

Assessment and Evolution of Surface-Subsurface Landform Connectivity of Jabal Al Qarah in Saudi Arabia: A Potential World-Class Geomorphological Heritage

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Abstract

Worldwide, surface and subsurface connectivity of geomorphic processes, landform diversity, and their geoheritage importance are very interesting topics. Jabal Al Qarah is a mesa (residual hill), located in Al Ahsa, Saudi Arabia. This mesa offers unique diversity in surface and subsurface landforms. Therefore, the scope of this paper is a detailed geomorphological heritage assessment of Jabal Al Qarah, which was a gap. The geomorphological heritage assessment is considered based on scientific and additional value. The key landforms in Jabal Al Qarah are vertical slots, a rill network, a rectangular fault system, a rectangular cave system, a rock pillar, and an in-situ boulder, which belong to the IUCN Geoheritage Theme: Erosional, Cave and Karst System. Jabal Al Qarah comprises a deposition of marine sedimentation, which is followed by the orogeny of the tablelands and plateaus in the eastern part of Saudi Arabia. Due to weathering and denudation, this mesa unit detached from the Shedgum Plateau and formed the mesa. Following the rectangular fault system that is exposed at the surface, weathering forms a rectangular cave system. Jabal Al Qarah is a unique example with spectacular surface and subsurface landform diversity, high representation, well accessible, and a global example of the complex geomorphic process associated with cave formation. Therefore, Jabal Al Qarah is a strong candidate for inclusion in the world-class geomorphological heritage.

Introduction

Unlike a karstic region, a non-karstic landscape produces various distant subsurface landforms such as boulder caves (Halliday 2007), rooted slots (Migoń et al. 2020), and rectangular cave systems (Sen et al. 2023a). Such landforms are deeply connected with surface landforms like boulder-filled hollows and troughs, plazas, open cliffs, open slots, and boulder-filled slots. Such landforms are very prominently found in Poland and the Czech Republic (Migoń et al. 2023). One of the fundamental concepts of surface-subsurface connectivity processes has been explained through the origin of valley heads and canyons in sedimentary tablelands due to seepage and spring sapping in North America (Laity and Malin 1985; Howard and Kochel 1988). Surface water flow initiates erosional processes in various ways (Higgins et al. 2007): underground drainage flow that arises from high rock solubility and gradually forms secondary porosity (Ford and Williams 2007). The geomorphic process associated with the surface and subsurface landforms in the tableland has been well explored in Europe (see Migoń et al. 2023; Migoń 2018), but not completely explored in the Middle East, particularly in Saudi Arabia. Surface landforms in scarpland have been described in Rausch et al. (2014). However, limited attempts to explain the fundamental approach of the surface-subsurface process in the nonkarstic caves and associated landforms in the dissected mesas (residual hills) in the Eastern Provinces of Saudi Arabia.

Geomorphological heritage of tableland such as mesas, buttes, pinnacles, canyons, and wadis distributed across NEOM, AlUla, Wadi Al Disah, and Tuwaiq Mountain (Sen et al. 2024 b, c, e; Sen et al. 2025a, b; Sen et al. 2023b; 2024a, d). However, the entire tableland did not form a surface non-karstic cave structure as observed in Jabal Al Qarah (Sen et al. 2023a). In the eastern province, one of the unique landforms is Jabal Al Qarah, a typical mesa characterized by vertical slots, rock pillars, a faulted structure, and, following the fault, typical caves (Sen et al. 2023a).

Jabal Al Qarah, a residual hill (mesa), is situated in Al Ahsa, Saudi Arabia's eastern province, at an elevation of 225 meters above sea level (Fig. 1), and is characterized by a range of surface and subsurface landforms that are connected. Jabal Al Qarah stands out as an isolated mesa formed from mudstone and limestone. The hill is surrounded by an urban settlement and a farm of the date plant. Jabal Al Qarah, Al Ahsa, is part of a UNESCO Cultural Heritage Site.

Globally, the way karstic cave landforms and their evolution process have been appreciated; non-karstic landform evolution and its geoheritage value is not well explored. Especially, a unique cave and a wide range of surface landform enhances makes the Jabal Al Qarah absolutely unique in Saudi Arabia; so far, no similar example has been recorded. Globally limited case study shows the evolution of the surface-surface connectivity and its geomorphological heritage value. Therefore, this paper aims to explain the landform diversity, the geomorphological processes involved in the evolution of these landscapes, and the assessment of the geomorphological heritage. The outcome of this study is expected to enhance the explanation of the geomorphic processes and landforms in Migoń et al. (2018); Migoń et al. (2020), (2023).

Regional Geology

The opening of the Red Sea, which led to the drift of the Arabian Plate relative to the Eurasian Plate, developed the present-day landform. Broadly, Saudi Arabia can be divided into two main geological units: the Arabian Shield and the Arabian Platform (Powers et al. 1966). Jabal Al Qarah is part of the Arabian Platform, which comprises the sediment deposited in the Tertiary and Quaternary periods (Fig. 1. A, B). The Jabal Al Qarah (Mio-Pliocene deposit) is part of the Arabian Platform, which is characterised by the cyclic deposition of marine sediment, currently distributed in the northern, eastern, and southern parts of Saudi Arabia. In the Middle Miocene, the Arabian Platform was invaded by a remarkable transgression that reached the Al-Summan Plateau, west of the Shedgum Plateau, and formed a continental to shallow marine depositional environment, giving rise to the Dam and Hofuf formations (Powers et al. 1966). Therefore, the traces of the marine transgression and regression can be found in the remnants of the wave-cut platform at Jabal Al Qarah in Al Ahsa (Hötzl et al. 1978). Jabal Al Qarah, a detached mesa unit, is separate from the Shedgum Plateau, which includes Tertiary carbonate and evaporite deposits. A significant marine transgression occurred during the Middle Miocene, reaching the Al-Summan plateau (west of the Shedgum Plateau) and creating a range of depositional environments, from continental to shallow marine (Saner et al. 2005).

The lithology of Jabal Al Qarah comprises the Dam and Hufuf Formation (Fig. 2. C). The Hufuf Formation is characterized by calcareous sandstone and marl/claystone, which is overlaid by a thick caliche layer. The Hofuf Formation shows white to light grey, massive, calcareous sandstone interbedded with soft, reddish to yellowish brown marl and clay that can be observed in the cave entrance and walls of the cave galleries. The side walls of the caves are composed of stepped cliffs, formed from alternating layers of red and grey calcareous sandstone. The Hofuf Formation indicates a mudflat and lacustrine setting, formed under coastal marine conditions (Khandaker et al. 2006). Dam Formation comprises sandstone, mudstone, limestone, and marl layers, which are formed under a shallow marine depositional environment. In the work of Ali et al. (2021), strong mention that the facies of the Dam Formation show vertical change from the lower part, which comprises sandy limestone and marls rich in molluscs and foraminifera. The middle part becomes siliciclastic-dominated, which is overlain by bioturbated and channelized sandstones. The contact between the Hufuf and Dam Formation is characterised by the conglomerate layers (Fig. 2. C).

Methodology

A description card has been prepared for Jabal Al Qarah, providing essential information and photographs (300 dpi). During the field survey, photographs were taken to justify the representativeness, rarity, key locality, and integrity. A detailed literature review has been conducted based on the identification of scientific knowledge categories. The information related to the key landform associated with the Jabal Al Qarah has been gathered as supporting evidence; however, the literature review identifies a gap in addressing and exploring the potential of the geomorphological assessment. In the present study, scientific and additional value have been considered for the assessment.

Scientific Value

For the scientific value assessment, criteria have been followed: representativeness (Re), Rarity (Ra), Key locality (KI), Scientific knowledge (Sk), and Integrity (In). The details of the criteria and corresponding scores are explained in Table 1. The score has been divided into 5 classes, where 0 is the minimum and 1 is the maximum. The summation of the scores of five (5) criteria is divided by five (5) to get the final score of the scientific value (SV). The SV value will range from 0 to 1.

Table 1

Description of the criteria for the scientific and additional value for assessment of the geomorphological heritage. The score has been divided from 0 to 1. A score of 0 stands for a low value, and 1 stands for a high value.

Scientific Value	
Criteria	Description
Representativeness (Re)	0 = All the representative surface and subsurface landforms are destroyed
	0.25 = Majority of the surface and subsurface landforms are destroyed
	0.5 = Majority of the surface and subsurface landforms represent the geomorphological evolution of the area.
	0.75 = Key landforms are well represented, while some are difficult to understand the evolution process.
	1 = Surface and subsurface landform connectivity and geomorphic processes are well understood
Rarity (Ra)	0 = Landforms are ubiquitous
	0.25 = Landform can be found in different parts of Saudi Arabia and other countries
	0.5 = Landform can be found in other parts of the globe.
	0.75 = Landform was also found in other parts of Saudi Arabia.
	1 = Landform is an endemic feature in this area, and the best example in the world for understanding the Earth's surface and subsurface processes and connectivity.
Type or key locality (KI)	0 = Landform doesn't have any national and/or international status
	0.25 = Landform is partially protected by the local community/NGO/Private organization
	0.5 = Landform is protected by the State Government, National Centers, and Royal Commissions
	0.75 = The landform is protected by the national and international organizations like IUGS, IUCN, and UNESCO.
	1 = The landform is recognized by the national and international authorities, and the management authority is protecting the area.
Scientific knowledge (Sk)	0 = No published scientific literature
	0.25 = Published literature at the regional and local level
	0.5 = Published literature at the national level
	0.75 = Scientific documentation at the national and international level
	1 = Scientific documentation of landform, its processes, and other literature related to biodiversity, archaeology, history, and culture.
Integrity (In)	0 = The geological and geological features are completely extinct
	0.25 = Most of the landforms are partially destroyed by significant erosion/denudation and natural decay processes.
	0.5 = Key features remain intact; however, at high risk of decay
	0.75 = Key landforms remain intact, and limited risk of destruction
	1 = All the key landforms are intact and can be protected as they are.
Additional Value	
Cultural (CUL)	0 = No significant cultural feature
	0.25 = Cultural feature restricted to the local level

Scientific Value	
Criteria	Description
	0.5 = Cultural importance in the region
	0.75 = Cultural importance at the national level
	1 = National and international level recognition e.g. UNESCO World Heritage Property
Ecological (ECO)	0 = No ecological importance.
	0.25 = Limited ecological knowledge; however, possibility of ecological importance.
	0.5 = Existence of sensitive species and habitat associated with the geosite.
	0.75 = Existence of the IUCN Red Listed Species
	1 = Existence of the IUCN-high conservation species, Important Plant Area (IPA).
Aesthetic (AES)	0 = Limited scenic beauty
	0.25 = Local tourism spot
	0.5 = Tourism spot with limited tourism infrastructure
	0.75 = Iconic tourism spot with tourism infrastructure, viewpoint, and illustration facility.
	1 = The picturesque view of the landform and landscape that any international organization recognizes
Touristic (TOU)	0 = Nil
	0.25 = Low
	0.5 = Regional/national tourist destination with limited infrastructural facilities
	0.75 = Popular destination at the national and international levels with good connectivity, lodging facilities, and interpretation facilities.
	1 = Global recognition as a significant geotouristic site.
Economic (ECO)	0 = Nil
	0.25 = Low
	0.5 = Regional/national level
	0.75 = National and international level
	1 = Global recognition and significance

Scientific Value (SV)= (Re + Ra+Kl + Sk+In)/5

Additional Value

The additional value of the site is divided into cultural value (CUL), ecological value (ECO), aesthetic value (AES), touristic value (TOU), and economic value (ECO) (Table 2). Cultural value is measured by the importance of the geosite in the human landscape and its global recognition. Ecological value considers the importance for the ecosystem's development, mainly concerning fauna, particularly bat and bird species. Scores have been assigned for the CUL, ECO, AES, TOU, and ECO. The summation of values is divided by 5 (five) to get the final score of the Additional Value (AV) of each landform as follows:

Table 2
Description of the Scientific importance of Jabal Al Qarah, based on the five predefined criteria.

Landform Diversity	IUCN Theme	Representativeness	Rarity	Type or key locality	Scientific knowledge	Integrity
Mesa	Erosional System	Jabal Al Qarah shows various surface and subsurface landforms	This is the only representation in Saudi Arabia and a world-class geomorphological feature	Part of UNESCO Cultural World Heritage	Sen et al. (2023)a	The majority of the key landforms are maintaining their original condition. Although urbanization is a threat
Rib and furrow structure	Erosional System	This is a global example of valley development, hill slope processes, and weathering and mass wasting	No similar example can be found in Saudi Arabia.	Part of UNESCO Cultural World Heritage	No clear scientific documentation	Due to urbanization, some portions are destroyed.
Detached rock slab and Rockfall	Erosional System	This is a typical excellent example of the weathering and mass wasting process along the jointed and fractured hill slope.	This can be found in other escarpments in Saudi Arabia and worldwide.	Part of UNESCO Cultural World Heritage	No clear scientific documentation	Rockfall types of mass wasting processes are clearly visible.
Open Slot and hidden slot	Erosional System	Deep incision process are clearly represent vertical erosion.	This landform is spectacular and of significant interest for the geomorphological model.	Part of UNESCO Cultural World Heritage	Sen et al. (2023)a	Slots are a fragile landform due to nature process of weathering. Some areas are at high degradation risk due to urbanization
Boulder-filled slots and canyon	Erosional System	Global geomorphological model for understanding the erosional process along the faulted and fractured areas with subsurface connectivity.	Can be seen in other parts of the country and worldwide	Part of UNESCO Cultural World Heritage	Sen et al. (2023)a	Urbanization, rock, and construction partially destroyed some of the areas.
Hoodoo Rock	Erosional System	An ideal geomorphological example of rock decay and boundary landscape.	Can be found in the northwestern part of Saudi Arabia and various rocky deserts in the world.	Not protected	Sen et al. 2023a	High degradation risk. In the Southern part, several hoodoo rocks/landscapes have been destroyed.
Rectangular Cave System	Cave and karst system	Global example of fault-induced non-karstic cave development at street level	Spectacular and widely accessible caves are unique.	Part of UNESCO Cultural World Heritage	Khandaker et al. (2006)	Limited scope for the degradation risk.
Cave Tunnel	Cave and karst system	World-class geomorphology of the rectangular nonkarstic cave system.	Outstanding scientific example of the rectangular cave formation in the mesa.	Part of UNESCO Cultural World Heritage	Khandaker et al. (2006)	Limited potential for the degradation risk.

Additional Value (AV) = (CUL + ECO+AES + TOU+ECO)/5

The final score will fall within the range of 0 to 1. For better interpretation of the score of scientific value and additional value of each key landform, the value is divided into less than 0.25 = low, 0.26–0.5 = moderate, 0.51–0.75 = high, and more than 0.76 = very high.

Results and Discussion

Jabal al Qarah is characterized by a hard caprock surface of caliche in its central part, surrounded by softer rock, mainly consisting of limestone, marls, and clays of the Dam and Hofuf Formations (Miocene-Pliocene), which are highly susceptible to erosion, as represented in the photograph. The surface of the mesa is highly weathered, jointed, faulted, and fractured, allowing rainwater to penetrate the entire interior of the mesa and form a subsurface cave gallery.

Surface Landform Diversity

Mesa

In a broader division, a mesa is characterized by an undulating surface with various gulley features, in-situ bounders, and surrounded by the rugged slope, characterized by the slots, rib, and furrows, and towards the foothill part, the boulder landscape (Fig. 1). The mesa of Jabal Al Qarah, a spectacular erosional landform, is located around 10 km west of the Shedgum Plateau. The eastern side of the Shedgum Plateau is characterised by numerous buttes and mesas, such as Barqa Ar Rukban, Jabal Burayqa, and Jabal Sha'bah, but Jabal Al Qarah is unique for its scenic surface and subsurface landforms.

Rib and Furrow Structure

The term “rib and furrow” is not very popular and not well defined; some of the literature uses this term to denote the parallel arrangement of the valley and ridge in the sedimentary structure (Fletcher and Spicer 2003; Sen et al. 2020). Ridges indicate relatively elevated areas, and furrows indicate valleys. Photographs show the development of the rib (ridge) and furrows (valley) surrounding the mesa (Fig. 3). Initially, the parallel faults and fractures developed in mudstone belonging to the Hufuf Formation exposed in the surrounding area of the mesa. Gradually, rainwater infiltrates through faults and fractures, which can begin to degrade the rock and form furrows. As photographs show, the top of the mesa and the surface of the rib comprise the hard caliche layer, where erosion is relatively slower than in the underlying mudstone layer that produced the mushroom. Most interestingly, vertical faults within the rib, which are also eroded by rainwater, produce rock pillars such as the topography and the fairy chimney rock pillar in Cappadocia, Turkey (Dinçer et al. 2026) and Europe (Cole 2008).

Detached Rock Slab and Rockfall

Mass wasting process occurs in various ways: firstly, water percolates along the faults and fractures and gradually widens and deepens at the edge of the mesa, and gradually a large rock slab detaches, tilts, and collapses (Fig. 4). Secondly, the caliche crust and the mud beds are weakened due to physical and chemical processes of weathering, such as detaching rock block are filling the slots, open valleys, and further accumulate in the lower foothill part (Fig. 5). In the tableland topography, such weathering and mass wasting processes are very common and can be observed in Europe also (see Migon 2018).

Open Slot and Hidden Slot

Surrounding the mesa, massive vertical slots have developed, initially formed through faulting and fracturing. The deep incisions are formed by erosion-prone mudstone structures. The photograph shows the narrow linear slots that are formed in the foothills of the mesa (Fig. 6). The harder caliche and a blanket, which are mudstones, are eroding faster vertically, deepening the valley and forming the slots. Some time slots are covered with the harder caliche surface or may have a narrow opening. Gradually, the slots are the passage to the cave.

Boulder-filled slots and canyon

The detached mudstone and limestone boulders usually either form the in-situ structures or are washed by rainwater and fill the slots, canyon, and hoodoo rock. The photo shows the various types of boulder-filled slots and the canyon that appears in the foothills (Fig. 6). In-situ boulder structures occupy the top of the mesa, which is formed due to physical weathering, block disintegration, and the rocky caliche and mudstone areas.

Hoodoo Rock

Hoodoo rocks are accumulated boulders at the edge of the mesa, formed by the disintegration of rock, a typical example of the physical weathering that leads to their formation (Fig. 6). Another boundary is located in the deeply incised gorge, which is disintegrated and filled with debris along its course. The rock pillars are formed due to the disintegration of the sedimentary structure along vertical faults and fractures. The upper part of the rock pillars consists of caliche layers, while the lower part consists of marl, mudstone, and sandstone.

Subsurface Rectangular Cave Gallery

According to Hötzl et al. (1978), the formation of the caves and other geomorphological features occurred at the end of the Pliocene, a period characterized by marine transgression. The sea cliff plays a key role in the genesis of the caves. Furthermore, the Quaternary sea-level high played a role in the development of the spectacular cave system in Jabal Al Qarah. Along with marine erosion, various wave-cut gorges along the joint openings can be seen in the outer margin of the mesa. Further, subaerial weathering and enlargement of the well-defined joint and fracture systems in the Hofuf Formation support the formation of the cave. According to Khandaker et al. 2006, approximately 28 linear tunnels, totaling about 1.5 km in length, are in a rectangular area roughly 132 m x 216 m.

One of the famous caves is the Ghar An Nashab I cave; the geotrail represents the most picturesque structure of the cave gallery. Figure 9 shows the rectangular pattern of the cave, which follows the regional fault system. Photograph A shows the entrance of the cave, which is a massive normal fault extending up to the surface of the mesa, consistent with the rectangular fault system. Also, this is the entrance to the subsurface caves. The rock slab comprises mudstone, sandstone, and marl rock, detached, and in situ occurrence can be traced in photograph B, after a few steps inside the caves.

Cave Tunnel

In the context of limestone cave formation and evolution, Jabal Al Qarah exemplifies the surface and subsurface connectivity within a sedimentary mesa, as well as the development of fault-induced cave galleries (Fig. 9). Photograph 9. C shows the ceiling of the cave, which is exposed to sunlight. The geotrail track passes through the passage inside the cave and shows the linear narrow passage (Fig. 9. C, D), with a broader base and narrower towards the ceiling (Fig. 9. E). In photograph E, the alteration of the red and grey bed of the Hofuf Formation can be seen, and in more close can shows the typical pattern of intricate texture, which is interpreted as *rhizocretion* of mangrove plant roots, which is also strong evidence of the prevalence of the marine environment in the geological past.

One of the poorly appreciated yet very significant criteria is the aesthetics of the landform, as mentioned by Goudie (2002). The rock color, structures, and processes related to the geomorphological features draw the attention of non-geoscientists. In relation to that, Jabal Al Qara has significant aesthetic value, which needs to be elevated to a global level.

Jabal Al Qarah has remarkable geological and geomorphological features that illustrate different stages of the deposition process, as well as the development and formation of the current landforms. The often-overlooked aspect of landforms and their geomorphological evolution is the evidence of climate change in the Arabian Platform. The exposed Tertiary sections in Jabal Al Qarah exhibit significant marine sedimentation and wave-cut platforms, resulting in various linear incision structures along the outline of Jabal Al Qarah. The entire climate regime of the eastern parts of Saudi Arabia has shifted from a marine and fluvial-dominated environment to a hyper-arid one. Vegetation is much less abundant, and all the landforms and layers clearly reveal the landscape's evolution. An interesting feature in the central and eastern parts of Saudi Arabia is the flat-topped plateau, cuesta, and scarpland, which are often covered with sand seas. Considering the historical climate change in

the depositional environment, which is clearly visible in the exposed sections of the Jabal Al-Qarah, it is crucial to conserve this geomorphic heritage to preserve evidence of the Earth's dynamic processes. One particularly fascinating section is the fossilized areas, which not only emphasize the significance of the depositional process but also help preserve paleontological evidence from the Jurassic period.

Assessment of Geomorphological Heritage

The surface and subsurface landforms are mainly linked with the IUCN Themes: Erosional System, Cave, and Karst. Table 2 illustrates that all the landforms represent a clear relationship between the geomorphological processes and the corresponding landforms. Although the key landforms are in baseline condition, the hoodoo rocks located at the edges of the canyon are under threat. Most of the landforms are well documented in the recent scientific literature Sen et al., 2023a). Considering the criteria of representativeness, rarity, key locality, and integrity, undoubtedly, the erosion process of mesa formation and the development of landform diversity is a global example. Therefore, Jabal Al Qarah needs to be appreciated as an outstanding geomorphological case study of mesa evolution. Further, the importance of various landforms can be further enhanced by the cultural, ecological, aesthetic, touristic, and economic values of the various landscapes (Table 3). While discussing the cultural value of Jabal Al Qarah, the close relationship of the cave civilization can be established. The relatively cold environment of caves provides a safe and comfortable shelter for the local community. From the ecological perspective, caves and tunnels provide an ambient baseline condition for bats and birds. Although a limited taxonomic study can be found on the identification of the bat species, further verification is required as per the IUCN Red List. However, during the survey, various bat species were reported in the caves, which need a detailed taxonomic study. The erosional processes of weathering, carved into various surface and subsurface landscapes, are supported by the light color of the marls, limestones, and sandstone rocks, which enhances the scenic beauty of the landscape. Some portions of the Jabal Al Qarah caves are open for the tourist that supports review generation and promotes local business and employment. Therefore, immense future opportunities for the development of geotourism and economic development are possible in this area. Several scenic views of the landforms have been blocked by the buildings.

Table 3

Description of the Additional features associated with Jabal Al Qarah. The subsurface landforms are deeply associated with the cultural, ecological, aesthetic, tourist, and economic value. Walking trails and geotourism experiences enhance the economic opportunity.

Landform diversity	Cultural	Ecological	Aesthetics	Touristic Value	Economic Value
Mesa	Entrances to the caves. Part of UNESCO Cultural Heritage.	-	Local tourist spot. High Aesthetic Value. The gradual widening of the slot, the deep incised gorge, and the gradual formation of the rock pillars on the side wall of the gorge provide magnificent structures.	Potential geotourism site, but no infrastructure	The mesa top is used for commercial purposes like a telecommunication tower.
Rib and furrow structure	Entrances to the caves. Part of UNESCO Cultural Heritage.	-	No clear viewpoint for observing such a landscape. Although the scenic beauty is outstanding	Potentially a geotourism site, but no viewpoint or observation conditions.	-
Detached rock slab and Rockfall	-	-	Purely geomorphological interest, no clear observation conditions.	Potential geotourism site; however, the main viewpoints are blocked by buildings	-
Open Slot and hidden slot	Such slots are traced to the cave entrance; therefore, it has cultural importance. Historically, people used such a pathway to enter the caves.	-	The scenic beauty of the slots is of interest to geomorphologists.	Significant geotourism and geoeducational site with observational infrastructure and viewpoints	-
Boulder-filled slots and canyon	-	Various terrestrial fauna can be found.	The best place to see the weathering process and the scenic landscape of the mass-wasting process	Geotourism and geoeducational site with observation facility.	This is also part of the geotrail that supports the local economy.
Hoodoo rock			High Aesthetic Value. This is visible from the adjacent roads, but there are no interpretive facilities for these unique features.	Significant geotourism site, but high degradation risk in the future.	Part of the geotourism walk trail.
Rectangular cave system	An old civilization resided in the cave. Part of UNESCO Cultural Heritage.	Bat species are found but have limited scientific publications.	Local tourist spot. High Aesthetic Value	Well-established geotrail and geotourism developed	Revenue and local income generation surrounding the viewpoint.
Cave tunnel	Historically, people have used such tunnels as a passage inside the caves.	Bat species are found but have limited scientific publications.	Local tourist spot. High Aesthetic Value	A walking trail was established with tour guides, safety measures, and excellent observation	Revenue and local income generation through the geotrail

Landform diversity	Cultural	Ecological	Aesthetics	Touristic Value	Economic Value
				conditions for understanding the cave morphology.	

Table 4 shows the quantitative assessment of the scientific and additional value of the surface and subsurface landforms. From the illustration of the landforms and associated geomorphological processes, it is quite clear that all the landforms show the best textbook examples of weathering and mass wasting, subsurface water flow processes, response of the various rocks to erosion, and accurately represent their characteristics. Therefore, the representativeness value is high for all the landforms. Very few case studies nationally and globally can be found similar to Jabal Al Qarah, where the diversity of mesas and rectangular cave formation can be well developed. Therefore, the rarity score is also high. None of the landforms, despite their outstanding scientific value, has been overlooked by the geomorphological community worldwide. No global appreciation and geoconservation approach has been documented for the Jabal Al Qarah, individually or as a whole, except for some academic publications; therefore, the KI value is surprisingly low for all the landforms. Except for rib and furrow topography and its geomorphic evolution, most of the landforms have been documented in the scientific literature. Therefore, except for the rib and furrow, all the landforms have a high score. Despite the poor geoconservation approach, all the key landforms maintaining its original characteristics and are less affected by the degradation risk, although some of the hoodoo rocks and canyons are exposed to threats due to urban encroachment. Nevertheless, the overall score of the integrity (In) score is high. Considering all the criteria, the scientific value of all the landforms indicates the importance of global recognition, the geoconservation approach, and the promotion of geoeducation.

Table 4 Synthesis of the geomorphological heritage assessment based on the scientific and additional value.

Landforms Diversity	Scientific Value (Re+Ra+KI+Sk+In)/5						Additional Value (CUL+ECO+AES+TOU+ECO)/5=AV					
	Re	Ra	KI	Sk	In	SV	CUL	ECO	AES	TOU	ECO	AV
Mesa	1	1	0.25	1	0.75	0.8	0.5	0.5	0.75	0.25	0.25	0.45
Rib and furrow	1	1	0.25	0	0.75	0.6	0	0	0.75	0.25	0.25	0.25
Detached rock slab and Rockfall	1	1	0.25	1	0.75	0.8	0	0.25	0.75	0.5	0.25	0.35
Open slot and hidden slot	1	1	0.25	1	0.75	0.8	0.75	0.25	0.75	0.75	0.5	0.6
Boulder-filled slots and canyon	1	1	0	1	0.75	0.75	0	0.25	0.75	0.75	0.5	0.45
Hoodoo rock	1	1	0	1	0.5	0.7	0	0.25	0.75	1	1	0.6
Rectangular cave system	1	1	0.5	1	0.75	0.85	1	1	0.75	1	1	0.95
Cave tunnel	1	1	0.5	1	0.75	0.85	1	1	0.75	1	1	0.95

Note: less than 0.25 = Low, 0.26 – 0.5 = Moderate, 0.51 – 0.75= High, More than 0.76= Very High

Considering the cultural importance of the caves in the historical civilization of people, the CUL score is high; similarly, the open slots also score high because this is the historical pathway for entering the caves. Similarly, biodiversity studies are based on the observation of the fauna, specially bat and birds; the ECO score is assigned, and caves, and are considered to be a significant habitat. Therefore, the ECO score for the caves and the associated landscape is high. As discussed previously, the scenic beauty of the landscape is considerably high; therefore, the AES score is high. It is observed that AES and TOU are deeply related, because one of the main criteria of geotourism development is the aesthetic importance of the viewpoint (Migoñ and Pijet-Migoñ, 2017). For the mesa, rib, and furrow topography, no observation conditions can be developed yet, further quite challenging; therefore, the TOU score is low compared to other landforms. To observe such a landscape, a hot air

balloon ride is recommended to help to promote geoeducation. Tourism has been implemented in some of the caves, which supports the local economy directly. The museum represents the close relationship between human being and their cave life. Further, various local foods that are associated with this geomorphological site are hasawi rice (Red Rice), Khubz Ahmar (Red Bread), Asida, and Hasawi Miflaq, and harees, a globally famous food, which can be a potential to be a geofood. These foods are very popular among the civilization developed in the caves and surrounding Jabal Al Qarah. Moreover, rutabs (half-ripened yellow summer dates) are world famous because of their taste (<https://ich.unesco.org/en/RL/harees-dish-know-how-skills-and-practices-01744>). Rutab is one of the strong candidates for the nomination of the geoproduct. The geoproduct and geofood are enhancing the economic value (ECO) of Jabal Al Qarah. The various local restaurants and shops are selling traditional items, which again enhances the possibility for the promotion of the geofood, geoproducts, and more importantly, the development of geo-restaurants and geo-lodging. Therefore, TOU and ECO scores are high, where viewpoints are developed.

Geoconservation and Geotourism Issues

Considering the discussion, it is clear that Jabal Al Qarah is a global model for understanding mesa evolution and surface-subsurface connectivity, which helps to understand the Earth processes that lead to the various erosional landform, which has significant aesthetic properties that attract tourists. The tourism support in enhancing economic opportunity in Jabal Al Qarah. Based on the assessment, some points have been identified that need to be considered for geoconservation and geotourism development as follows:

Lack of a clear policy for geoconservation, limited awareness among the local people, and accelerated degradation risk of the cave ecology. The occasional picnics and campfires hinder the cave ecology.

One portion of the cave of Jabal Al Qarah is open for tourism. Lighting, transport, tourist guides, and other basic support are available. Moreover, for the geoscientist, it is an immense opportunity to see all the geomorphic and geological features clearly, ranging from the bedding structure to the Hoodoo rock, caves, faults, vertical slots, and boulders. But the major gaps are that no illustration boards are available, and guides are not aware of the geomorphological and geological processes. Therefore, Jabal Al Qarah is underrated and overlooked, and contributes less to geoeducation.

Although the whole area is part of the UNESCO World Heritage Property, practically, several portions are unprotected, which potentially causes human encroachment. In some portions, hoodoo rocks are damaged.

The management strategy for this is lacking, with no rangers, and the tourism center is not adequately addressing the issues related to climate change and geohazard mitigation.

The aesthetics of the landscape, good connectivity, communication facilities, and other factors for the development of tourism are available and immensely potential in Jabal Al Qarah; the right policy and international recognition can lead to the development of a global tourism destination.

One of the important opportunities could be the geotrail with an educated guide explaining the connecting surface-cave-mesa top, which explains the geomorphic evolution process, geology, surface, and subsurface connectivity.

One of the major threat for the Jabal Al Qarah is the risk of degradation due to massive urban encroachment along the southern boundary (Fig. 10). Buildings are gradually encroaching into the canyons. The large building is blocking the scenic view of the landforms. The lack of a land use policy and poor management of geoheritage resources can lead to damage to the various hoodoo rocks and rock pillars. If this continues, the hoodoo rocks will be destroyed or eliminated from the surrounding areas of the Jabal Al Qarah.

Conclusion

Jabal Al Qarah (residual hill) is probably the rarest landscape on Earth, with a single mesa unique for its diverse surface and subsurface features. A labyrinthine cave network, which is typical of the fault system and controlled by the rock composition. From a global perspective, this area could serve as a worldwide reference for geomorphologists, particularly in the study of the connectivity between surface and subsurface landscapes. Therefore, the present work strongly recommends that Jabal Al Qarah is sensu to the World-Class Geomorphology of the IUCN Erosional Theme, under the “*Criterion (viii) - to be outstanding examples representing major stages of Earth’s history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features*” (Mc Keever and Narbonne 2021).

The periphery of the Jabal Al Qarah is gradually degraded by urban encroachment, indicating a high risk of degradation for this area, although its integrity is maintained. A detailed assessment of scientific and ecological parameters reveals the significance of the landscapes of Jabal Al Qarah. One of the key strengths is the high representation, integrity, and scientific evidence that demonstrate the importance of the geoconservation approach. Failing to adopt geoconservation will result in the loss of this unique landscape on Earth forever. At present, one of the significant issues is the lack of national policy to protect the geoheritage. Therefore, the urban encroachment towards Jabal Al Qarah can not be safeguarded. Even the current Environmental Impact Assessment (EIA) did not address the impact assessment in the geoheritage sites. Therefore, it is a serious future threat to several parts of Jabal Al Qarah to maintain its integrity. The present study strongly argues for the adaptation of the geoconservation policy to protect this unique geomorphological heritage.

Declarations

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Author Contribution

S.S.conducted the pioneering geomorphological heritage research in Jabal Al Qarah. Conducted the identification of landforms, geomorphological heritage assessment, and manuscript writing.

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Declaration of competing interests

No competing interests to declare that are relevant to the content of this article.

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Figures



Figure 1

A top view of the surface of the mesa, which is faulted and fractured, gradually modified by rainwater; surrounded by parallel slots, which are widened in the outer part (Photos by Subhajit Sen).

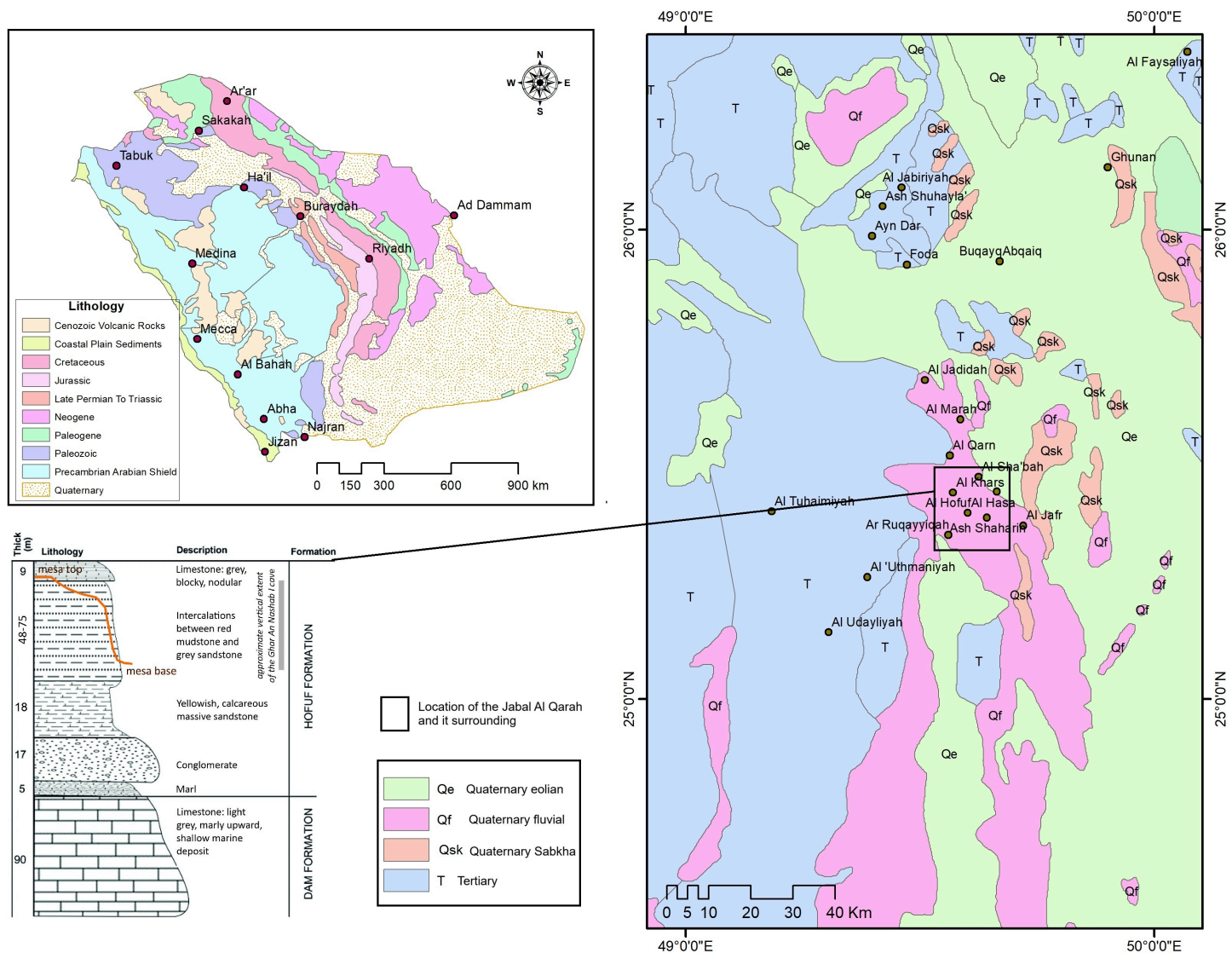


Figure 2

Maps show the geological background of the study area. (A) represents the geological map of Saudi Arabia, showing the location of Jabal Al Qarah in the eastern part of Saudi Arabia. (B) The regional geological map of Jabal Al Qarah (Tertiary-Quaternary formation). (C) Lithological sections showing that the main mesa comprises the Dam and Hufuf Formation (Source: Saudi Geological Survey and United States Geological Survey open database).

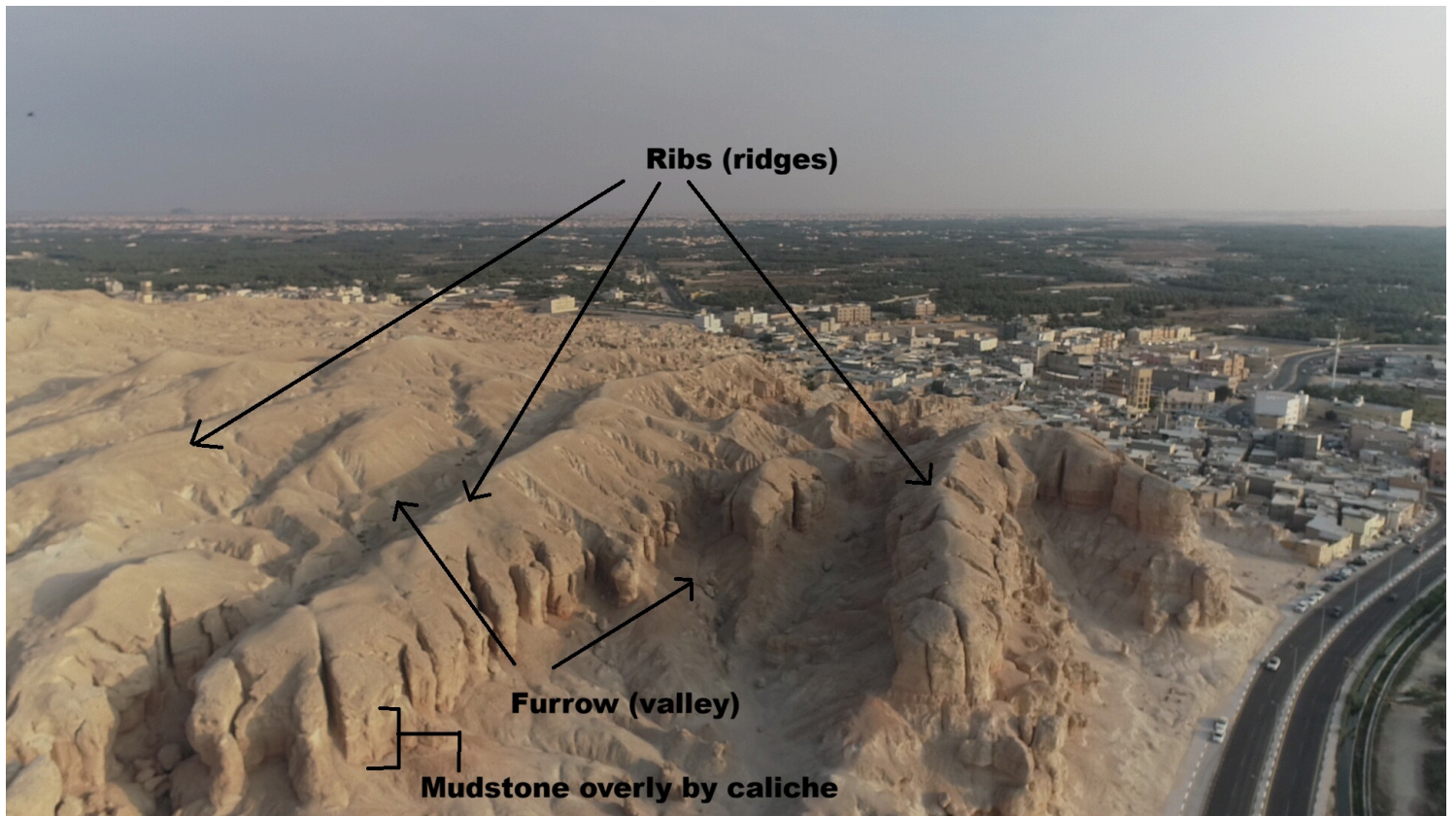


Figure 3

The photograph shows the parallel rib and furrow topography. The rib is characterized by a linear ridge, a capping caliche layer, highly fractured, forming a rock pillar in the outer margin due to erosion along the vertical faults. Furrows are the parallel valleys bounded by the two adjacent ribs. (Photos by Subhajit Sen).

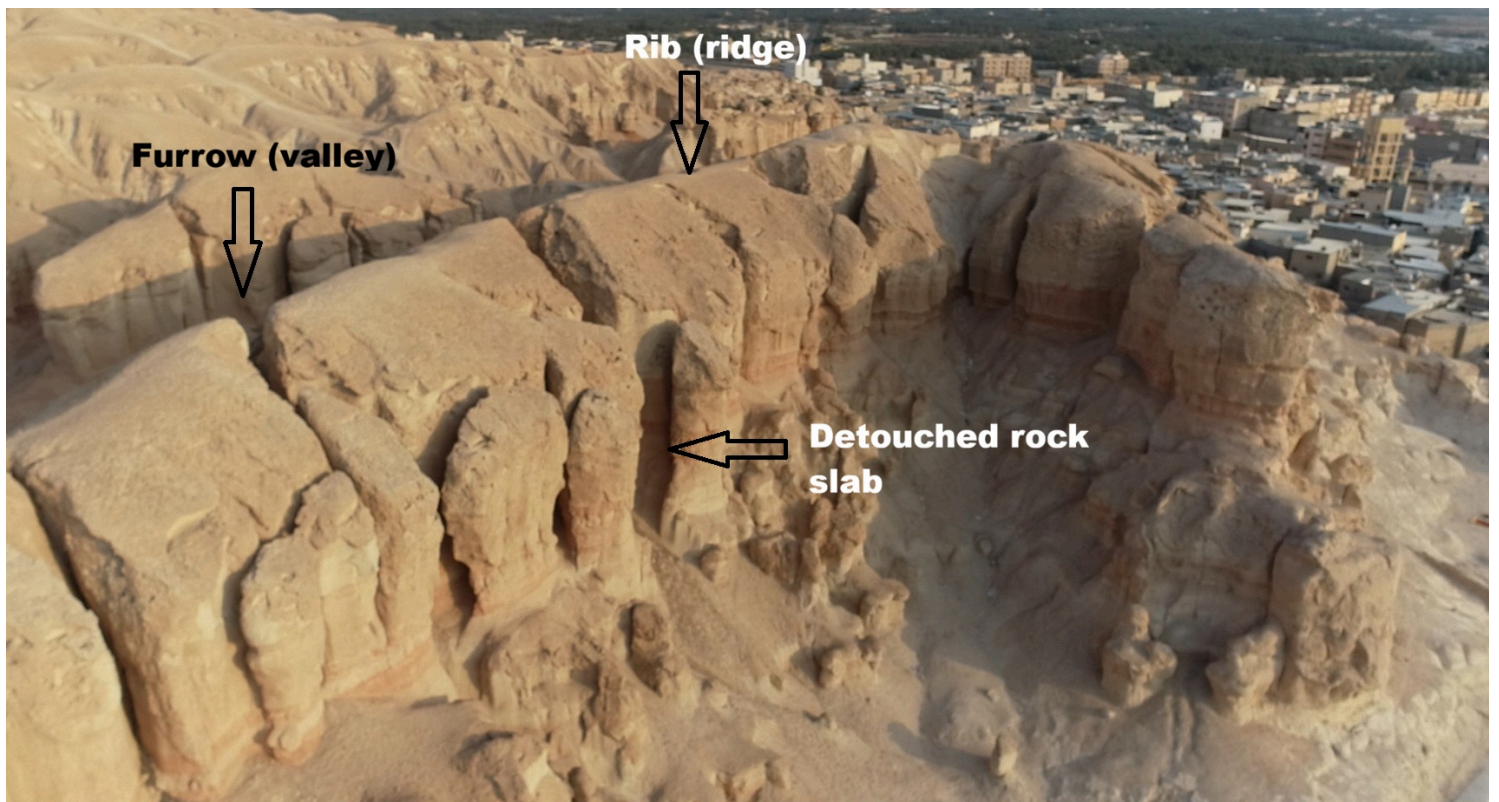


Figure 4

The side wall of the rib is gradually collapsing due to the gradual decay and detachment of the rock slab along the fault. The base of the rock slab is connected to the main rib structure (Photos by Subhajit Sen).



Figure 5

In the northern part of the mesa, the scrap face is highly fragmented due to the widening of joints and fractures in a rectangular shape, and rock blocks collapse, and rectangular boundaries of caliche layers are occupying the slope and foothill of the mesa. (Photos by Subhajit Sen).

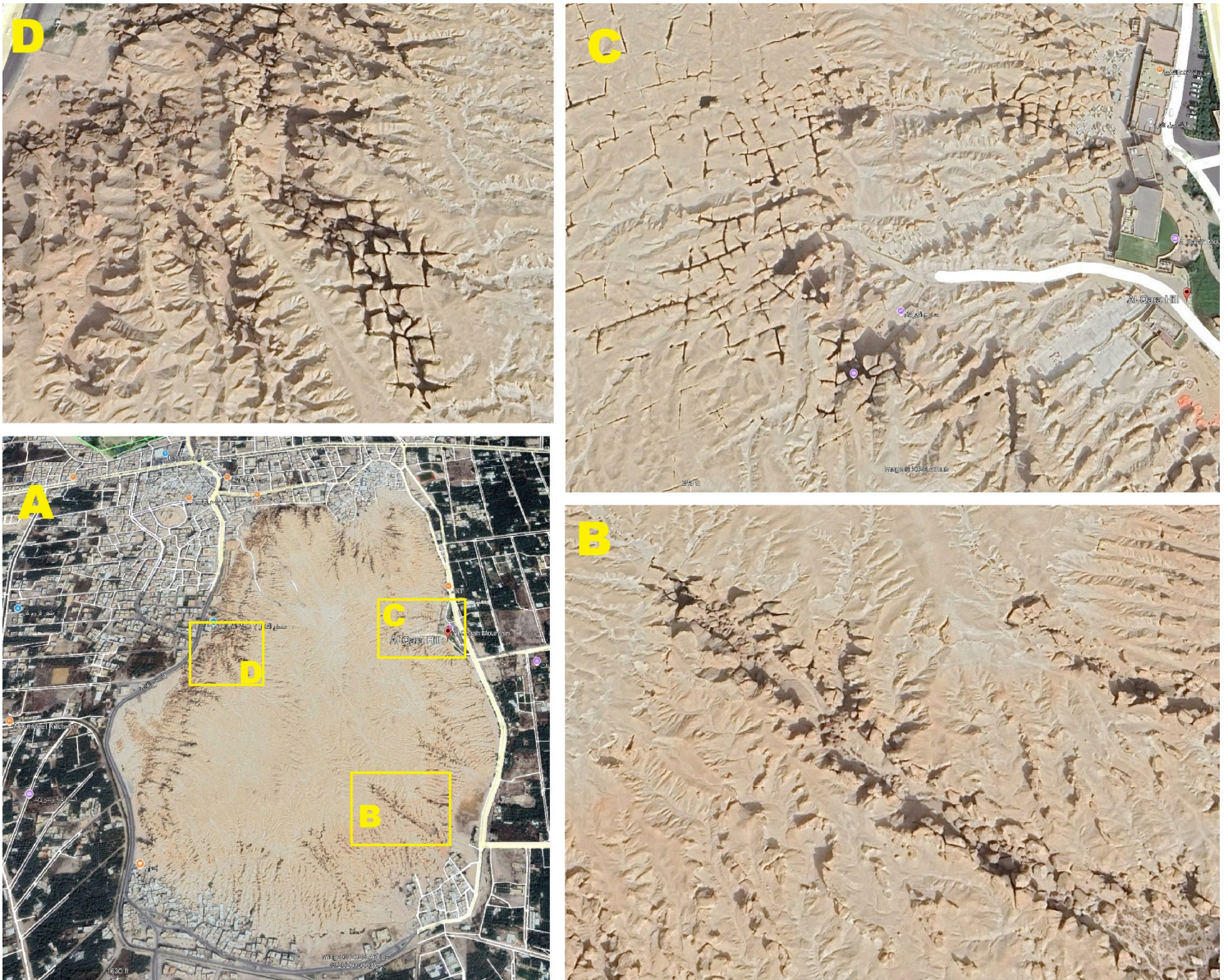


Figure 6

(A) The outer part of Jabal Al Qarah is characterised by (B) open slots filled with boulders, (C) Open slots coincide with the open-up canyons, which is also a street passage to the cave, and (D) closed slots towards the mesa. The slope of the main scarp is fragmented. (Photos by Subhajit Sen).

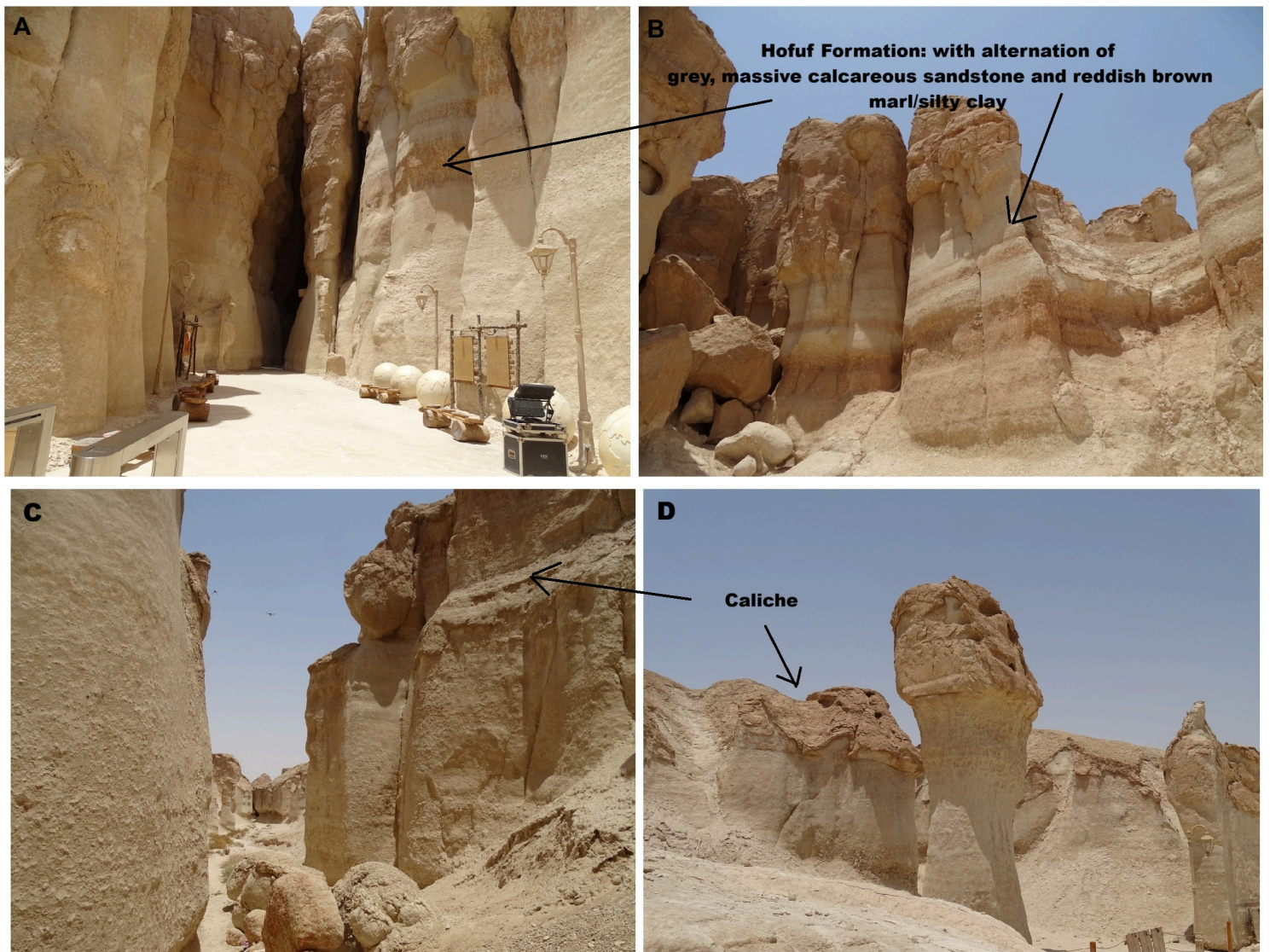


Figure 7

Vertical faults as a passage of connectivity to the surface and subsurface structure (A), which also support in initiating canyons (B). The detached boulder rocks (Hofuf Formation), due to mechanical erosion, are filling the canyon (C). The linear slots in the periphery of the mesa coincide with the parallel fault structures—the side wall of the canyon is characterized by vertical fractures, which eroded and formed rock pillars (D) (Photos by Subhajit Sen).

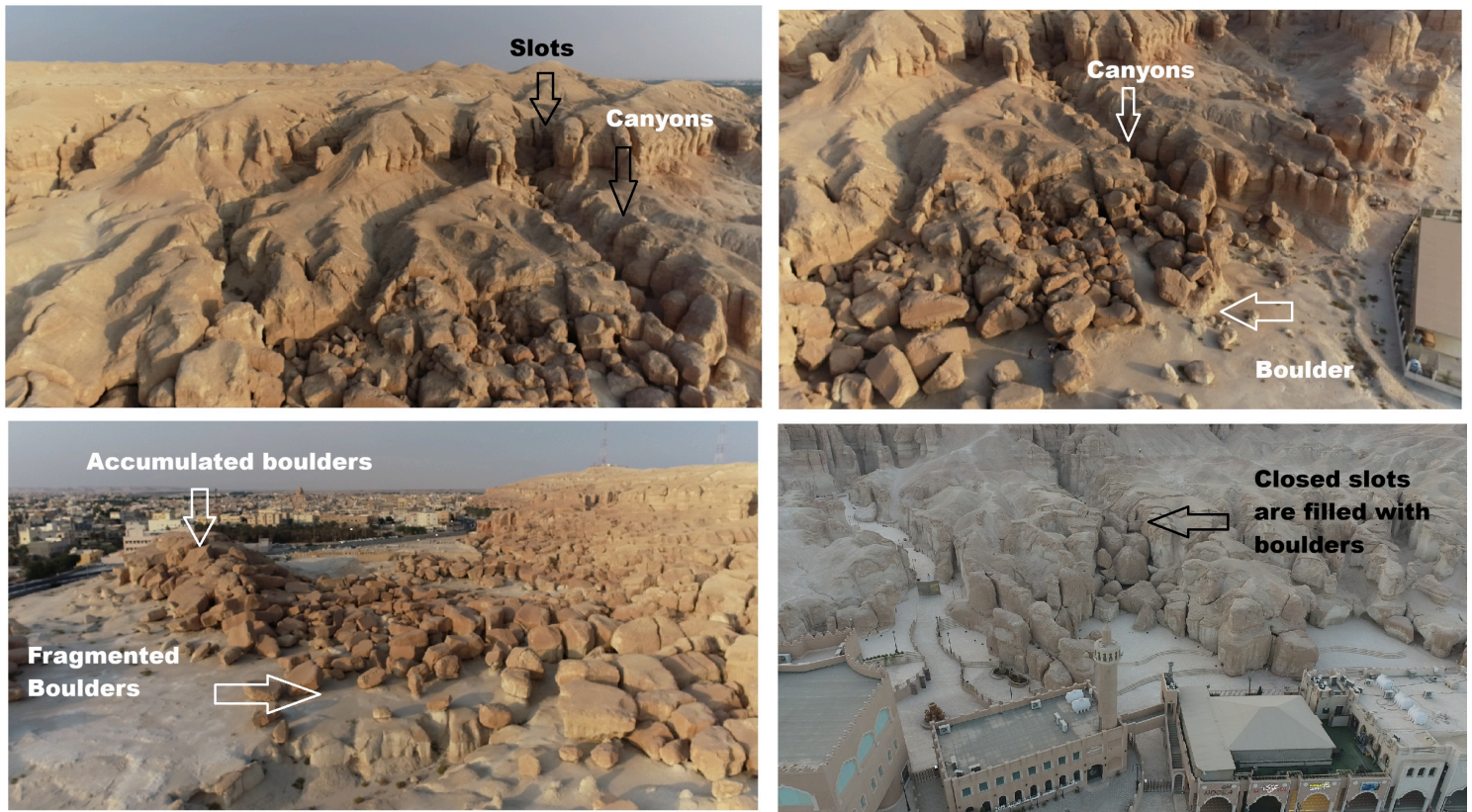


Figure 8

The rectangular joints and fractures detached the boulders from the main units, which are collapsing, forming the Hoodoo rock. (A) Photographs show the fragmented slope of the scarp. Various slots open up to the canyons, which are gradually widened towards the outer part. (B) Detached rectangular boulders occupy the open slots and canyons. (C) The closed and rooted slots are filled with boulders at the entrance of the cave. (D) The eastern part of the mesa is characterized by a linear belt of rectangular boundaries and washout along the canyons; it is composed mostly of claystone, sandstone, and mudstone, either fragmented or accumulated (Photos by Subhajit Sen).

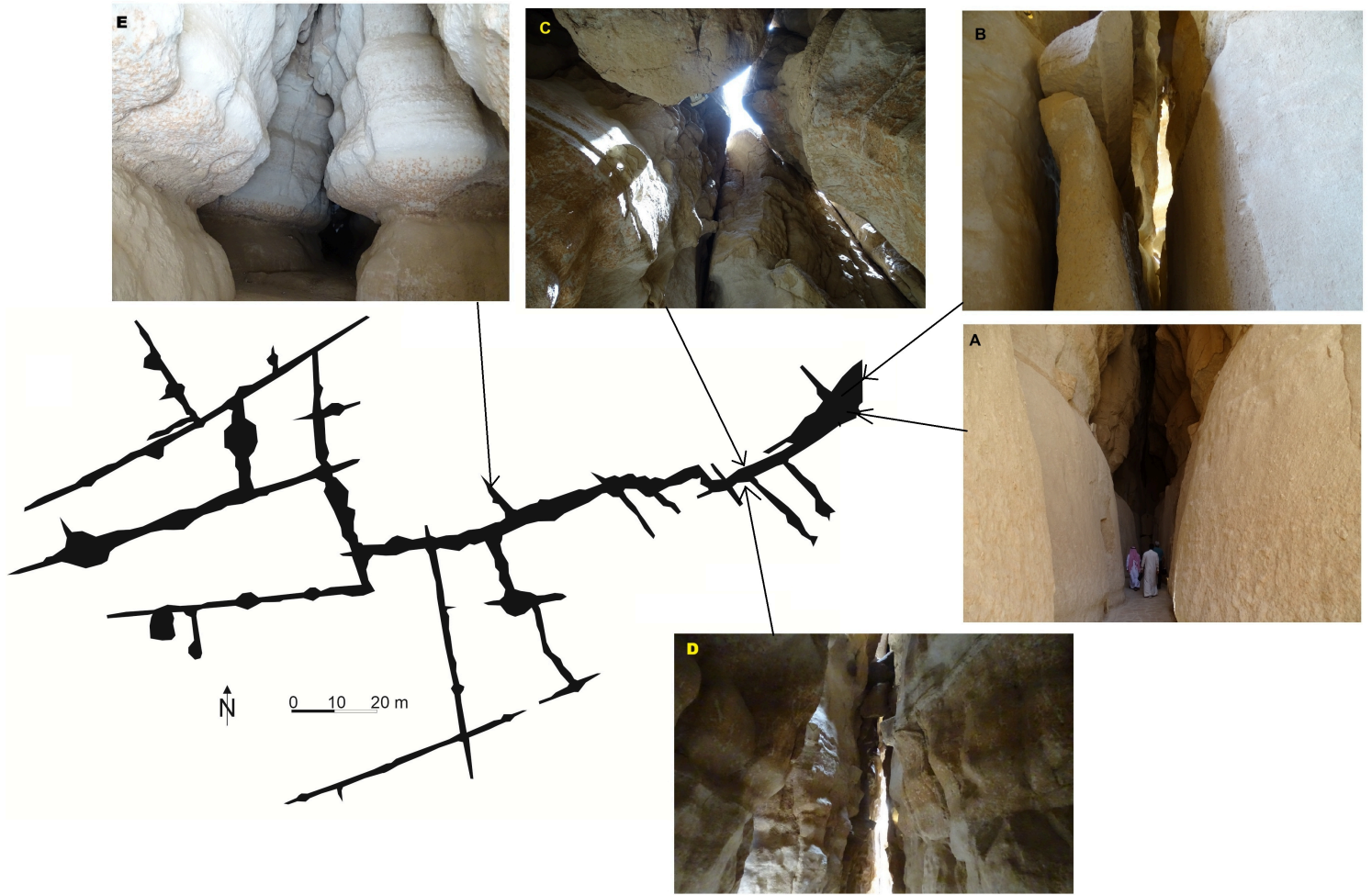


Figure 9

The diagram shows the Ghar An Nashab I cave chambers following the joints and rectangular fault system (Khandaker et al. 2006; Hotzl et al. 1978). Narrow entrance of the cave (A), with the vertical rock blocks detached along the vertical fractures and partially collapsed due to mechanical weathering (B). The ceiling of the cave, exposed to the surface (C), is rectangular, predominantly oriented in NNW and NE directions, and coincides with the rectangular surface fault system (D). (Photos by Subhajit Sen).

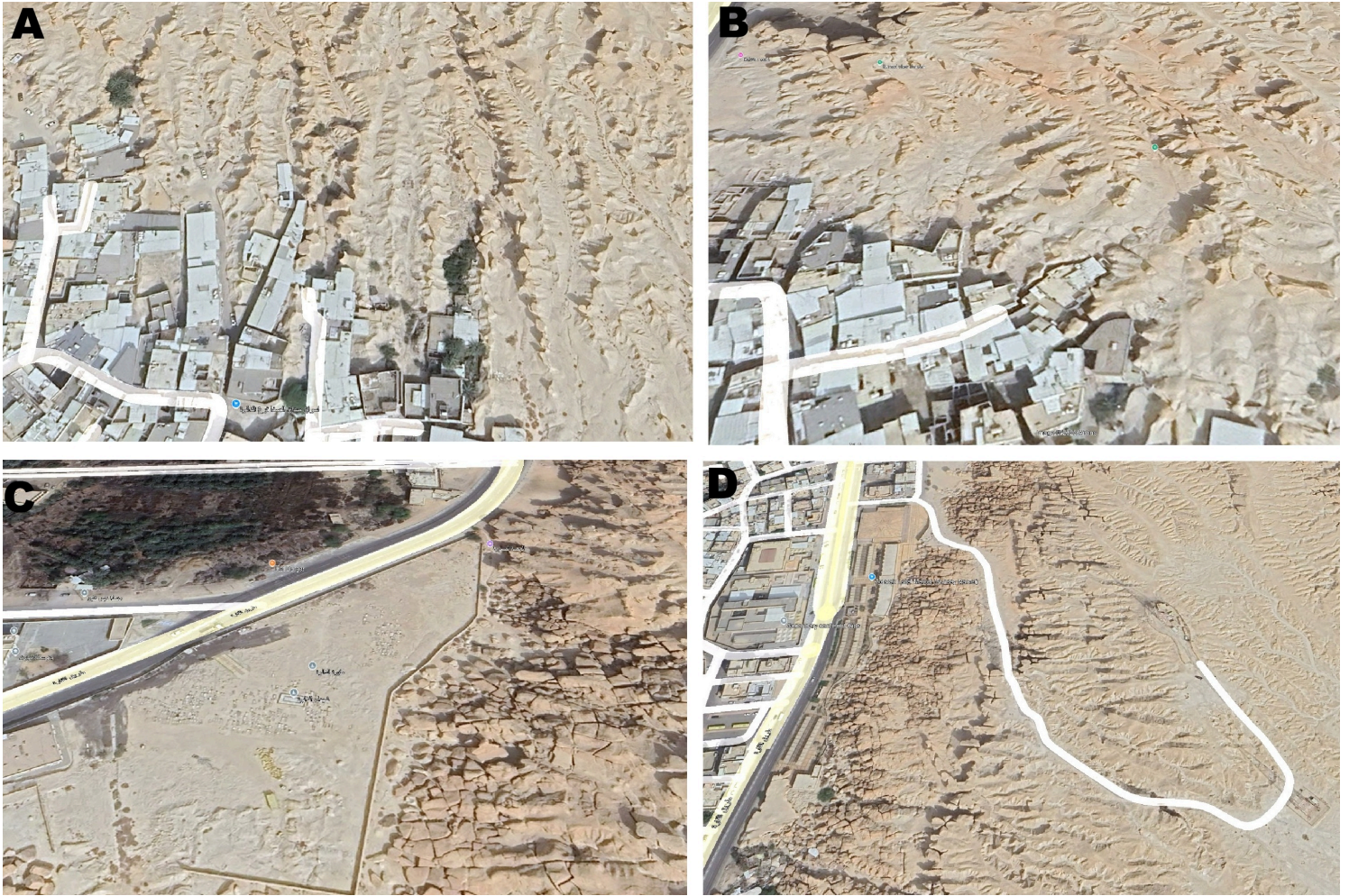


Figure 10

(A) Urban encroachment towards the denuded scarp of Jabal Al Qarah. Hoodoo Rocks and the rock pillar are eliminated. (B) The photograph shows the encroachment of buildings toward the canyons. (C) In the western part, a large boulder field has been transformed into a built-up area. (D) In the north-western part, a telecom town has been constructed. A road has been constructed along the slope to the mesa top. The built-up areas block the scenic view, observational conditions, and, most importantly, the destruction of the hoodoo rock landscape in some of the areas.