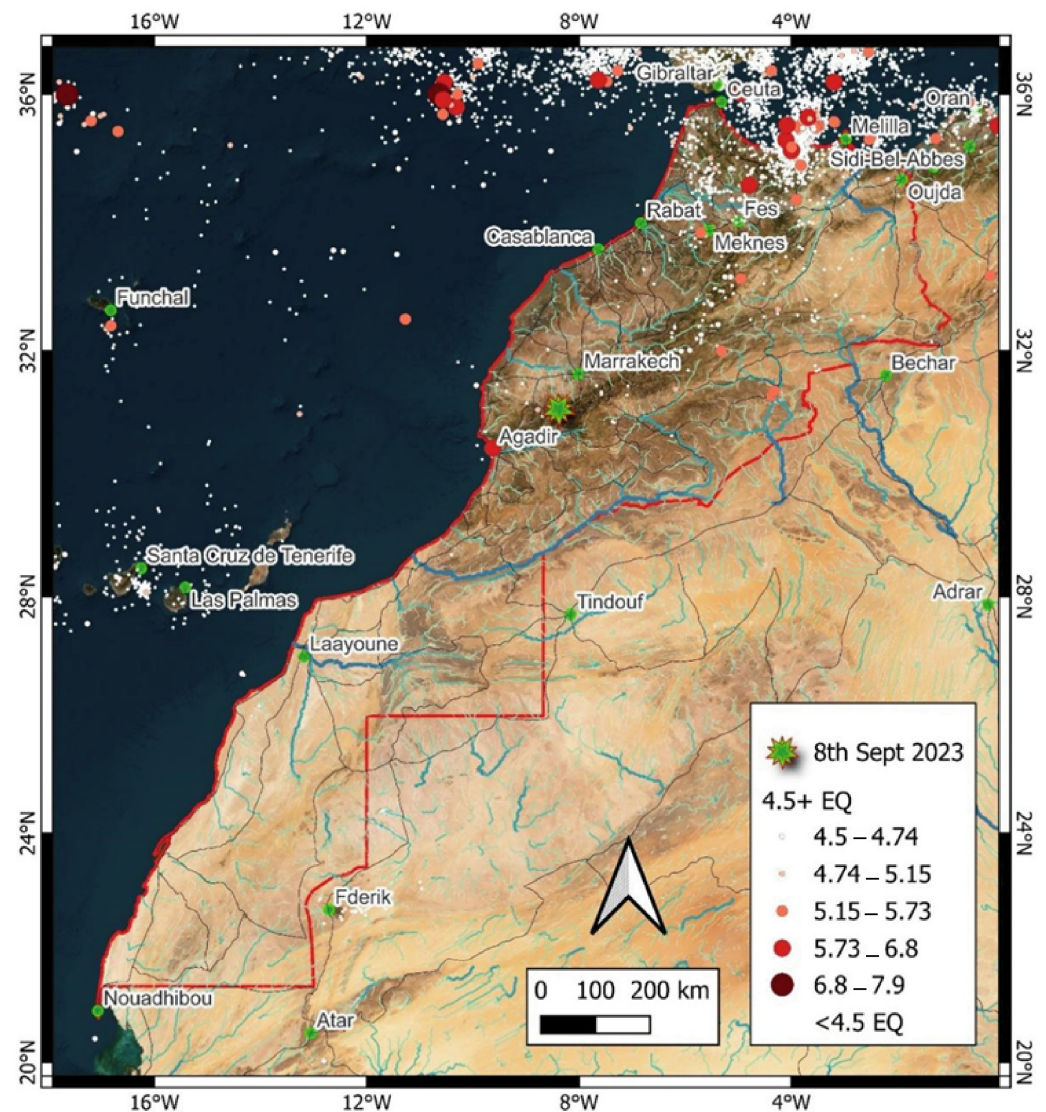


Figure 3. Morocco seismic architecture based on the USGS Earthquake Catalogue data. The 8th of September 2023 Earthquake occurred along a central tectonic zone that marks the Atlas Mountains, while the country's main seismic zone is in the northern areas.

3. Geological and Tectonic Context of the High Atlas

The High Atlas is an intracontinental mountain belt formed by the inversion of a Mesozoic aborted rift during the Cenozoic Alpine Orogeny [57]. With peaks exceeding 4000 m, it is the highest segment of the North African Alpine system, which is an active seismic zone with notable large magnitude earthquakes (M4.5+) (Figure 3). Crustal shortening began in the Late Cretaceous [58] and intensified during the Neogene [59–61], producing flexural loading that led to the formation of discontinuous syn-orogenic basins. These include the El Haouz, Bahira, and Tadla basins to the north, and the Souss and Ouarzazate basins to the south [59] (Figure 4). The southern basins are delimited by the crustal-scale South Atlas Fault (Figure 4), a major structure that separates the High and Anti-Atlas domains [62–64]. This reverse fault extends northeastward and reactivates the steeply dipping Tizi n'Test Fault [65]. To the north, the Western High Atlas is bounded by the North Atlas Fault, which marks the transition to the Mio-Pliocene El Haouz basin [66] (Figure 4). Farther north, the south-dipping North Jebilet Fault places the Jebilet inlier over the Neogene Bahira plain [67]. Alpine deformation is characterized by thick-skinned fold-

ing and thrusting in the Western High Atlas [67], progressively evolving into thin-skinned tectonics toward the external forelands [66,68,69] (Figure 4).

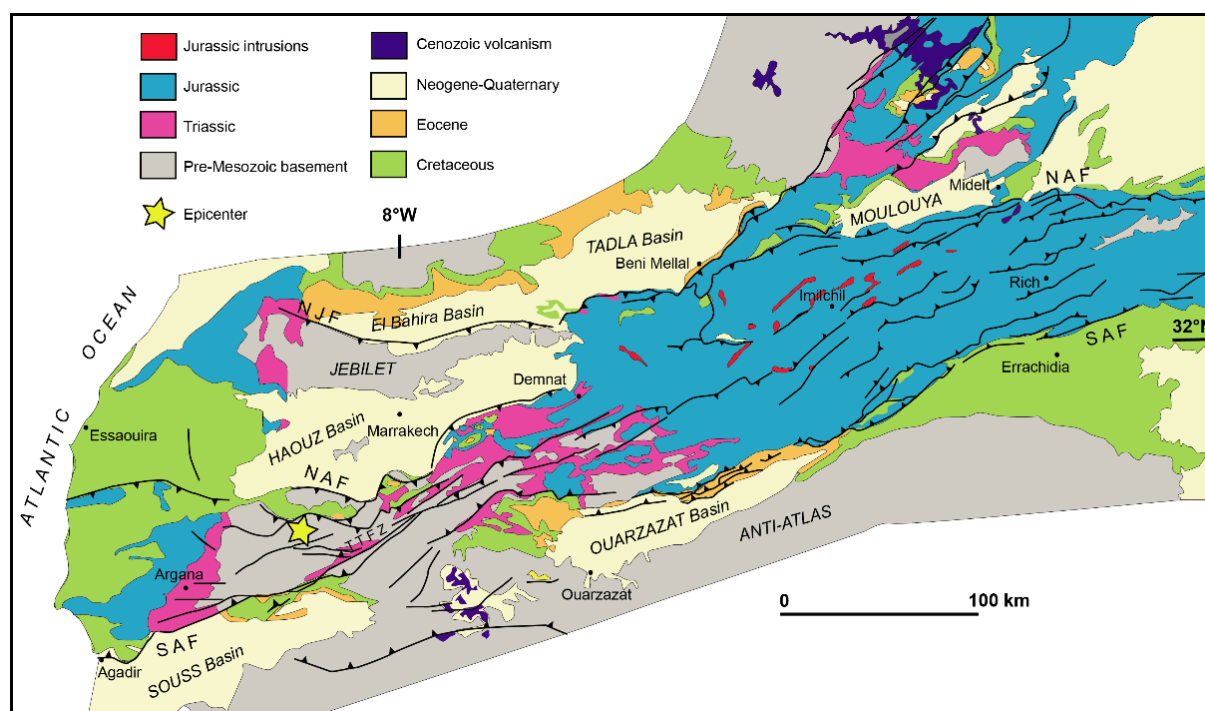


Figure 4. Simplified geological map of the High Atlas Mountains showing the main geological exposures and structural features of the range (redrawn from Teixell et al., 2007 [70]).

4. Results

4.1. Research Output Pattern

The complex geological and tectonic evolution has directly generated exceptional geodiversity across lithologic, structural, geomorphologic, and paleontological dimensions. This diversity is expressed in the remarkable density and variety of rock types within a relatively small area, including Triassic volcanic and sedimentary units, Jurassic carbonate platforms, Bathonian–Callovian red beds, and extensive magmatic intrusions such as gabbroic and doleritic dykes and sills (e.g., Imilchil, Tassent, and Msadrid ridges) [57,69–72]. Strong polyphase deformation has further exposed these formations in narrow anticlines, broad synclines, and fault-bounded blocks, allowing the simultaneous visibility of multiple stratigraphic levels and tectonic structures—an uncommon feature in the High Atlas [57,69–74]. In addition, the region hosts internationally significant paleontological sites, including diverse dinosaur track assemblages, crocodylomorph traces, and invertebrate ichnofossils, adding another layer to its exceptional geodiversity [75–78].

Research on geoheritage is an emerging field in Morocco, as a Scopus survey identified 50 scientific papers, most published within the last 20 years (Figure 2b). Although 50 research outputs are not yet a robust database for clearly identifying trends, they are sufficient to note that geosite recognition and inventory building are the main research priorities so far in Morocco’s geoheritage context. In contrast, earthquake or seismic research is far more established in the Moroccan context (Figure 2a). There are significant clusters in building stability, tsunamis, and general geological aspects of various structural elements, which are key research output clusters. In the global scene, 210 research papers were identified as relevant to some form of structural geology research in the context of geoheritage, suggesting that earthquake heritage remains a relatively restricted research subject (Figure 2a).

Uplift, folding, faulting, and salt tectonics have exposed sedimentary, volcanic, and metamorphic rocks in a spatially condensed area, creating diverse landscapes such as high plateaus, incised valleys, canyons, karst systems, and volcanic edifices. Tectonic activity has also brought extensive fossiliferous strata to the surface, revealing dinosaur tracks [75–78], Carboniferous paleoflora [79], and other significant paleontological sites. Such structural and stratigraphic heterogeneity underpins the scientific, educational, and aesthetic value of the High Atlas geosites. The richness of geodiversity is reflected in the volume and diversity of research conducted in the region. Based on a review of international academic databases (Scopus, ScienceDirect, and Google Scholar), 42 peer-reviewed studies (Table 1) have catalogued, evaluated, and promoted geomorphosites, structural sites, and paleontological remains, particularly in the Central High Atlas and the M’Goun UNESCO Global Geopark [80–90] (Table 1). Other studies have addressed the potential of geotourism and geo-education, highlighting the link between geoconservation, sustainable development, and local socioeconomic benefits [85,91–95]. Advanced methods, including GIS-based mapping, multi-criteria assessment, and machine learning, have been increasingly applied to identify and promote geosites [96–100]. The convergence of these studies demonstrates that the High Atlas is not only a repository of geological and geomorphological wealth but also one of the most intensively studied regions in Morocco, reinforcing its status as a flagship area for geoconservation, geoeducation, and sustainable geotourism initiatives (Figure 5, Table 1).

Table 1. This overview summarizes peer-reviewed studies from the High Atlas, based on a review of international academic databases, including Scopus, ScienceDirect, and Google Scholar. An earlier review of the geoheritage research landscape [101] identified a significant body of work across the broader Moroccan region. Initial research indicated that most studies focused on the Atlas region and paid little attention to earthquakes or the concept of “dark geoheritage.” This table offers an updated and comprehensive summary of geoheritage research, building upon previous evaluations [101].

Authors (Year)	Title	Major Findings
Enniouar et al. (2014) [75]	A Middle Jurassic Sauropod Tracksite in the Argana Basin, Western High Atlas, Morocco: An Example of Paleoichnological Heritage for Sustainable Geotourism	The authors highlight the significant scientific and tourist importance of a Middle Jurassic site in the Tafaytour region (Argana Basin, Morocco) that contains tracks of six large sauropod dinosaurs, as well as its potential to enhance local geotourism initiatives.
Bourchich et al. (2015) [102]	Geotourism in Ida Outananes, Moroccan Western High Atlas: State of Valuation and Opportunity for Improvement	The assessment of the Ida Outanane area indicates deterioration that jeopardizes its Geosystems, Ecosystems, and tourist appeal. This decline is attributable to the opening of the area to tourism without a management plan that integrates geopreservation efforts with sustainable funding.
Bouzekraoui et al. (2018a) [82]	Inventory and Assessment of Geomorphosites for Geotourism Development: A Case Study of Aït Bou Oulli Valley (Central High-Atlas, Morocco)	The project entailed inventorying, selecting, and quantitatively evaluating outstanding geomorphosites to classify them. The findings identify 81 potential sites, of which 24 are appropriate for geotourism. These suitable locations comprise nine fluvial landforms—five offering scenic vantage points and four being karst forms—along with four structural landforms, three glacial landforms, two gravity landforms, one anthropogenic landform, and one lacustrine landform.
Bouzekraoui et al. (2018b) [81]	Mapping Geoheritage for Geotourism Management, a Case Study of Aït Bou Oulli Valley in Central High-Atlas (Morocco)	This study focuses on creating a new geotourism map of the Aït Bou Oulli Valley through digital mapping tools and fieldwork. The map features geosites and high-mountain landscapes, providing an overview of the valley’s geoheritage. It also includes information about tourist infrastructures to assist visitors. Additionally, the map emphasizes the valley’s geodiversity and aims to promote geotourism by establishing three new geo-hiking trails.

Table 1. *Cont.*

Authors (Year)	Title	Major Findings
Bouzekraoui et al. (2018c) [80]	Mapping Geosites as Gateways to the Geotourism Management in Central High-Atlas (Morocco)	This article outlines three geotourism routes showcasing the key geosites in the rural Demnate and Upper Tessaout valleys. These itineraries help explain the regions' significant potential as tourist attractions.
Achkir (2018) [103]	An Asset for Integrated Geotourism (Case of Assif Melloul Crossing (Common Territorial of Anergui and Tillouguite) in the Province of Azilal; Béni Mellal-Khénifra-Region/Morocco)	This article reports the initial findings from a survey of geomorphosites in the rural communes of Anergui and Tillouguite. It also seeks to improve strategies for the protection, promotion, and management of these geomorphosites, with the aim of integrating them into sustainable development. This approach offers new incentives and opportunities for sustainable tourism, positioning geo-tourism as a leading frontier.
Amine et al. (2018) [76]	Inventory and Management of Dinosaurs Traces: A Case Study of Azilal Region, Morocco	This work contributes to the preservation and promotion of dinosaur-track deposits by detailing the geology and geomorphology of the Azilal area, developing Geographic Information Systems (GIS) maps, and proposing models for their enhancement and protection.
Ait Omar et al. (2019) [83]	Nouvelle Méthodologie d'inventaire et D'évaluation des Géomorphosites dans le Contexte du Géoparc M'goun (Maroc)	This article presents a new methodology for inventorying and assessing geomorphosites within the M'goun Regional Geopark. The approach was tested on two geomorphosites—Ain Asserdoune and Canyon Moudj—located within the geopark, specifically south of the town of Béni Mellal in Morocco.
Amine et al. (2020) [77]	Dinosaurs Footprints of the High Atlas Morocco by Using Geological Heritage Information System	This work contributes to the preservation and protection of dinosaur track deposits by using geographic information to describe and map the study area and, ultimately, to propose models for the development and conservation of these geosites.
Arrad et al. (2020a) [92]	From Geoheritage Inventory to Geoeducation and Geotourism Implications: Insight from Jbel Amsittene (Essaouira Province, Morocco)	This document presents an initial, detailed analysis of Jbel Amsittene's geoheritage, combining quantitative and qualitative evaluations of its geological and geomorphological sites to highlight their significance and support geoconservation efforts.
Arrad et al. (2020b) [91]	Inventory, Evaluation, and Promotion of the Essaouira Province Geoheritage (Morocco): Toward a Local and Socio-Economic Sustainable Development	This work aims to inventory, assess, and promote key geodiversity features in Essaouira that remain unknown or underutilized for conservation and development.
Lkebir et al. (2020) [78]	The Anza Tracksite: Ichnological Heritage and Geoeducational Significance of Dinosaur and Pterosaur Tracks in Coastal Morocco	The authors highlight the scientific, geo-educational, and ichnological significance of the Anza site and emphasize the need for a strategy to conserve and safeguard it.
Rais et al. (2021) [104]	Geological Heritage in the M'Goun Geopark: A Proposal of Geo-Itineraries Around the Bine El Ouidane Dam (Central High Atlas, Morocco)	This work seeks to identify and select exceptional geosites within the Bine El Ouidane Lake region and to propose itineraries that promote this mountainous area.
El Alami et al. (2021) [105]	Biodiversity, An Essential Component for The M'Goun Global Geopark Development (Morocco)—An Overview	This article aimed to assess the inventory and development of geosites, wildlife diversity, biodiversity conservation, human–carnivore conflict, and the management of endangered species in the M'goun Global Geopark within Morocco's central High Atlas.
Elkaichi et al. (2021) [106]	Quantitative Assessment of the Geodiversity of M'Goun UNESCO Geopark, Central High Atlas (Morocco)	This article quantitatively evaluates geodiversity in the M'Goun UNESCO Geopark through two approaches. Both methods reveal the richness and spatial distribution of geodiversity elements within the geopark. Additionally, they identify areas with high geodiversity indices, offering useful insights for geopark managers to develop effective geoconservation strategies.

Table 1. Cont.

Authors (Year)	Title	Major Findings
Ait Omar et al. (2021) [84]	Les Géopatrimoines de la Partie Nord-Est du Géoparc Régional du M’Goun (Maroc): Représentations Sociales et Valorisation Géotouristique	This article aims to identify geosites with strong social reputations in the northeastern part of the M’Goun Regional Geopark, based on a questionnaire survey that elicited local stakeholders’ social perceptions. The identified geosites have also been assessed. Additionally, the study examines the role of local associations in promoting geotourism and geoconservation.
Ait Barka et al. (2022a) [107]	The Geosite of Travertine Waterfall of El Ksiba (Morocco), A Heritage to Enhancement and Preserve	In this work, the authors outlined strategies to boost and safeguard the El Ksiba travertines as a part of rural socio-economic development, focusing on geotourism and geoeducation initiatives.
Ait Barka et al. (2022b) [108]	The Karst Landscapes of Beni Mellal Atlas (Central Morocco): Identification for Promoting Geoconservation and Tourism	The authors detail the study area’s wide variety of karst features and processes, including caves, dolines, underground watercourses, and Karren, along with its biological and cultural diversity. This region has strong potential to develop into an appealing area and a significant economic resource for the local community through sustainable development.
Louz et al. (2022) [86]	Geological Heritage of the Taguelft Syncline (M’Goun Geopark): Inventory, Assessment, and Promotion for Geotourism Development (Central High Atlas, Morocco)	This study seeks to document and assess the geological heritage of the Taguelft syncline, located south of Béni Mellal, and to promote geotourism and geodidactic initiatives to support its sustainable geoconservation.
Ait Omar et al. (2022a) [85]	A Quantitative method for Inventory and Assessment of Geoheritage in the Mountains of Morocco: A Case Study of the Tagleft Syncline in Beni Mellal Atlas	The paper introduces a quantitative approach for identifying and assessing geological and geomorphological sites, applied specifically to the Tagleft syncline in the Beni Mellal Atlas, Morocco.
Ait Omar et al. (2022b) [109]	Contribution of Social Perception for Identifying Geomorphological Potential and Touristic Practices in the North-Eastern part of the M’Goun Regional Geopark, Morocco	The paper introduces a quantitative approach for identifying and assessing geological and geomorphological sites, applied specifically to the Tagleft syncline in the Beni Mellal Atlas, Morocco.
Aichi et al. (2022a) [110]	Cultural Heritage in Imghranes Massif (Drâa-Tafilalet Region, Morocco): An Optimist’s Contribution and Opportunity for the Local People and Sustainable Tourism	The authors highlight the rich geological, archaeological, and cultural heritage of the Imghranes massif (Drâa-Tafilalet region, Morocco), emphasizing its potential for geotourism, geoeducation, and cultural tourism.
Aichi et al. (2022b) [111]	From Geoheritage to Geoeducation and Geotourism: The Imghranes Massif, Drâa-Tafilalet Region, Morocco	This work presents the first detailed analysis of geoheritage in the Imghranes area of the central High Atlas of Morocco. It includes both quantitative and qualitative evaluations of its geosites and geomorphosites to highlight their significance and support geoconservation efforts.
Bussard et al. (2022) [112]	Les Paysages Géomorphologiques du Haut Atlas Central (Maroc): Potentiel Educatif et Éléments pour la Médiation Scientifique	This article explores the educational opportunities offered by the eight geomorphological landscapes within the M’Goun UNESCO Global Geopark in the Central High Atlas, Morocco.
Bussard (2022) [93]	Heritage Value and Didactic Potential of Geomorphological Landscapes: the Case of Eight Sites in the Central High Atlas (Morocco)	The authors highlight the educational value of eight geomorphological landscapes within the M’Goun Geopark (Central High Atlas, Morocco). These sites are of significant scientific interest and have the potential to promote geotourism.

Table 1. Cont.

Authors (Year)	Title	Major Findings
Bussard (2023) [94]	Geomorphological Landscapes of the M’Goun Geopark (Morocco): Potential for Geotourism and Local Guides’ Perspective	This study explores the potential for geotourism within the geomorphological landscapes of the M’Goun Global Geopark, Morocco. It emphasizes site selection based on educational value and local guides’ perspectives. Eight key landscapes are identified for interpretation, considering their visibility and complexity. Interviews with guides reveal a strong interest in geomorphology and palaeontology, despite limited familiarity with specific geological terms. The findings stress the crucial role of guides in conveying geological information and highlight the need for effective interpretation methods to boost geotourism.
Elkaichi et al. (2023) [96]	Evaluation of Geotouristic Station Suitability Using GIS-Based Multi-criteria Decision Analysis: A Case Study of the M’Goun UNESCO Geopark, High Atlas (Morocco)	The study employs a multi-criteria decision-making approach that integrates AHP and GIS to identify suitable sites for geotourism stations within the M’Goun UNESCO Geopark. It assesses natural features, landscape quality, and safety factors, creating a synthesis map that supports local authorities in planning and managing geotourism activities in the geopark.
El Khalki et al. (2023) [113]	M’Goun UNESCO Geopark (Central High Atlas, Morocco), a Lever for Sustainable and Integrated Territorial Development: What Approach to Adopt?	This study aims to highlight Morocco’s rich geodiversity and to explore the potential for establishing geoparks to enhance geotourism, environmental awareness, and local socioeconomic development. It highlights the M’Goun UNESCO Geopark as a prime example of sustainable regional development, showing how geoparks can foster economic growth, generate employment, and support traditional crafts. As Africa and the Arab world’s first geopark, M’Goun exemplifies how geopark initiatives can benefit rural and mountain communities through integrated geotourism strategies.
Louz et al. (2023) [87]	Inventory and Assessment of Geosites and Geodiversity Sites of the Ait Attab Syncline (M’Goun Unesco Geopark, Morocco) to Stimulate Geoconservation, Geotourism and Sustainable Development	The Ait Attab syncline in the Moroccan Central High Atlas is a region of high geodiversity, with substantial geological, palaeogeographical, and cultural significance. An inventory identified 8 geosites and 11 geodiversity sites, emphasizing their scientific and educational value and potential for geotourism development. Most sites are subject to medium degradation risk, while palaeontological and magmatic sites are at high risk.
Si Mhamdi et al. (2023) [95]	Enhancing the Geological Heritage of the Errachidia Area in the High Atlas, Morocco: Inventory and a Proposal for a Pedagogic and Geotouristic Trail	The study introduces a pedagogical and geotouristic trail in Errachidia province, Morocco, renowned for its geological formations and mineral resources. It highlights nine important geosites, encompassing structural, stratigraphic, paleontological, and geomorphological features, each offering considerable scientific, educational, and tourism benefits. The trail’s goal is to boost education and tourism via guided walks and informational signage, while fostering geotourism and supporting local socio-economic growth.
Bouzekraoui et al. (2024) [114]	La Carte Géotouristique des Communes de Foug El Ancer et Taghzirt Comme Moyen de Valorisation Géotouristique, Atlas de Béni Mellal, (Maroc)	This study examines the geotourism potential of the communes Foug El Ancer and Taghzirt in Béni Mellal province, situated at the base of the Middle Atlas. It identifies multiple geosites formed through magmatic, sedimentary, structural, and geomorphological processes. The goal is to develop a geotourism map that showcases and promotes these geosites, which hold considerable promise for boosting geotourism and enhancing the region’s geoheritage and tourism development.
Elkaichi et al. (2024) [97]	Canyons as Potential Geotourism Attractions of Central High Atlas, Morocco: Comparative Analysis of Aït Bouguemaz Valley and Zaouiat Ahnsal-Taghia valley by Using GAM Model	The study evaluates two popular geo-destinations in the Moroccan Central High Atlas: Aït Bouguemaz and Zaouiat Ahnsal-Taghia valleys, using the Geosite Assessment Model (GAM). Aït Bouguemaz shows high principal scores (9.75) and moderate additional scores (8.25), while Ahnsal-Taghia has moderate principal scores (8) and lower additional scores (5.25). Despite their strong scientific and aesthetic appeal, both sites require improvements in functional and tourism-related aspects, particularly in management, planning, and infrastructure, to enhance geotourism.

Table 1. Cont.

Authors (Year)	Title	Major Findings
Naimi et al. (2024) [98]	Leveraging Machine Learning Algorithms to Identify Potential Geosites for Geotourism Promotion in Ziz Upper Watershed in Southeastern Morocco	This study aims to identify the optimal locations for geomorphosites in the Ziz Upper Watershed (ZUW), southeastern Morocco, using machine learning classifiers (MLCs) to enhance geotourism. A detailed inventory of 120 geomorphosites was compiled, and the Bagging algorithm was used to create a predictive model with an AUC of 0.935. The model identified highly suitable areas covering approximately 12% of the region, primarily in the western part, with mountainous terrain and high elevations. These results provide useful insights for decision-makers to enhance the discovery of geomorphosites and promote geotourism development.
Ouacha et al. (2024) [115]	Geological Sites of the Anergui Region: Description and Place in the Alpine Geological History of the M’Goun UNESCO Global Geopark (Morocco)	This study details 16 key geosites within the M’Goun UNESCO Global Geopark in Morocco, emphasizing their scientific, educational, and geotourism importance. These sites highlight the region’s geodiversity and provide insights into major geological phases, including the extension of the High Atlas basin, carbonate platform formation, magmatic activity, and uplift during the Tertiary and Quaternary periods. The objective is to enhance the geopark’s collection of geosites and foster greater geological awareness locally.
Wakass et al. (2025) [116]	Geosites of High Atlas of Marrakech (Morocco): Geological Characterization, Accessibility, and Potential Interests for Sustainable Tourism	This study reviews four potential geosites in Morocco’s High Atlas, emphasizing their geological features, historical significance, and accessibility. The sites, such as Toubkal National Park and Ifni Lake, are reachable via well-maintained roads and are equipped with tourism amenities. The study suggests additional research to better develop the geosites for sustainable tourism.
El Ouali et al. (2025a) [90]	Geosites and Geodiversity Sites of the Tinghir–Dades–Imilchil Area, Morocco: Toward Conservation, Education, and Tourism Development	The research examined 25 geological sites in the Tinghir–Dades–Imilchil region, emphasizing their scientific, educational, and tourism value. The assessment aimed to encourage geotourism and environmental awareness, focusing on preserving and enhancing the area’s geological heritage to support sustainable growth.
El Ouali et al. (2025b) [89]	Quantitative Assessment and Enhancement of 12 Sites of Geological Interest South of Midelt City (Tizi N’Talghemt, Central High Atlas, Morocco)	This research highlights twelve geological sites in the Tizi N’Talghemt region of Morocco’s Central High Atlas, focusing on their scientific, educational, and tourism value. It identifies four Geosites with high scientific importance and eight Geodiversity sites with notable potential. The study stresses the importance of safeguarding these sites and aligns with the Moroccan National Program for Geology MNPG-2030 and UNESCO guidelines to conserve the region’s geological heritage and support sustainable development.
Louz et al. (2025) [88]	Identification of Potential Areas for the Development of Geotourism in the Northern Part of the M’Goun Geopark (Morocco) Using Multi-Criteria Analysis and Sig	The study evaluates the geotourism potential of the unexplored portion of the M’Goun Regional Geopark in the Moroccan High Atlas using GIS and AHP. It identifies key geosites with high potential, such as the Ouzoud waterfalls and the Ait Attab syncline, thereby emphasizing regions with notable geodiversity. The findings provide a strategic guide for advancing geotourism and effectively managing the geopark.
Elfaiz et al. (2025) [117]	Inventory and Assessment of the Geoheritage Potential of the Imilchil District (Central High Atlas, Morocco)	The Imilchil region in the Moroccan Central High Atlas is renowned for its diverse geology, hydrogeology, and geomorphology, and features notable geosites, including dinosaur fossils and magmatic rocks. The study underscores the area’s scientific, educational, and tourism significance and emphasizes the need for a preservation plan to safeguard these geosites from potential deterioration.
Kchikach et al. (2025) [100]	Digital Promotion of Geoheritage Along a Tourist Route in M’Goun UNESCO Geopark (Central High Atlas, Morocco) and Visitor Typology Analysis	This study assesses the tourism potential of the M’Goun UNESCO Global Geopark in Morocco’s central High Atlas, employing an experiential approach to evaluate the area’s natural heritage. It highlights five main factors influencing destination choice and categorizes four different visitor groups based on statistical analysis. An interactive map was developed and shared online to showcase the region’s geoheritage. The results are intended to support tourism management by enabling local authorities to more effectively allocate resources and plan land use.

Table 1. Cont.

Authors (Year)	Title	Major Findings
Manaouch et al. (2025) [99]	Enhancing Geotourism in Southeastern Morocco Through Machine Learning-Based Geomorphosite Identification	The study assesses three machine learning classifiers—Random Forest, Multi-Layer Perceptron, and M5 Prime—aimed at mapping potential geomorphosites in Ziz, southeast Morocco, to promote geotourism. After cataloging 120 geomorphosites, the Multi-Layer Perceptron outperformed the other models, achieving an area under the curve of 0.91. It identified highly suitable regions, covering 60% of the area, mostly in the western mountainous zone. This research provides a useful tool for decision-makers, facilitating the discovery of geomorphosites while saving time and reducing costs.
Ait Haddou et al. (2025) [79]	Late Carboniferous Paleoflora of El Menizla Formation (Argana Corridor, Morocco): Implications for Geotourism and Geoconservation	This research explores the Late Pennsylvanian paleoflora of the El Menizla Formation in Morocco’s Argana Corridor, indicating a warm, humid environment with seasonal dryness. The fossil collection holds significant scientific, educational, and touristic importance, enhancing the site’s prospects for geotourism and geoconservation. The El Menizla area is proposed as a central feature of a geopark, fostering geological heritage and supporting local communities.

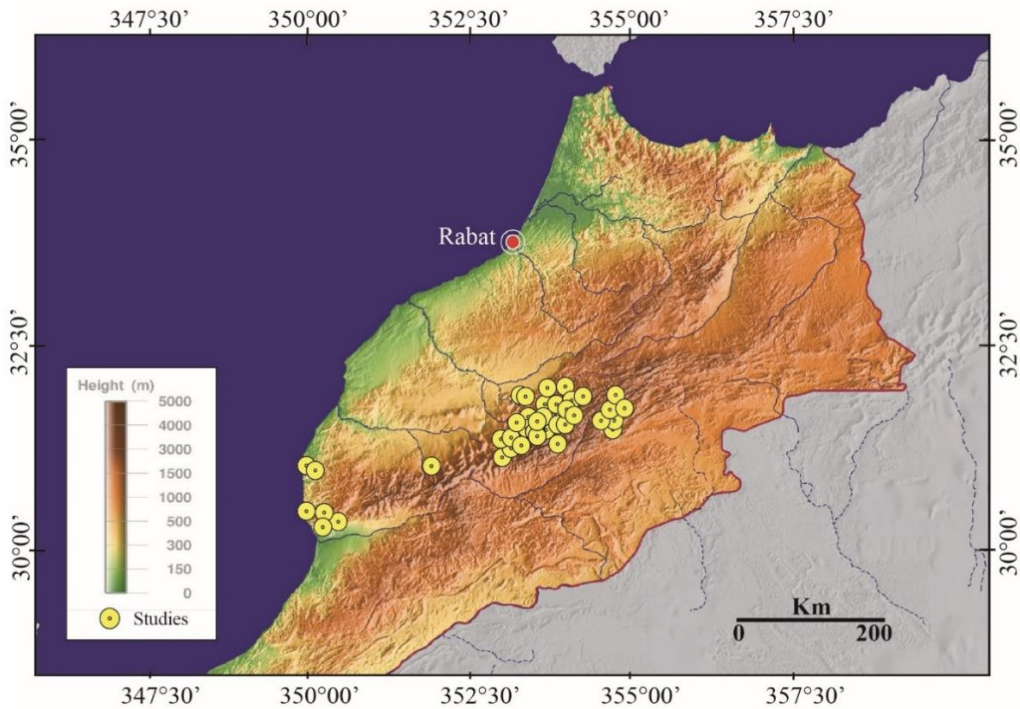


Figure 5. Spatial distribution of peer-reviewed geodiversity and geoheritage studies conducted in the Moroccan High Atlas, based on a review of international academic databases (Scopus, ScienceDirect, and Google Scholar).

4.2. The 2023 Al Haouz Earthquake: Processes and Impacts

On 8 September 2023, at 11:11 p.m. local time, a severe earthquake struck the High Atlas Mountains near the town of Oukaïmedene in western Morocco, with its epicenter located in the rural commune of Ighil, approximately 72 km southwest of Marrakech (Figure 6). This seismic event, locally known as the Al Haouz earthquake, represents the strongest instrumentally recorded earthquake in Morocco to date, with a magnitude of 6.8–7.2 and a focal depth estimated between 10.7 and 27 km depending on the reporting agency (USGS, EMSC, Moroccan National Institute of Geophysics). A significant aftershock of Mw 5.7 occurred twenty minutes later, followed by a series of smaller aftershocks that characterized the post-seismic sequence.

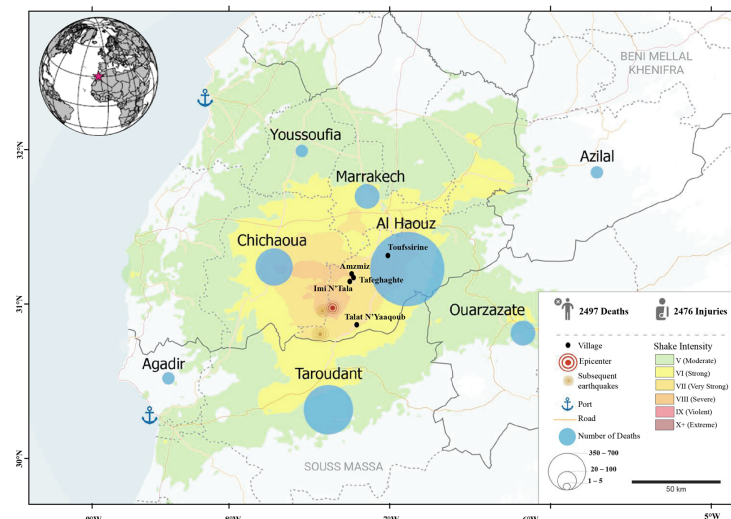


Figure 6. Macroseismic intensity map of the Mw 6.8 Al Haouz earthquake. Modified from USGS (<https://earthquake.usgs.gov/earthquakes/eventpage/us7000kufc/dyfi/intensity>) (accessed on 25 September 2025). The map illustrates the spatial pattern of shaking intensities (MMI V to X+), together with the epicenter, subsequent earthquakes, and the most affected villages. Circle sizes represent the number of reported fatalities in each province, with a total of 2497 deaths and 2476 injuries across the region.

The earthquake struck a region traditionally considered low-seismicity, making it one of the deadliest natural disasters in Morocco in decades [118–123]. The epicentral provinces most affected included Al Haouz, Taroudant, Chichaoua, Marrakech, and Ouarzazate. The event resulted in approximately 2946 fatalities, over 5500 injuries, and damage or destruction to around 60,000 houses, including 580 schools, displacing more than 500,000 people (Figure 7). Significant damage was reported in the historic Medina of Marrakech, a UNESCO World Heritage site (<https://whc.unesco.org/en/list/331>, accessed on 30 December 2025), with many traditional adobe and masonry structures affected, including cracks in the Koutoubia and Kasbah mosques (Figure 7). Despite the destruction, some structures, such as the Koutoubia minaret, remained standing due to reinforcement measures like steel and timber bracing. The Al Haouz earthquake occurred along a north-dipping high-angle fault, part of an orogen-scale WSW–ESE transpressional shear zone in the High Atlas. The region’s tectonic evolution is primarily governed by oblique convergence of tectonic plates, while asthenospheric upwelling plays a minor role. The rupture extended unusually deep, reaching up to 25 km, beyond typical seismogenic depths, and produced intense shaking with a maximum macroseismic intensity of MMI IX in the epicentral area, gradually decreasing to MMI VI–VII in Marrakech ([124]; <https://earthquake.usgs.gov/earthquakes/eventpage/us7000kufc/dyfi/intensity>) (accessed on 25 September 2025). Ground deformation included tectonic uplift of up to 20 cm along the axial zone due to reactivation of compressive faults, low-displacement gravitational movements on medium to steep slopes composed mainly of Paleozoic and Upper Cretaceous rocks, and rapid gravitational movements, including rockfalls, cliff collapses, and boulder falls, particularly in metamorphic, magmatic, and limestone formations. The complex geological structure and rugged topography amplified seismic effects. Steep slopes, ridgelines, and fractured rock masses contributed to localized focusing of seismic energy, while sedimentary basins and resonance effects increased ground motion in some areas. The spatial distribution of landslides and rockfalls was strongly influenced by slope geometry, fault density, and rock mass fragmentation. The earthquake caused widespread structural damage, particularly in rural settlements at the foothills of the High Atlas, such as Amizmiz, Tafeghaghte, Toufssirine, and Talat N’Yaaqoub (Figures 6 and 7). Satellite

and field observations reveal extensive destruction, including nearly complete levelling of villages like Tafeghaghte and Imi N'Tala (Figure 6), where rockfalls caused more than 80 fatalities. In urban areas such as Marrakech, damage patterns included collapse or overturning of façade walls, exacerbated by weak interfaces between adobe and stone masonry, cracks along walls and arches in historic mosques, including Koutoubia and Kasbah mosques, often stabilized with steel and timber bracing, and damage to minarets due to their slender structure, leading to vertical and sub-horizontal cracking at the interface with mosque structures. The earthquake triggered numerous co-seismic gravitational movements, with failure mechanisms controlled by high slope gradients that increase downslope forces. These fractured and weak lithologies facilitate the detachment of rock blocks and topographic amplification, which focus seismic energy along ridges and slopes (Figure 8). Mapping these movements using slope analysis, fault networks, and field inventories revealed that most failures initiated near ridgelines and fault intersections, highlighting the interplay between the morpho-structural setting and the distribution of seismic energy. These observations are consistent with prior studies linking seismic shaking, slope instability, and landslide hazard in high-relief terrains [123–129].

4.3. Geoheritage Significance of the 2023 Al Haouz Earthquake

The 2023 Al Haouz earthquake constitutes a landmark event in the geoheritage history of the High Atlas, serving as both a powerful geological agent and a catalyst for the creation, modification, and destruction of geosites. With a shallow focal depth of 15–35 km [119,122,130,131] below the surface and a magnitude estimated between Mw 6.8 and 7.2, the earthquake generated a suite of co-seismic deformations that left permanent, clearly identifiable imprints on the landscape. Surface ruptures extending for more than 25 km, widespread landslides, catastrophic rockfalls, cliff collapses, and pervasive ground cracking now form a unique archive of seismic processes within a high-relief, tectonically active environment (Figure 8). These newly formed features—ranging from large landslide scars on steep Paleozoic slopes to displaced limestone blocks and uplifted strata along reactivated fault zones—illustrate the dynamic interplay between tectonics, topography, and lithology, providing rare direct evidence of earthquake mechanics expressed at the Earth's surface. Beyond their immediate geomorphological and scientific significance, these elements carry profound implications for geoheritage. The earthquake has generated new landforms that enrich the geomorphological diversity of the region, creating tangible case studies for understanding slope instability, co-seismic mass movement, and post-seismic landscape evolution [127,132–135]. At the same time, it has altered or partially obliterated pre-existing geosites, underscoring the intrinsic fragility and non-renewable nature of geological heritage. Historical terraces, minor fault scarps, geomorphological micro-forms, and cultural–geological sites that once formed part of the local geoheritage have been displaced, buried, or erased, as also documented in other major seismic events such as the damage to cultural heritage sites following the 6 February 2023 Kahramanmaraş earthquakes in southeastern Türkiye and the loss of historic structures and landscape features in the Hatay Province after the same sequence of earthquakes, highlighting the urgent need for rapid field documentation and heritage assessment in the aftermath of seismic disasters. The scientific value of the Al Haouz event is further amplified by the preservation of seismic signatures across the landscape. The spatial pattern of landslides, rockfalls, and ruptures closely corresponds to structural lineaments, lithological contrasts, and intensely fractured zones. The catastrophic failure at Imi N'Tala—where massive Upper Cretaceous limestone blocks collapsed, resulting in more than 80 fatalities—illustrates how high-relief, structurally complex terrains can record and amplify seismic energy, leaving highly diagnostic sedimentological and structural evidence. Such preserved features constitute an excep-

tional natural laboratory for studying earthquake-triggered gravitational processes, fault kinematics, and slope responses. Notably, the earthquake also triggered hydrogeological changes, adding a new dimension to its geoheritage significance. According to official reports presented to the Infrastructure, Energy, Mines and Environment Committee of the House of Representatives, notable variations were observed in groundwater discharge following the event [136]. Some springs showed increased flow, others decreased, and—most remarkably—new water sources appeared. Remote sensing analysis conducted in coordination with the Royal Centre for Space Remote Sensing identified 69 newly formed springs, distributed across the provinces of Al Haouz (32), Taroudant (19), Ouarzazate (10), and Chichaoua (8) [136] (Figure 9). These hydrogeological responses reveal how seismicity can reorganize subsurface water pathways, fracture permeability, and aquifer connectivity, creating new hydrological geosites that enrich the region’s geoheritage. The 2023 Al Haouz earthquake thus highlights the dual nature of seismic events: while highly destructive to buildings and cultural heritage, they simultaneously generate new natural features and scientific opportunities. Fault traces, uplifted terrains, landslide complexes, hydrological anomalies, and newly emergent springs now form part of the region’s non-renewable geoheritage, demanding careful conservation and long-term monitoring. Integrating these features into geoeducation initiatives, geotourism circuits, risk-awareness programs, and scientific research can deepen public understanding of seismic hazards and Earth dynamics, while preserving the memory and lessons of this transformative event. Ultimately, the Al Haouz earthquake demonstrates that seismic disasters are not only agents of destruction but also potent creators of geological knowledge and landscape heritage, leaving behind a legacy of features that are scientifically valuable, educationally enriching, and culturally meaningful.

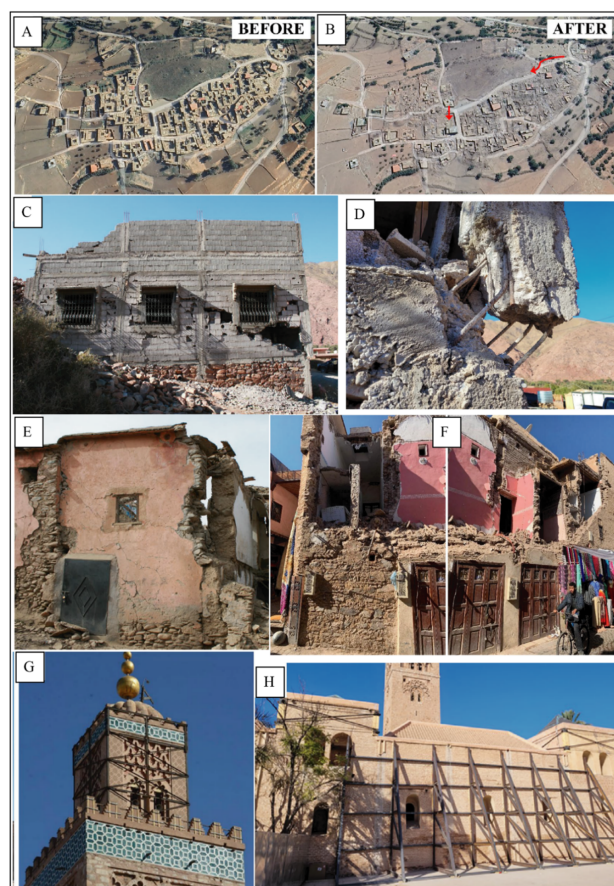


Figure 7. (A,B) Google Earth images showing the Tafeghaghte area ($31^{\circ}11'48.16''$ N, $8^{\circ}13'26.02''$ W) before (28 December 2022) and after the 2023 Al Haouz earthquake (9 September 2023), with visible

zones of widespread structural damage. (C) Severely damaged façade of a hybrid reinforced-concrete-masonry building in Talat N'Yaaqoub ($30^{\circ}59'31.28''$ N, $8^{\circ}11'2.32''$ W). (D) Close-up view of the shear failure affecting reinforced-concrete pillars at the corner of the same structure. (E) Typical vernacular stone-masonry buildings exhibiting extensive cracking and partial collapse in Amizmiz ($31^{\circ}12'53.06''$ N, $8^{\circ}14'48.87''$ W). (F) Out-of-plane collapse of a traditional façade in the Medina (center) of Marrakech ($31^{\circ}37'53.004''$ N, $7^{\circ}59'12.012''$ W). (G) Emergency stabilization interventions at the top of a minaret in Marrakech, and (H) Temporary perimeter bracing was installed around the Koutoubia Mosque to prevent further structural deterioration following the earthquake ($31^{\circ}37'28''$ N, $7^{\circ}59'35''$ W). (All images adapted from [134].

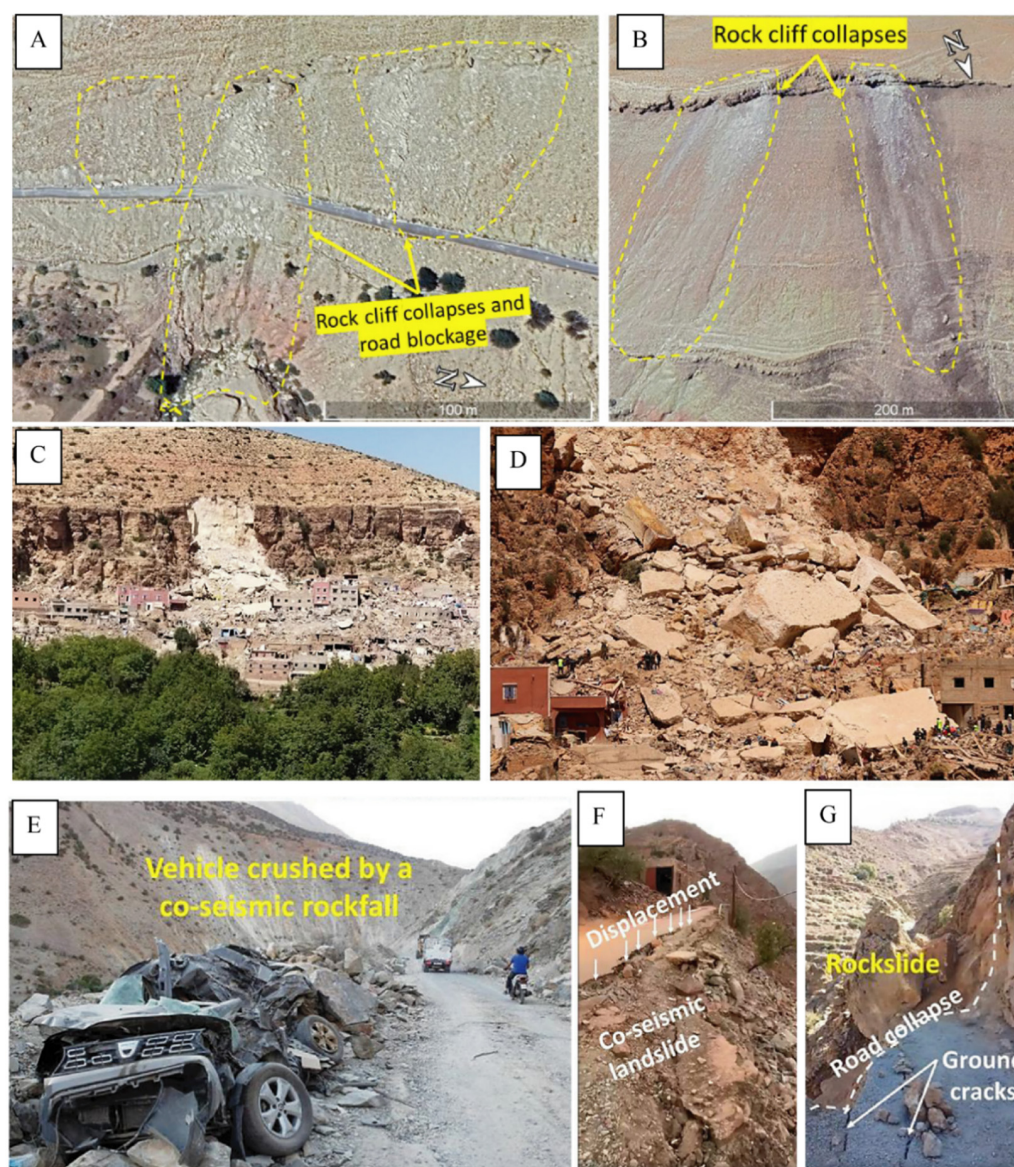


Figure 8. Examples of rockfalls and rock collapses triggered by the 2023 Al Haouz earthquake [127]. (A,B) Google Earth imagery (19 September 2023, ten days after the event) showing cliff collapses, including a major failure blocking the road near Ighermene village, Chichaoua Province ($31^{\circ}8'58.71''$ N; $8^{\circ}26'7.50''$ W) and large-scale rock detachments along adjacent slopes ($31^{\circ}9'11.79''$ N; $8^{\circ}23'57.78''$ W). (C,D) Complete destruction of the village of Imi N'Tala ($31^{\circ}7'44.85''$ N; $8^{\circ}16'4.30''$ W) caused by the catastrophic collapse of massive Upper Cretaceous limestone blocks, which resulted in over 80 fatalities. (E) Co-seismic rockfall crushed a vehicle along the Talat N'Yaaqoub road. (F) Co-seismic landslide with lateral displacement and associated rockfalls in the Ighil commune. (G) Rockslide, ground cracking, and road collapse in Idaghassen village.

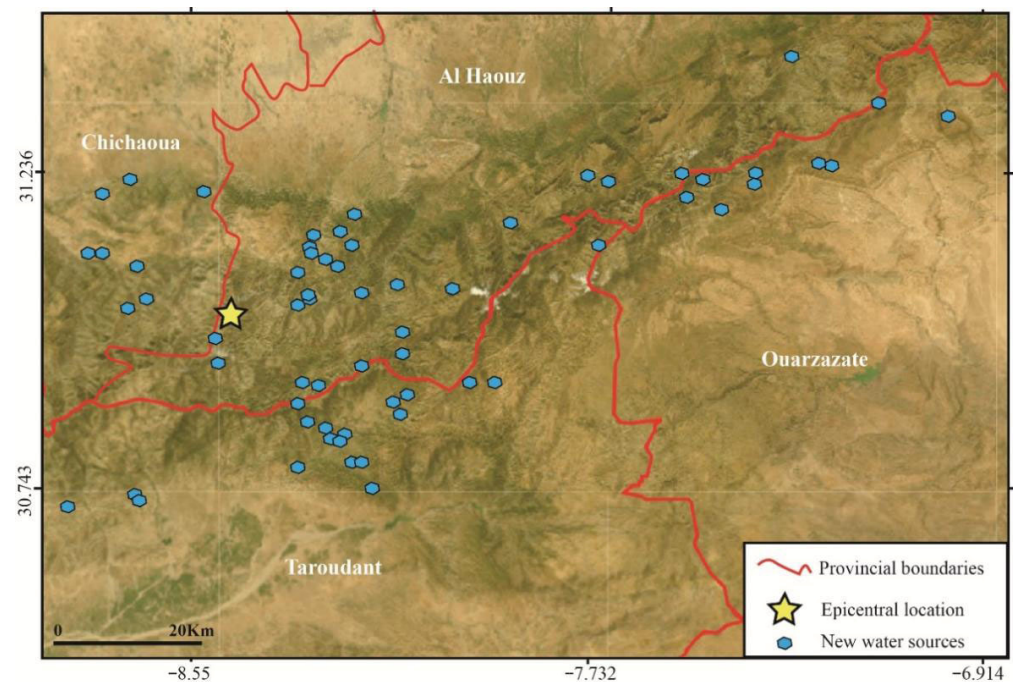


Figure 9. Spatial distribution of newly emerging water sources reported after the Mw 6.8 Al Haouz earthquake. Blue markers indicate locations where springs or water discharge increased or newly appeared, as documented by the Moroccan Ministry of Equipment and Water. The yellow star marks the epicentral location, and red lines delineate provincial boundaries. Modified from SNRT News (2023) [136].

5. Discussion

5.1. Challenges for Documentation, Access, and Preservation

The 2023 Al Haouz earthquake has highlighted significant challenges in documenting, accessing, and preserving the newly formed and modified geoheritage of the High Atlas. One of the foremost challenges is the rapid pace of landscape change (Figure 10). The earthquake triggered widespread landslides, rockfalls, and surface ruptures, many of which continue to evolve under gravitational forces, rainfall, and seasonal weathering. This dynamic environment makes it difficult to capture accurate, long-term records of co-seismic features before they are altered or erased. The urgency of documenting these geological features is heightened by their fragility and non-renewable nature, which can lead to their loss before systematic study is undertaken.

The mountainous and rugged terrain of the High Atlas presents another substantial barrier. Many of the most dramatic earthquake-induced features, including fault scarps, cliff collapses, and landslide deposits, occur on steep slopes, narrow valleys, and remote ridgelines (Figure 10). Accessing these areas safely requires specialized equipment, local knowledge, and significant logistical effort. In several cases, villages such as Tafeghaghte, Talat N'Yaaqoub, and Imi N'Tala are in topographically challenging areas that are heavily affected by structural damage, complicating field surveys and site verification.

Technical limitations in monitoring and documenting these changes also constrain effective geoheritage preservation. While tools such as satellite imagery, drones, and DInSAR analysis provide powerful means of capturing surface deformation and slope movements, they may lack the resolution or temporal frequency needed to detect small-scale landslides, fractures, or rockfall deposits (Figures 11–13). Ground-based surveys, while more precise, are labor-intensive and constrained by accessibility and safety risks. The combination of technical and logistical limitations underscores the need for integrated, multi-method approaches to earthquake geoheritage documentation.

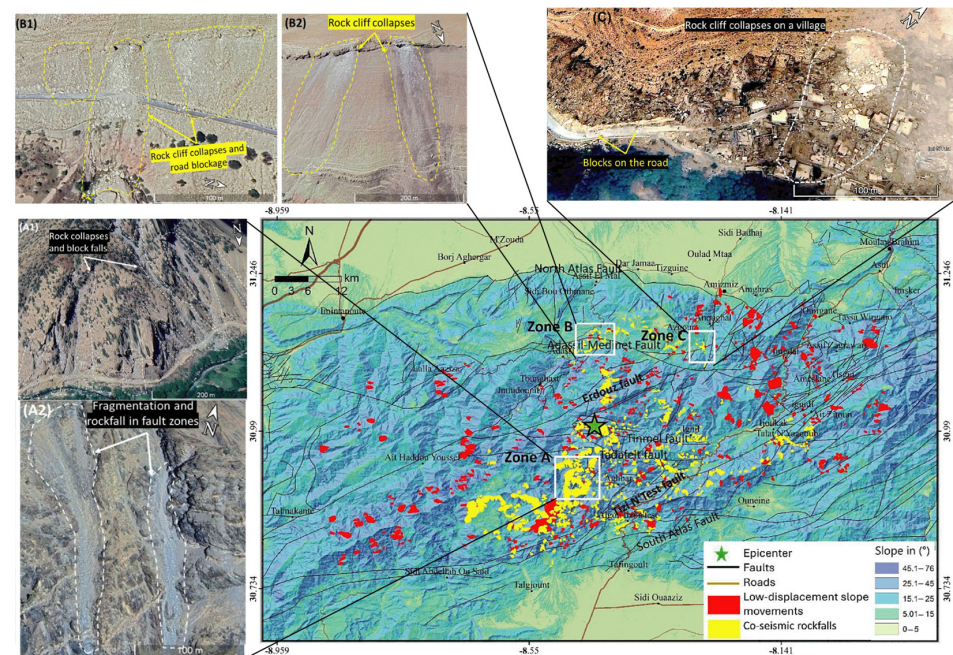


Figure 10. Spatial distribution map of rockfalls and low-displacement slope movements induced by the Al Haouz earthquake, overlaid on a background representing the relief, slope, and main fault network of the region [127]. Examples of rockfalls and rock collapses triggered by the Al Haouz earthquake, observed in Google Earth images dated 19 September 2023, 10 days after the earthquake. (A1) Rockfalls and collapses in the rural commune Aghbar (Lat = $30^{\circ}53'32.77''$ N; Long = $8^{\circ}29'20.09''$ W); (A2) Rockfalls in a fault zone (Lat = $30^{\circ}54'41.75''$ N; Long = $8^{\circ}28'11.13''$ W); (B1) Cliff collapse blocking the road near Ighermene village, Chichaoua province (Lat = $31^{\circ}8'58.71''$ N; Long = $8^{\circ}26'7.50''$ W); (B2) Cliff collapse (Lat = $31^{\circ}9'11.79''$ N; Long = $8^{\circ}23'57.78''$ W). The tragic co-seismic collapse of massive rock formations onto the village of Imi N'Tala (zone c, Lat = $31^{\circ}7'44.85''$ N; Long = $8^{\circ}16'4.30''$ W), resulting in the deaths of more than 80 people; (C) Google Earth image taken only five days after the earthquake on 14 September 2024, showing the total destruction of the village caused by the collapse of Upper Cretaceous limestone formations at Imi N'Tala.

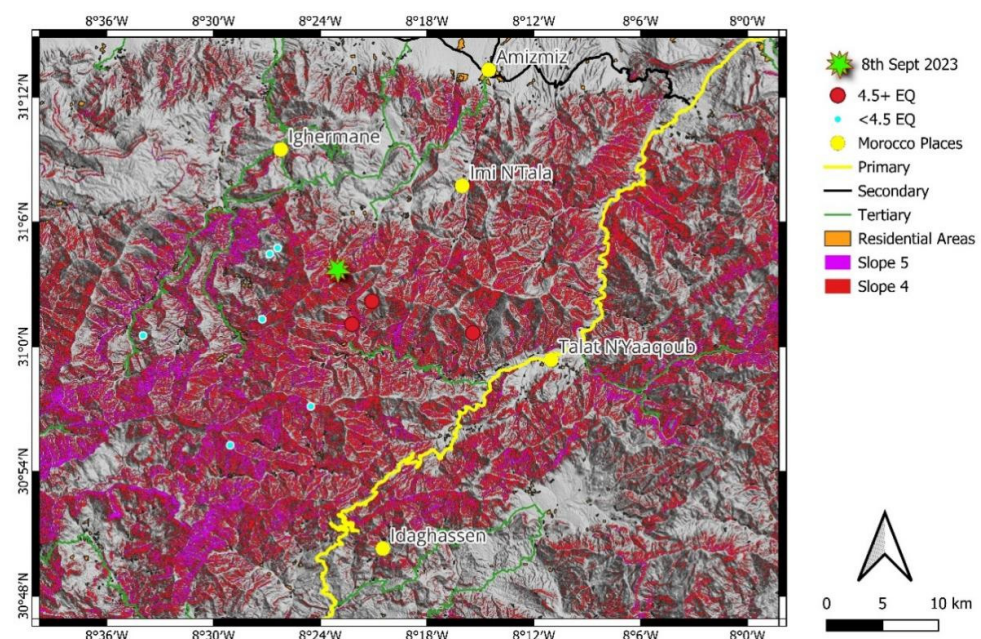


Figure 11. Very steep areas are prime locations for earthquake-induced rock falls or landslides. Slope 4 refers to slope angles between 30 and 40 degrees, while Slope 5 indicates slope angles higher than 40 degrees.

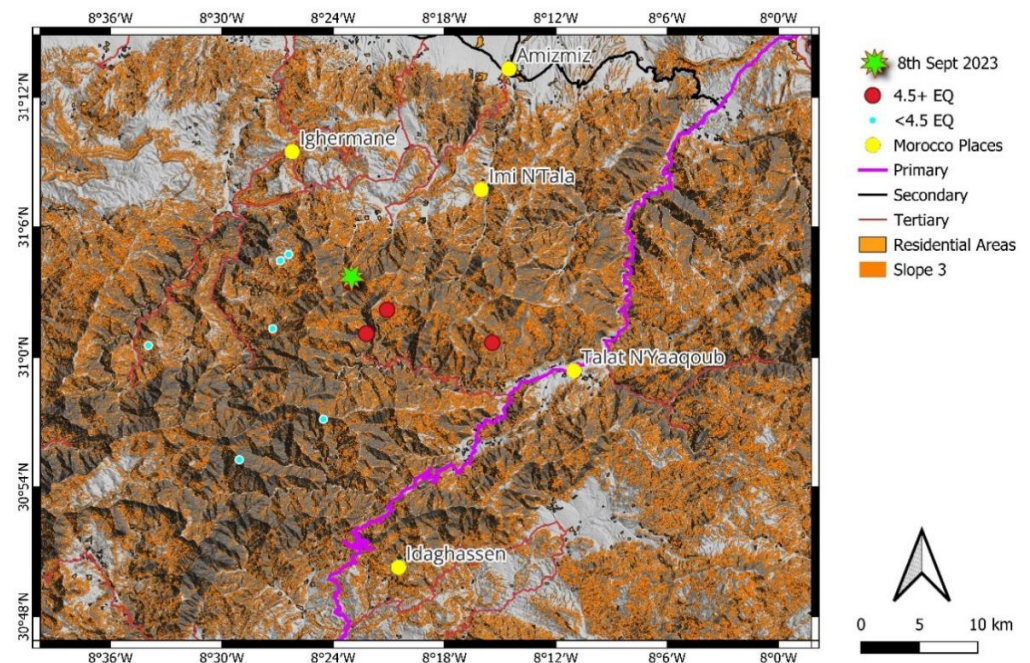


Figure 12. Steep slopes (Slope 3 indicates slope angles between 20 and 30 degrees) are unstable grounds and potential hazard zones after earthquakes.

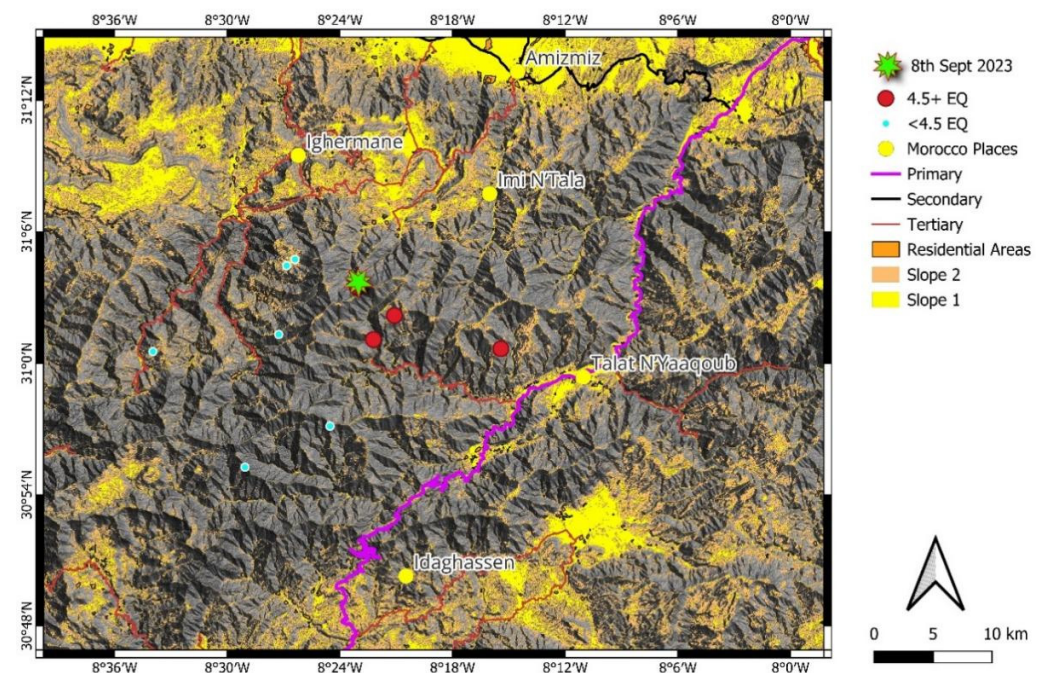


Figure 13. Flat areas (Slope 1, with slope angles less than 10 degrees, while Slope 2 refers to slope angles between 10 and 20 degrees) are potential regions where mass movements can carry debris. Debris flow hazards are expected after earthquakes.

Safety concerns for field teams are paramount. The post-seismic environment often includes unstable slopes, loose rock masses, and residual seismic activity, creating hazards that may prevent researchers from accessing certain areas. Earthquake-induced landslide hazard is significant in the High Atlas. In addition, damaged infrastructure, collapsed roads, and disrupted communication networks limit the deployment of emergency monitoring teams and hinder the timely assessment of affected geosites.

5.2. Social Memory, Cultural Heritage, and Community Perspective

The 2023 Al Haouz earthquake not only reshaped the High Atlas's physical landscape but also profoundly affected the region's social and cultural fabric. Unlike slow geological processes, earthquakes strike suddenly and violently, leaving collective trauma etched into the memories of affected communities. In Al Haouz, nearly 3000 fatalities and thousands of injuries created a profound social impact, fostering a shared memory of loss and resilience among survivors. This social memory contributes to the region's intangible heritage, as experiences, narratives, and oral histories are passed down, influencing local identity and community cohesion.

Building on this, the concept of dark geocultural heritage can be applied to the Al Haouz region. This term refers to the legacy of tragic events such as earthquakes, in which geological and cultural elements are intertwined. The physical traces left behind by the earthquake, such as fault scarps and landslide deposits, are not only part of the region's geological features but also represent the community's experience of loss and recovery.

However, there is often tension between the desire to erase these signs of trauma and the need to preserve them for educational purposes. While rebuilding may encourage the removal of these features, keeping them could be crucial for hazard resilience education, teaching future generations about the risks posed by earthquakes and the importance of preparedness. These geosites can serve as powerful mementos of resilience, offering a way to reflect on the past while preparing for the future.

Traditional knowledge of natural hazards is crucial to shaping community responses and preparedness [137–142]. Indigenous practices, local observations of slope stability, and vernacular architectural techniques have historically guided settlement patterns in earthquake-prone areas. The Al Haouz earthquake has revealed both the strengths and vulnerabilities of these practices, highlighting where modern interventions must complement traditional knowledge to reduce future risk while respecting cultural practices.

The destruction of built heritage compounds the earthquake's social and cultural impacts. Historic sites, mosques, and traditional dwellings—particularly in Marrakech's Medina and villages such as Tafeghaghte and Talat N'Yaaqoub—suffered extensive damage. The collapse of adobe and rubble-stone structures, historic walls, and mosque minarets represents an irreplaceable loss of cultural heritage, with both aesthetic and symbolic significance. The damage is not merely structural but also affects community identity, as cultural landmarks anchor collective memory, local rituals, and social life.

Cultural landscapes—agricultural terraces, mountain villages, and historically significant pathways—also face risk in the post-seismic environment. Landslides, surface ruptures, and hydrologic changes threaten both the functionality and the visual character of these landscapes, undermining centuries of human–environment interaction. The earthquake underscores the interconnectedness of geological processes, human settlement, and cultural expression, revealing the fragility of heritage embedded within dynamic landscapes.

In this context, understanding the social memory and cultural dimensions of earthquake impact is essential to integrated disaster response and heritage preservation. Documenting community experiences, mapping affected cultural landscapes, and incorporating local knowledge into reconstruction and geoconservation strategies ensure that both tangible and intangible aspects of heritage are preserved. This holistic perspective emphasizes that geoheritage and cultural heritage are inseparable in regions where natural hazards shape both landforms and human societies.

5.3. Geoeducation, Risk Awareness, and Resilience

The 2023 Al Haouz earthquake offers a unique opportunity to integrate seismic events into geoeducational frameworks, linking geological processes, social memory, and risk awareness. Earthquakes, as both destructive and creative forces, leave tangible traces in the landscape, including fault ruptures, landslide scars, and altered topography, which serve as direct teaching tools. By studying these co-seismic features, students, local communities, and visitors can develop a deeper understanding of tectonic processes, seismic hazards, and landscape evolution. Incorporating field-based learning in affected areas enhances experiential knowledge and connects theoretical geoscience with real-world observations. Seismic heritage can also serve as a medium for fostering community resilience. Documenting earthquake-induced damage, preserving post-seismic landforms, and mapping at-risk zones can be used in educational programs to illustrate the consequences of seismic events and the importance of preparedness. Community workshops, participatory mapping, and local training sessions enable residents to actively engage in hazard assessment, emergency planning, and reconstruction initiatives, transforming traumatic experiences into actionable knowledge. Museums, heritage centers, and interpretive signage play an essential role in mediating this educational process. For example, exhibitions in regional museums or temporary displays in affected villages can illustrate the earthquake's geological and social impact, while virtual platforms, including online maps, 3D reconstructions, and interactive learning modules, extend access beyond the immediate region. These tools link the earthquake's memory to broader awareness, highlighting the interplay between human vulnerability and geological processes.

By linking collective memory to education, preparedness, and resilience-building, seismic heritage becomes a resource for both scientific learning and community empowerment. Residents can gain a clearer understanding of local hazards, improve disaster response, and reinforce sustainable building practices. At the same time, geoeducational initiatives cultivate broader public appreciation for Morocco's dynamic landscapes and the non-renewable nature of seismic geoheritage, emphasizing that knowledge of past events is essential for mitigating future risks.

5.4. Geoheritage Valorisation and Geoproduct Opportunities

The 2023 Al Haouz earthquake, despite its profound human and social impacts, has created important opportunities to valorize seismic landscapes within Morocco's geoheritage framework [80–87,89–101,113,143–147]. The newly formed and modified landforms, including fault scarps, co-seismic landslides, displaced blocks, and surface ruptures, constitute a scientifically valuable and visually striking record of tectonic activity. These features position the High Atlas as a natural laboratory for geotourism, geoeducation, and scientific research. Designing geotourism trails that highlight these co-seismic structures can attract both national and international visitors with interests in earth sciences, natural hazards, and landscape evolution, fostering a sustainable relationship between local communities and their environment.

Community-based geoproducts offer a complementary pathway for geoheritage valorization. Local populations can develop artisanal creations, storytelling practices, guided tours, and educational materials that interpret the earthquake's effects in accessible, culturally meaningful ways. These initiatives help transmit traditional knowledge, enhance community participation, and support alternative livelihoods in the post-disaster period.

Scientific tourism also holds significant potential. Researchers, universities, and field schools can benefit from direct access to exceptional exposures of active fault traces, landslide deposits, and freshly modified geological structures. These features offer rare

opportunities to study earthquake mechanics, slope dynamics, and geomorphic responses in situ, yielding new data and fostering interdisciplinary collaboration.

Notably, the earthquake occurred during the 10th International Conference on UNESCO Global Geoparks in Marrakech, offering a unique opportunity for scientists to engage directly in the aftermath of the seismic event. This alignment of a major earthquake with a geological conference provided valuable opportunities for field trips and on-site studies, exemplifying how such events can be integrated into scientific tourism and educational activities [148].

Digital geoproducts—including 3D visualizations of surface ruptures, virtual reality reconstructions of affected valleys, and interactive mobile applications—extend access to the region’s seismic heritage beyond the field. These tools enrich public understanding of seismic hazards, promote geoeducation, and enable students, researchers, and the wider public to explore the earthquake landscape through immersive digital environments.

A particularly promising initiative is the creation of an Earthquake Interpretation Center in the Al Haouz region (Figure 14). The center could combine educational exhibits, scientific information, and interactive technologies, most notably earthquake simulators, which allow visitors to safely experience the intensity and motion of real seismic events. By offering a controlled, immersive experience of earthquake tremors, the center would enhance public awareness of seismic risks and strengthen community preparedness and resilience. It could also serve as a hub for school visits, scientific outreach, and cultural interpretation, linking local knowledge with cutting-edge geoscience.



Figure 14. (A) Conceptual design for the Al Haouz Earthquake Interpretation Centre, featuring interactive displays and immersive seismic visualization tools to enhance public understanding of regional seismicity and geohazards. (B) Traditional-style earthquake simulator within the centre, allowing visitors to experience the shaking intensity of real seismic events safely.

In addition to these valorisation strategies, the 2023 Al Haouz earthquake also raises the possibility of establishing a future geopark in the region. The High Atlas, with its exceptional seismic landscapes, active faults, co-seismic landforms and long-term tectonic evolution, provides a strong scientific basis for a geopark candidacy. Earthquake-related features could form a dedicated thematic axis within such a geopark, positioning seismic manifestations as key components of Morocco's geoheritage. Embedding these elements into an institutional geopark framework would further support geotourism development, enhance community engagement, strengthen geoeducation, and contribute to long-term risk awareness and regional resilience.

Overall, the post-earthquake Al Haouz landscape offers a multidimensional opportunity to valorize geoheritage. By integrating field-based geotourism, community-driven initiatives, scientific research, digital technologies, and interpretive infrastructure, the region can transform a tragic geological event into a driver of education, economic revitalization, and sustainable heritage management. These approaches ensure that seismic events contribute not only to scientific advancement but also to local resilience, cultural continuity, and the promotion of Morocco's exceptional geological legacy.

5.5. Turning Dark Geoheritage into Forward-Thinking Geohazard Resilience Development

The 2023 Al Haouz earthquake underscores the dynamic nature of geoheritage, showing that seismic events are not only destructive but also potent agents of landscape transformation and geological learning. The earthquake created new landforms, exposed previously hidden faults, and altered existing geomorphological features, highlighting the capacity of natural hazards to generate non-renewable geological heritage. These co-seismic structures preserve a rare record of tectonic processes, offering a unique opportunity for scientific study and public education. As such, earthquakes can be seen as active contributors to the ongoing evolution of the geoheritage inventory, rather than merely threats to it.

From a geoheritage management perspective, the event reveals both opportunities and vulnerabilities. The rapid modification of the landscape, combined with the fragility of cultural and built heritage, underscores the need for timely documentation and monitoring. Remote mountainous terrain, complex topography, and accessibility challenges further complicate conservation efforts, while site-specific amplification and slope instabilities highlight the role of geomorphological factors in shaping the preservation potential of seismic features. Recognizing these challenges is crucial for developing strategies that integrate scientific observation, risk awareness, and heritage protection.

The Al Haouz earthquake also underscores the interplay between geological events and societal dimensions. Collective memory, traditional hazard knowledge, and the destruction of built heritage collectively shape local perceptions of seismic risk. Integrating this social dimension into geoheritage planning can enhance resilience and community engagement by linking awareness of seismic landscapes to preparedness strategies. Educational programs, interpretive signage, and digital platforms can bridge scientific understanding with public consciousness, transforming earthquake-impacted landscapes into tools for learning, awareness, and cultural continuity.

Policy implications are substantial. Effective geoconservation must recognize earthquakes as both destructive and creative forces, promoting rapid assessment of affected sites, protection of vulnerable heritage, and sustainable use of newly formed geological features. Legal frameworks and planning guidelines should reflect the dynamic nature of seismic landscapes, ensuring that reconstruction and development initiatives do not compromise geological or cultural heritage. Furthermore, fostering geotourism and geoproduct development around seismic features can align conservation goals with socioeconomic benefits, creating a sustainable model for both heritage management and community resilience.

In summary, the Al Haouz earthquake underscores that seismic events are active agents in shaping geoheritage, offering scientific, educational, and socioeconomic opportunities while also posing preservation challenges. Integrating these insights into policy, conservation, and community programs is essential to safeguard Morocco's dynamic geological legacy and transform hazard impacts into enduring learning and development platforms.

6. Conclusions

The 2023 Al Haouz earthquake is a rare and compelling example of geoheritage formation, showing how seismic events can simultaneously destroy, modify, and create landscapes of scientific, educational, and cultural significance. The co-seismic landforms, fault traces, and slope failures generated by this event provide a non-renewable record of tectonic activity that is invaluable for understanding the geological evolution of the High Atlas region. This unique geological footprint underscores the importance of viewing earthquakes not solely as hazards but as dynamic agents shaping Morocco's geoheritage.

The event also underscores the urgent need for interdisciplinary research that integrates geology, geomorphology, seismology, cultural studies, and the social sciences. Rapid documentation, advanced monitoring, and detailed mapping of affected areas are essential to preserve fragile seismic features and enhance our understanding of earthquake-driven landscape processes. Incorporating social memory, traditional knowledge, and heritage considerations ensures that the human and cultural dimensions of seismic events are preserved alongside their geological signatures.

Strategically, the Al Haouz earthquake presents opportunities for Morocco to advance geoheritage valorization and sustainable development. By promoting geotourism routes, community-based products, and digital geoproducts that interpret seismic landscapes, the country can leverage this natural event to support education, scientific engagement, and local livelihoods. In addition, the region now offers a strong foundation for exploring the creation of a future geopark, where earthquake-related landforms and active tectonic features could form a dedicated thematic axis for geoeducation and risk awareness. Integrating these initiatives—including potential geopark development—into national geoconservation and disaster-preparedness strategies strengthens resilience and enhances the visibility of Morocco's geological heritage at regional and global scales.

In conclusion, the Al Haouz earthquake is a landmark case that bridges natural hazard science and geoheritage conservation, emphasizing the dual imperatives of research and strategic valorization to safeguard Morocco's dynamic and fragile geological legacy.

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