Rock Slope Instabilities Affecting the AlUla Archaeological Sites (KSA)

José Ignacio Gallego, Claudio Margottini, Ingrid Perissé Valero, Daniele Spizzichino, Tommaso Beni, Daniela Boldini, Francesca Bonometti, Nicola Casagli, Riccardo Castellanza, Giovanni Battista Crosta, Paolo Frattini, William Frodella, Giovanni Gigli, Edoardo Lusini, Serena Rigamonti, Giulia Rusconi, and Lorenzo Vitrano

Abstract

The paper focuses on the geomorphological processes and potential geo-hazards affecting the cultural heritage rock-cut sites of AlUla region. Its best-known site is Hegra, with more than 110 monumental tombs with elaborated façades carved directly into the sandstone rock. In addition, AlUla hosts a number of fascinating historical and archaeological sites such as its Old Town, surrounded by an ancient oasis, and Dadan, the capital of the Dadan and Lihyan kingdoms. The study is mainly aimed at investigating the local rock material, evaluating characteristics of rock masses, understanding rock degradation processes and characterizing the potential impact of slope instabilities on the conservation of cultural heritage.

Keywords

Geomorphological processes · Rock slope instabilities · Cultural heritage

J. I. Gallego
RCU Royal Commission for AlUla, AlUla, Saudi Arabia
e-mail: j.revilla@rcu.gov.sa

C. Margottini (✉)
UNESCO Chair on the Prevention and Sustainable Management of Geo-Hydrological Hazards, University of Florence, Florence, Italy

I. Perissé Valero
AFALULA French Agency for the Development of AlUla, Paris, France
e-mail: ingrid.perisse@afalula.com

D. Spizzichino
ISPRA Geological Survey of Italy, Rome, Italy
e-mail: daniele.spizzichino@isprambiente.it

T. Beni · N. Casagli · W. Frodella · G. Gigli
Department of Earth Sciences, UNESCO Chair on the Prevention and Sustainable Management of Geo-Hydrological Hazards, University of Florence, Florence, Italy
e-mail: tommaso.beni@unifi.it; nicola.casagli@unifi.it; william.frodella@unifi.it; giovanni.gigli@unifi.it

D. Boldini
Sapienza University of Rome, Rome, Italy
e-mail: daniela.boldini@uniroma1.it

F. Bonometti · R. Castellanza · G. B. Crosta · P. Frattini · S. Rigamonti · G. Rusconi · L. Vitrano
University of Milano Bicocca, Milan, Italy
e-mail: riccardo.castellanza@unimib.it; giovannibattista.crosta@unimib.it; paolo.frattini@unimib.it

E. Lusini
University of Bologna, Bologna, Italy
e-mail: edoardo.lusini@unibo.it

1 Introduction

The present paper focuses on the preliminary assessment of the ongoing and potential geo-hazards affecting the AlUla archaeological sites. Located at 1100 km West from Riyadh, AlUla covers an archaeological area (e.g., necropolis, quarries and settlements) of more than 22,000 m^2 (Fig. 1), where it is possible to walk in a luxury oasis through ancient world heritage sites in a rock cut landscape shaped over million years (Margottini and Spizzichino 2021). Its best-known site is Hegra, the main southern city of the Nabataean kingdom, before becoming a Roman outpost, and the first UNESCO world heritage site in Saudi Arabia. It is conserving over 110 monumental tombs with elaborated façades carved into the sandstone rock. In addition to Hegra, AlUla hosts a number of fascinating historical and archaeological sites such as its Old Town, surrounded by an ancient oasis; Dadan, the capital of the Dadan and Lihyan kingdoms, considered one of the most developed cities of the first millennium BC in the Arabian Peninsula; and thousands of ancient rock-art sites (e.g. Abu Ud, Jabal Ikmah).

Many rock-cut monuments are affected by different natural threats such as surface weathering and erosion, rising dampness, rock surface detachment and large-volume slope instabilities. To ensure the long-term conservation of sites affected by such natural threats, detailed investigations, monitoring and consolidation measures are required, specifically developed for rupestrian cultural heritage sites (Spizzichino et al. 2016; Boldini et al. 2017; Margottini and Spizzichino

© The Author(s) 2023

I. Alcántara-Ayala et al. (eds.), *Progress in Landslide Research and Technology, Volume 2 Issue 2, 2023*, Progress in Landslide Research and Technology, https://doi.org/10.1007/978-3-031-44296-4_24

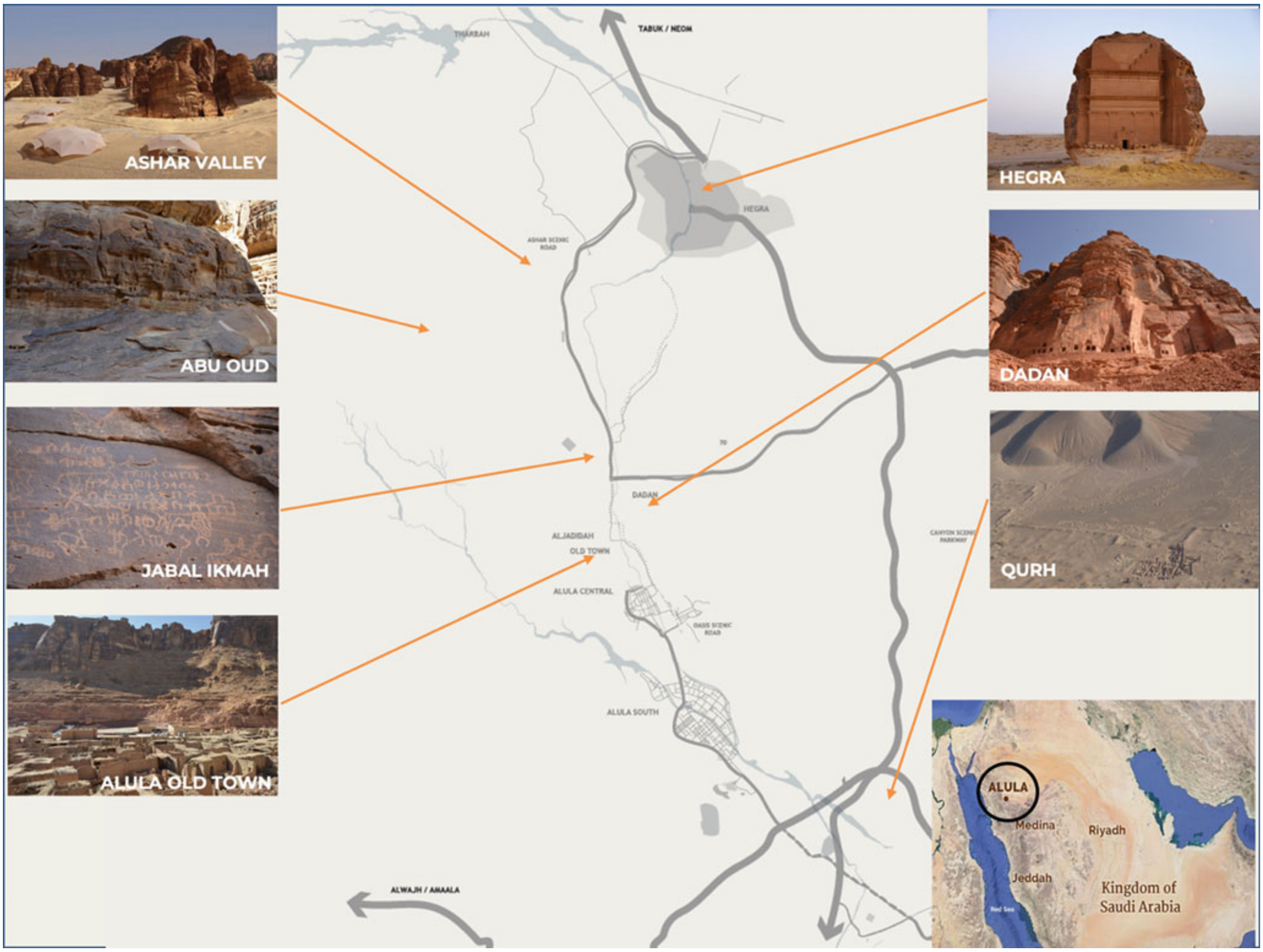


Fig. 1 Map of AlUla oasis and investigated archaeological and natural sites

2022). The activities are characterized by a thorough multidisciplinary approach including competencies in archaeology, engineering geology, rock mechanics, landslide risk assessment and management as well as in conservation, protection and mitigation measures.

To define the main physical and mechanical proprieties of the rock materials, two laboratory test campaigns were carried out, in 2020 and 2021. The structural setting of the rock-mass (bedding planes, joints, faults), related to the stratigraphical genesis, the tectonic activity of the Red sea, and the geomorphological evolution of the slope, was identified and classified. Local rock-mass conditions were found to promote slope instabilities (e.g., rockfall, sliding, toppling) that may affect both the heritage itself and visitors.

This preliminary assessment of prevailing kinematics and potential geo-hazards will allow the implementation of a general master plan, to be considered as a first step for the following detailed design stage. The master plan will contain a first selection of the most appropriated mitigation and consolidation measures, characterized by a low environmental impact and employing, as much as possible, traditional knowledge to site preservation.

2 The AlUla Archaeological Section

The province of AlUla keeps and shows extraordinary human and natural heritage. Its homonym capital is in the center of Wadi Al-Qura, an impressive valley carved out of sandstone, in which there is evidence of human presence, at least, since 200,000 BP. The AlUla *wadis* were a meeting point and a natural route for millennia, crossed by important trade routes used since prehistory, and with special intensity since the first millennium BC. With the flourishing of the cultures of Dadan—Lihyan, and Nabatean one later, the Incense Route, which from the south of the Arabian Peninsula crossed the AlUla region, reached the main eastern ports of the Mediterranean Sea. In this sense, the discussion on the introduction

Fig. 2 Nabatean tombs in the Hegra archaeological site

and spreading of the Neolithic phenomenon in the peninsula is also particularly interesting. These traditional communication routes are punctuated by an astonishing dispersion of rock art and monumental rock structures that provide us with a wealth of information. Regarding the latter, the research projects promoted by the Kingdoms Institute of the Royal Commission for AlUla (Thomas et al. 2021) detected close to 1400 Mustatils. It was possible to obtain the absolute dating of them with 14C, that takes us to the late Neolithic, around 6000 BC (Ramsey 2020; Reimer et al. 2020). AlUla is home to some of the main archaeological landmarks of Arabia, such as the site of Al-Khuraybah, ancient Dadan, capital city of the Dadanite and Lihyanite kingdoms. Dadan was likely one of the most developed cities of the first millennium BC. of the region. As an indisputable heritage legacy, the sandstone valleys also protect thousands of inscriptions in several different languages and alphabets, from Dadanite to modern Arabic. Jabal Ikmah, Abu Ud or Al-Aqra'a are an undoubted and powerful human testimony in the area. Without a doubt, the most recognized archaeological site is Hegra. Extending over 52 hectares, Hegra was the most important Nabatean city and royal cemetery in the south of their kingdom, since at least the first century BC (Fig. 2). UNESCO world heritage site since 2008, Hegra protects more than a hundred monumental tombs from this period, and had continuity during the Roman period, probably as one of the southernmost places in the province of Arabia Petrea. After the transition to Islam in the seventh century, the cities of Q'uhr and AlUla appeared in written sources as important places for pilgrimage routes. Testimony of this is reflected both in the archaeological remains of the first, next to the town of Mughaira, and in the Old Town of AlUla, whose streets, squares, and farms seem frozen in time.

The latest reflection of this evolution is made up of the characteristic elements of the Ottoman presence, both in the form of various fortifications and military equipment, as well as that of the Hijaz railway. Its construction, which was intended to complete the connection of Damascus with Madinah, was suspended by the First World War. Figure 3 summarizes the chronology for AlUla civilization.

3 Geological Setting

From the geological point of view, the area of AlUla is located at the border between the basement complex and the Arabian foreland, constituted by coarse clastic sediments (mainly sandstone). The detailed distribution of the various geological formations is reported in Fig. 3 (modified after Donald and Hadley 1987).

Outcropping succession in the AlUla archaeological region includes the Siq Sandstone and Quweira Sandstone and the upper Quaternary alluvial deposits. The sandstone layers are sub-horizontal, gently dipping about 5° in N-NE (330°N). From the geological profile reconstructed by Buro Happold Engineering (2019) it is possible to notice that, due to this gentle dipping and due to topography, the Siq Red Sandstone is mainly outcropping in AlUla and surrounding (Dadan, Old Town, etc.) while, in the Hegra area, the Quweira Sandstone is dominant. The Quweira occurs in cross-bedded stratifications with bed thicknesses of 2 to 5 m (Table 1).

The Siq Sandstone, dark red to brownish-red and medium-grained, is divided into three sub-units, namely the Lower (sandstone conglomerate of white quartz cobbles), Middle (fine, fractured strata) and Upper Siq (massive and very compact) Sandstones (Fig. 4).

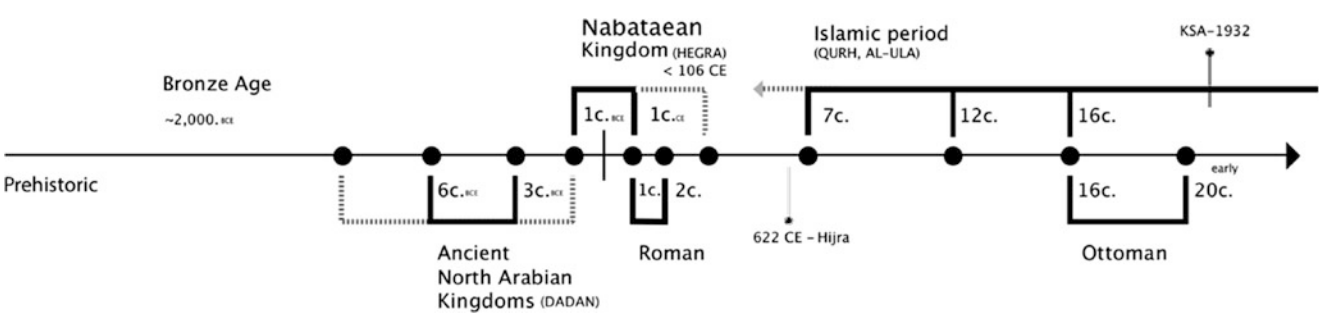


Fig. 3 The AlUla chronology (source https://www.rcu.gov.sa)

Table 1 Litho-stratigraphic units and sub-units in the region of AlUla

Age (period)	Geological unit	Sub unit
Early Ordovician	Saq Sandstone	
Late Cambrian	Quweira Sandstone	
Middle Cambrian		
Early Cambrian	Siq Sandstone	Upper
		Middle
		Lower
Proterozoic basement (pre-Cambrian Arabian shield)	Jibalah Group and basement	

The panoramic photograph in Fig. 5, taken on 2014 from the "highpoint" on top of Harrat (lava plain or volcanic field of Al Uwayrid west of AlUla - Wahbi), displays most of the lytho-stratgraphic succession in the area. This division is evident from the erosion profile of the outcrops in the area (Fig. 5).

4 Physical and Mechanic Characterization of Rock Mass and Rock Material

4.1 Field Survey and Rock-Mass Characterization

Geo-mechanical characteristics of the AlUla rock formations were investigated through geomechanical field surveys and laboratory tests, these latter executed directly in Italy

SYMBOL	ID	AGE	UNIT	MATERIAL
	Qal	Quaternary		Alluvium
	Qu			Alluvium
	Tb	Quaternary	Harrat	Flood basalt
	Qeqr	Ordovician – Cambrian	Saq Sandstone, Quweira group,	Sandstone
	€s		Siq group	Sandstone
	Ju	Proterozoic	…	…
	dq		…	…
	aju		Lower Jiddah group	Lava and pyroclastic rock

Fig. 4 Geological map of AlUla region (modified after Donald and Hadley 1987)

(Gallego et al., in printing). The surveys were carried out following the recommendation of the International Society for Rock Mechanics (ISRM 1978a, b, 1981). The following activities were carried out directly during field surveys in Hegra and Dadan (Table 2):

1. geo-structural analysis of the slope façades (orientation and main characteristics of discontinuities);
2. Barton's profilometer tests for reconstructing the joint roughness (JRC);
3. sampling of blocks to be used for laboratory testing;
4. Schmidt-hammer tests on joint surfaces and intact rock blocks for in-situ assessment of the uniaxial compressive strength (JCS);
5. tilt tests for base friction angle assessment (φ_b).

The rock mass classification index GSI was also assessed (Table 2).

4.2 Laboratory Tests

During the December 2020 campaign (Gallego et al. 2022), five rock samples were collected near the cities of Mada'in Salih (better known as Hegra) and Dadan (Fig. 5). They consist of two Yellowish Sandstone blocks, belonging to the Quweira Group, and three Red Sandstone blocks of the Siq Group (Fig. 6). A total of 40 specimens were prepared for the mechanical tests, of which 22 for the uniaxial compression test (Fig. 7a), with a diameter of about 25 mm, and 18 for the Brazilian test (Fig. 7b), with a diameter of about 50 mm. Uniaxial compression tests and Brazilian tests were performed using a 10 and 50 kN load cells, applying respectively a load rate of 0.5 MPa/s and 200 N/s (ISRM 1978c). Before the mechanical tests, the P wave velocity was also measured on all the specimens. The average values of the physical and mechanical properties for each sample are summarized in Table 3.

The increase in porosity reduces significantly V_P values for both rock formations, with differentiated trends for the Yellowish and Red Sandstone samples (Fig. 7).

The uniaxial compressive strength σ_c ranges from less than 10 MPa for a specimen of the sample 2 to over 50 MPa for a specimen of the sample 1, both belonging to

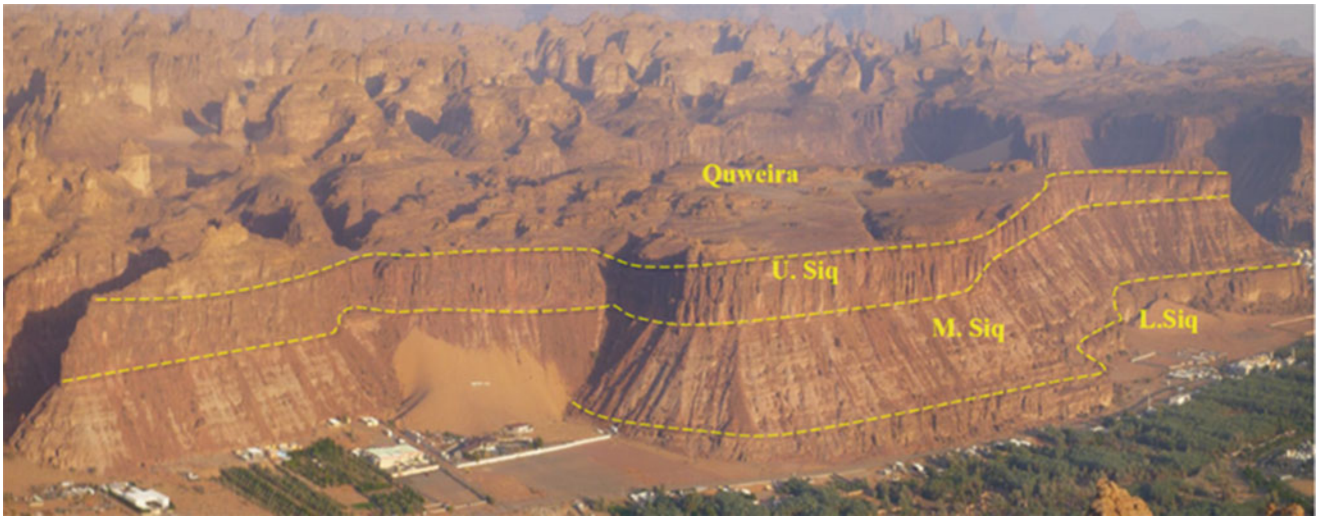


Fig. 5 Panoramic view (slightly vertically-exaggerated) of the litho-stratigraphic succession in the AlUla area, taken from the highpoint of Harrat Al Uwayrid, west of the town of AlUla. Sandstone units are recognized in this section, except for the Saq Sandstone, which outcrops out further north of this area (Wahbi 2014)

the Yellowish Sandstone lithotype. Specimens prepared from the Red Sandstone blocks are characterized by σ_c values in the range 18–42 MPa.

Consistently, specimens from samples 1 and 2 display respectively the highest and lowest values of the tensile strength σ_t, from almost 8 MPa in the case of the first block down to about 0.5 MPa in the second one. Values of σ_t similar to those obtained for the sample 1 were identified for specimens obtained from samples 3 and 4, while significantly lower values were attained by the two specimens cored from sample 5. In general, inspection of the two figures highlights the substantial influence of porosity on the rock material strength (Fig. 8).

5 Geo-hazards and Morphological Processes Threatening the Sites

The term geo-hazards includes very different types of morphological processes and involve both long-term and short-term geological processes. In the following, the main instability and weathering problems affecting the sites at different scales are briefly described.

The different archaeological sites of AlUla region are completely carved and realized into the Quweira and Siq Sandstones. The local quality of the rock-mass is directly depending on:

1. lithology and rock material of depositional layers (e.g. minerals, texture and composition);
2. level and typology of weathering and erosion;
3. structural setting (e.g. joints, fractures, faults).

The slope angle for most of the rock faces is prevalently higher than 80°, with frequent overhanging surfaces consequent to erosive processes or block collapses at their base. Slope kinematics, and thus potential failure modes, is mainly ruled by high and medium dip angle of the main discontinuities versus local slope orientation. Also the presence of horizontal discontinuities (bedding planes) is conditioning failure modes and volumes of potential instability (see Fig. 10).

Following is a description for each investigated site.

5.1 Hegra

The archaeological area of Hegra occupies a flood plain in the orographic left area of the northern part of the AlUla oasis. It is characterized by the outcrop of small hills formed by sandstone blocks (QEqr) completely immersed in a real small desert of gravel deposits (Qu).

Table 2 Average discontinuity and rock mass parameters for Hegra and Dadan sites from the first campaign in 2020 (Gallego et al. 2022)

	JCS	JRC	φ_b	GSI
	MPa	–	(°)	–
Hegra	32–42	2–6	37–43	67
Dadan	28–41	4–8	40–45	65

Fig. 6 Location of rock blocks collection

The characteristic formations that host the Nabatean necropolis are the final and cumulative result of two different and combined (mutually interdependent) morphological processes. The first, with very slow evolution, concerns the effects of wind erosion and precipitation. The second, in rapid evolution, concerns the diffused collapse phenomena that develop along the edges of the façades for structural and geo-mechanical factors.

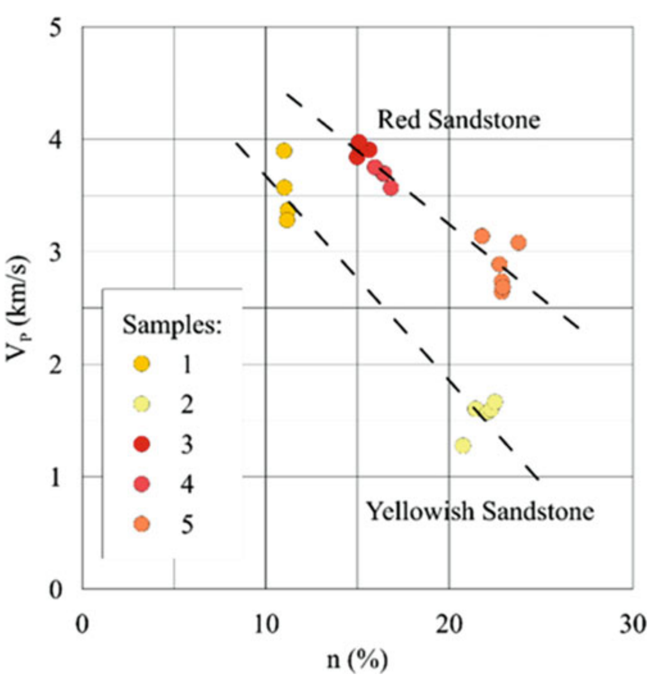


Fig. 7 P wave velocity against total porosity (Gallego et al. 2022)

The first process leads to the creation of spectacular weathering and erosive forms typical of these geological formations which in their final stage produce the so-called rock mushroom (Fig. 9).

In the second case widespread processes of morphological instability or geo-hazards (mainly rockfall) occur, which characterize both the external and internal portion of the tombs and also the rock masses in which they were built.

The erosional phenomena promote also the thinning of different support structures (pillar, eves, rock wall, architraves and gates) inside and outside the tomb as well along and on the top of natural slope.

The main instability processes affecting the whole Hegra archaeological area are:

1. Rockfall, rock sliding, wedge failure, toppling, free fall (from small to medium to large dimensions) affecting both the rock façade and the slope in which the tombs are carved;
2. Collapse (from very small to medium dimensions) involving directly the carved architectonic structure of the Tombs;
3. Weathering and erosion processes (from small to large scale) affecting both the slope facade and Tombs.

Some examples of the three typologies above mentioned are reported in the following Fig. 10.

Table 3 Summary of the physical and mechanical properties of the rock materials (Gallego et al. 2022)

Sample	ρ_{dry} (Mg/m^3)	ρ_s (Mg/m^3)	n (%)	V_p (km/s)	σ_c (MPa)	σ_t (MPa)
1	2.390	2.688	11.1	3.5	50.24	6.83
2	2.087	2.669	21.8	1.5	9.93	0.50
3	2.265	2.679	15.8	3.9	38.51	7.68
4	2.238	2.678	16.4	3.7	41.18	6.46
5	2.060	2.694	23.6	2.9	24.85	2.74

All the 138 tombs were investigated, collecting parameters that are synthesized in the following Table 4. Geometrical data were provided by a laser scanning survey TLS (Fig. 11).

All the information were managed within a GIS software, providing detail information about the state of conservation for each tomb. A global rank about the state of conservation among all tombs was also provided, giving an outcome as showed for some examples in Fig. 12.

5.2 Dadan

The site of Dadan is landscaped composed by an alluvial plane with archaeological remains only partially excavated, a gentle slope with few tombs, a vertical cliff that in the lower part was used as a quarry to collect stones for the construction of nearby village and where, at later stage, many tombs belonging to people with high social status were digged, the upper part of the mountain where ritual installations, rock art and defensive installation are located (Fig. 13).

From the previous landscape zoning it is quite evident that the highest energy of relief, a quantitative parameter representing the maximum difference in elevation between the highest point and the lowest point measured in a given area, is concentrated on the vertical cliff were the quarry and the tombs are located. High energy of relief means high susceptibility of cliff instabilities, potentially involving both archaeological remains and visitors.

From a mechanical point of view, the area of Dadan (Fig. 14) is characterized by a 20 to 25 m thick massive sandstone layer in the upper Siq (SU), laying directly over the transition from the Middle Siq to the Upper Siq unit (characterized also by a small thickness silty to clayey beds, such as SM). The SU layer was quarried because of the position and of the physical and mechanical characteristics that made the rock material suitable for construction. Excavation was carried out with different techniques that can be identified by the presence of natural and induced fractures or linear pick marks. Extraction was performed both parallel and perpendicular to the slope face. Some evidence of the quarrying activities is the presence of holes for placing scaffolding-like structures or for moving along the slope or for anchoring ropes. Quarrying was performed by taking advantage of weak bedding or lamination planes, and open or latent discontinuities. Chisels, points, hammers, picks,

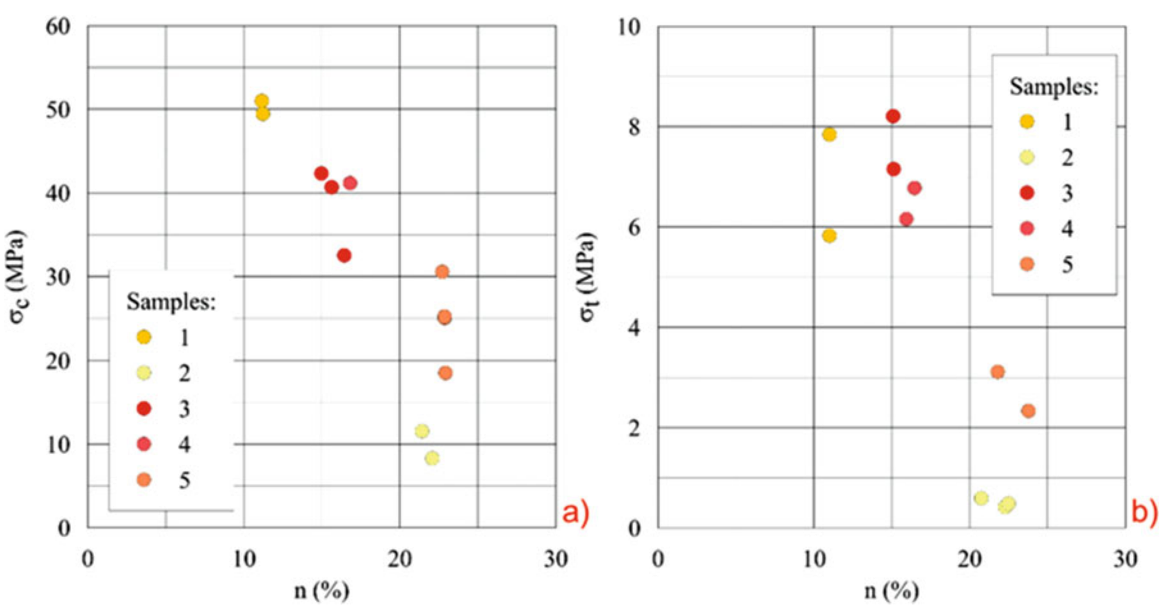


Fig. 8 Uniaxial compressive strength (**a**) and tensile strength (**b**) against total porosity (Gallego et al. 2022)

Fig. 9 Typical weathering and erosional patterns in the Hegra site

saws, and wedges were used to cut, excavate and open artificial fractures or for removal of large blocks by a progressive lowering of the upper rock face surface.

In the upper part, the Quweira sandstone (Q) is outcropping.

As a matter of fact, the area of Dadan is highly affected by rockfalls in general. Some relevant examples of potentially unstable blocks affecting the rocky cliff were surveyed during field investigations and are summarized in the following. The slopes are prevalently sub vertical to vertical (>80°), especially along the quarry area, and gentler along the talus and quarry waste deposits. The outcropping sandstone

Fig. 10 Example of the main instability processes affecting the different tombs in Hegra: upper sequence of photos stands for rock slide and free fall; middle sequence is reporting small cracks, fractures and detachment affecting the tomb façade; lower sequence is showing weathering and erosive processes present in the area

Table 4 Information provided for each tomb

	Parameters	Description
P1	Generalities	Group, Name of the tomb (if any); Number; coordinates
P2	Map	Topography or Google Earth image
P3	Photo	Number
P4	TLS	
P5	Archeology	Brief description of the tomb and relevant index
P6	State of conservation from visual inspection	Describe surface erosion, weathering, small falls etc.; excellent; very good; good; low; very low—endangered;
P6–1	Numerical ranking	(Ranking: 100–75–50–25–0)
P7	Geomorphological phenomena	Describe occurred or potential rockfall, wedge, planar, toppling instabilities and their possible volume (cm^3)
P8	Geology	
P9	Groundwater	
P10	Rock/soil materials	Density, UCS (Hammer), JCS, Tilt test, GSI
P11	Kinematic analysis	Stereo plot
P11–1	Slope face	Dip direction and dip angles (α and β)
P12	Possible monitoring	Proposal
P13	Potential evolution or risk	Hypothesis
P14	Notes	

presents a few prominent sub vertical discontinuity sets (N-S, E-W, ENE-WSW) whose origin, especially the joint system parallel to the slope face, can be associated to main regional tectonic trends. Unstable blocks, kinematics and the potential failure modes are mainly ruled by steeply dipping discontinuities sub parallel to the local slope orientation (see Fig. 14) and the sub horizontal bedding. These generate detachments with overhanging elements and only very minor sliding components.

In addition, it can be noted that the main joint sets have been used as weak planes along which quarrying activities were carried. The presence, spacing and continuity of bedding are conditioning factors controlling both the failure modes and unstable block volumes (Fig. 15).

According to the geomorphological survey of the area, the main typologies of instability processes are rockfalls (planar slide, wedge failure, toppling and free fall) in the vertical cliff with Upper Siq sandstone and Quweira on top of the area and rill erosion in the gentle slope where the Middle siq is outcropping. More in detail it is possible to recognize the following processes and related dangerous situations:

1. potential planar slide, wedge failure, toppling and free fall (from small to medium to large dimensions), affecting the whole rocky cliffs, both in the vertical Upper Siq sandstone and in the topmost Quweira sandstone;
2. runout of blocks collapsing from the cliff, falling, bouncing and rolling in the lower part of the cliff, mainly concentrated along the gorges of the slope but also along the talus;
3. fall of loose small blocks and debris, standing on the various morphological terraces above the quarry. This category can be considered a subset of item 1;
4. in the intermediate Siq formation, represented by the inclined deposit at the bottom of the cliff, also partially covered by collapsed blocks and debris from the quarry, in occasion of heavy rainfall some important rill erosion may occur.

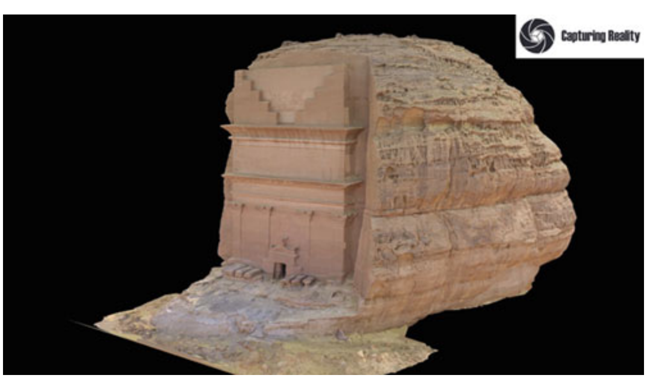


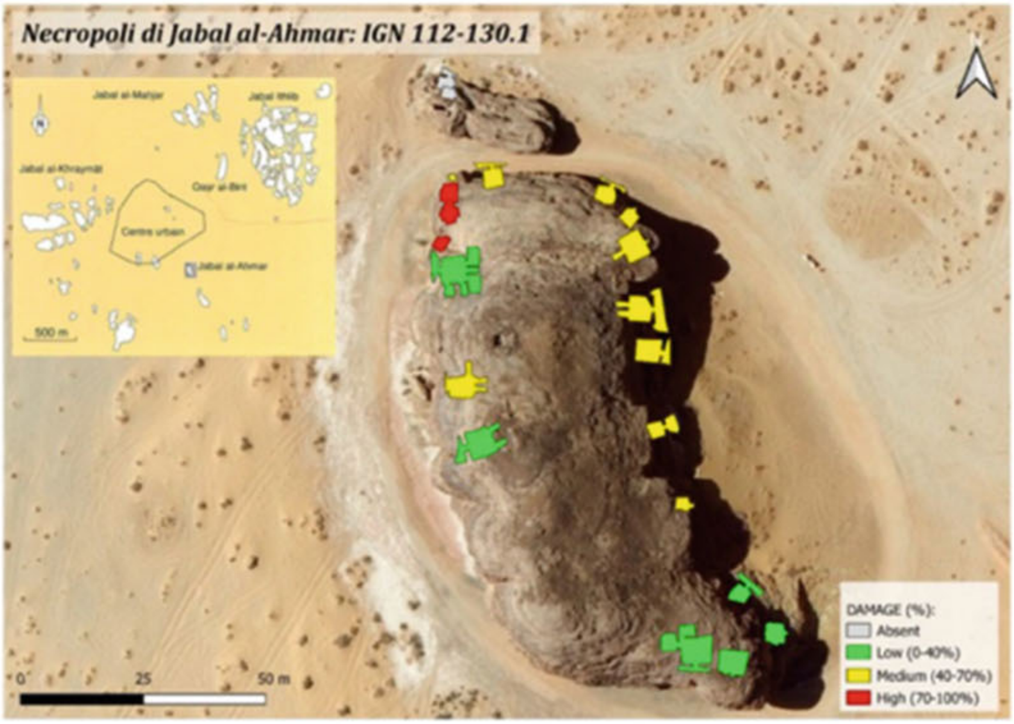
Fig. 11 Example of laser scanner survey (TLS) in Hegra: the tomb of Al Farid (courtesy of Factum Foundation)

Figures 16, 17, 18 and 19 show the above four typologies of geomorphological instability processes.

When looking at the impact of previous processes (hazard) on exposed elements, it is important to notice the following (Fig. 20):

1. the collapse of small/medium blocks from the quarried part of the cliff may damage the archaeological remains, i.e. the tombs carved on the cliff, either directly impacting on them or having the carved tomb as part of the collapsing block (Fig. 18);

Necropolis of Jabal al-Ahmar



ID tomb	State of conservation	Geom. Phenomena	Damage	Geology	Groundwater	Kinematic analysis	Slope face	Possible monitoring	Potential evolution or risk	notes	estimated tomb height (m)
112	75%	E(b), I	L	Q	N	2	190/87	VI	Ev(I,u)	CI(u), Di	10
113	75%	E(b), K	L	Q	N	1	185/85	VI	EvK(i)	NR	10
114	75%	S(u)	L	Q	N	1	78/85	VI	EvK(e,u)	CI(u), Di	7
115	75%	S(u)	L	Q	N	1	40/88	VI	EvI, Co	NR, Co(e,I)	7
116	50%	O(u)	M	Q	N	2	92/70	VI	EvI(u)	Im(a)	2
116,1	50%	S(u)	M	Ab	Ab	0	65/89	VI	Ev(u)	Im(a)	4
117	50%	S(u)	M	Q	N	2	102/90	VI	Ex(i), Ck(fa)	NR	5
118	50%	S(u), K(fa), De(i)	M	Q	N	0	260/90	VI	EvI(I), K(c)	Pr	8
119	50%	E(b),In(fa)	M	Q	N	0	66/90	VI	C(u)	Di	8
120	50%	E(b), In (fa)	M	Q	N	0	56/90	VI	In	Di	7
121	50%	E(b)	M	Q	N	0	30/85	VI	EvI(I), Rf(u)	Im(a)	6
122	50%	E(b)	M	Q	N	0	175/85	VI	EVI(I), Rf(u)	NR	7
123	25-50%	C	M	Q	N	0	284/90	VI	EvC(I,i)	Ua	2
124	20%	C, I(u)	H	Q	N	1	285/90	VI	C(r)	Su, Co	3
125	20%	I, O(f)	H	Q	N	0	285/90	VI	C(f)	Di	2
126	20%	E(fa), C(r)	H	Q	N	0	285/90	VI	C(r)	Su	3
127	75%	K, In	L	Q	N	0	276/90	VI	K	Ks, Im(a)	6
128	25-50%	C, E(b), K(a)	M	Q	N	3	265/90	VI	C(a), I(I), Rs, Rf(u)	Su, Di	7
129	75%	E(b), I(I), O(u), De(ev)	L	Q	N	2	253/90	VI	F	Di	7
130	Ab	Ab	Ab	Q	N	Ab	Ab	Ab	Ab	Ab	Ab

Fig. 12 Global ranking for the state of conservation of Hegra tombs. Example from Necropolis of Jabal al-Ahmar. The color is indicating the degree of damage

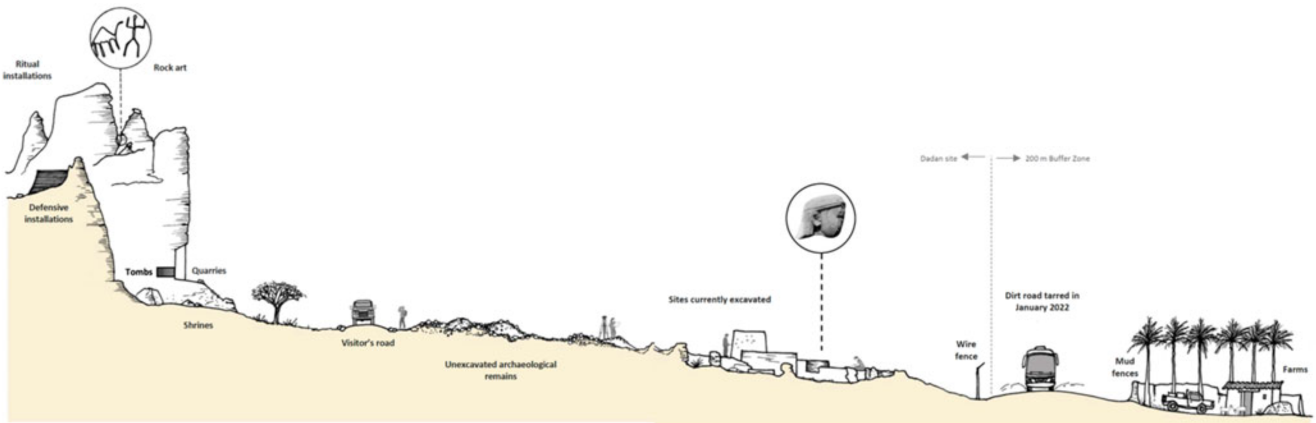


Fig. 13 The landscape zoning with major archaeological settlements in Dadan area (After Moriset and Gandreau 2022)

2. fallen blocks from the upper part of the cliff, during the runout, may potentially impact on visitors at the toe of the slope (Fig. 21) and on cars driving on the earth road inside the archaeological park; such block can also damage the tombs located in the intermediate Siq formation (Fig. 22);
3. the already detached small blocks and debris standing on the various morphological terraces above the quarry may potentially impact on visitors at the toe of the slope;
4. the occasional rill erosion in the medium Siq formation may also damage the tombs located in this part of the slope.

5.3 AlUla Old Town

AlUla Old Town is currently exhibiting an important development. Buildings are under restoration and the main road is showing new shops and commercial activities (Fig. 23).

In the present situation is becoming essential to understand the potential impact on people and buildings of falling blocks coming from the Western cliff, investigating their possible trajectory and runout.

According to Varnes (1978), rockfall events involve the detachment (sliding, wedge, toppling and free fall) of rock mass fragments, which are then transported by gravity (runout) through free fall, bouncing, rolling, sliding, and are ultimately deposited on a talus cone or as individual debris deposits. Thus, rockfalls can be damaging events, and assessing rockfall potential and past rockfall events are important to analyse potential risks and discuss mitigation strategies. Review works on rockfall hazard assessments are provided by Ferrari et al. (2016), Gerber (2019), Loew et al. (2021) and Marija et al. (2022).

The measurement of size and shape for a large number of boulders (rock blocks) in the field is cumbersome and very time-consuming. Nevertheless, the size (volume) and shape of the boulders belonging to a rockfall are expected to provide helpful information for the understanding of transport

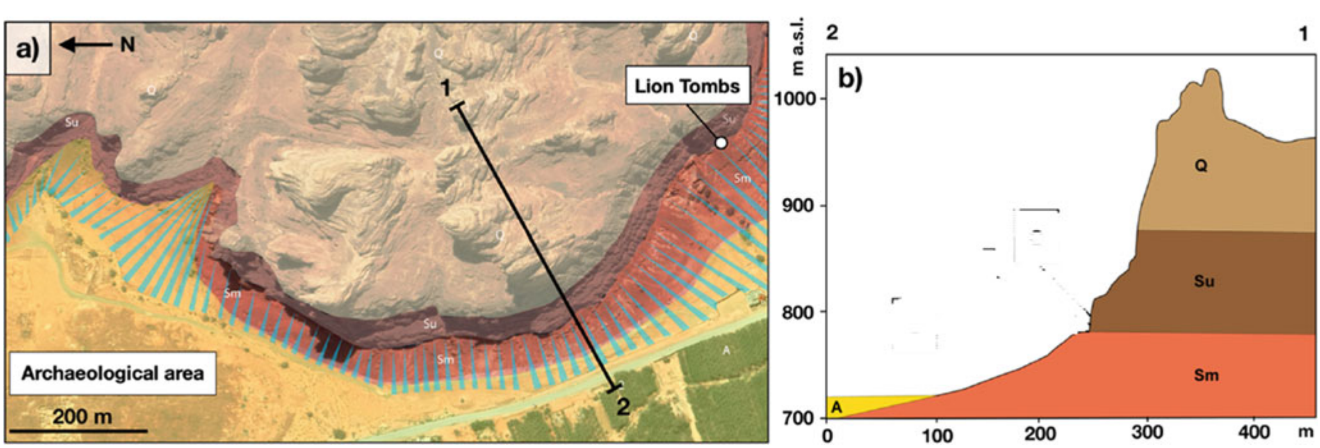


Fig. 14 Geological insights of the Dadan archaeological area: (**a**) the geologic chart projected on the satellite image (from Google Earth©), the blue lines represent the debris from the old quarry, as well as the debris cones and the talus accumulation, "Sm" stands for Middle Siq sandstone, "Su" for Upper Siq sandstone, "Q" for Quweira sandstone and "A" for alluvial deposits

Fig. 15 Examples of rock façade at Dadan site. Type, spacing and fracturing of the joints are clearly evident. The lower strata are interested by the quarry excavated during the Dadanite time. In the latter joints and discontinuities were used to facilitate the carving of the quarry, as well as of the ancient tombs

Fig. 17 Rock boulders freely running on the slope after the collapse, until resting at the toe of the cliff

and run-out dynamics of rock particles as well as calibration for modelling. Therefore, lidar point cloud and satellite images were used to measure the size (volume), the shape and the run-out length of most boulders.

Such approach provided a landslide inventory map, in terms of surface block distribution, as relevant input data for a 3D rockfall simulation model, coupled with topographic and geotechnical data. The map in Fig. 24 represents the accumulation area where the boulders runout after the detachment from the cliff. Figure 24 provides also a detail of the general rockfall inventory map and the related frequency/ distance chart.

Fig. 16 Example of rockfall affecting the rocky cliff of Dadan

Considering the difficulties in the direct identification of source areas in the field, due to the elevated morphology, a relevant support was provided by the use of a semi-automatic kinematic analysis (Gigli and Casagli 2011). From this tool, the identification of susceptible areas was developed and coupled with field survey. Figure 25 shows the global kinematic index, summing up the hazard for the various typologies of instabilities (Gigli and Casagli 2011).

The rockfall runout simulation was performed by using the 3D model Hy-STONE (Agliardi and Crosta 2003; Crosta and Agliardi 2003).

The 3D models are able to simulate block motion along a slope by including lateral dispersion of trajectories due to large and small scale morphological complexity (Descoeudres and Zimmermann 1987: Guzzetti et al., 2002; Agliardi and Crosta 2003; Crosta and Agliardi 2003; Dorren et al. 2006). The obtained results are spatially distributed over the entire study area, without need for any interpolation of

Fig. 18 Already detached small blocks and debris on the cliff terraces, potentially falling on visitors

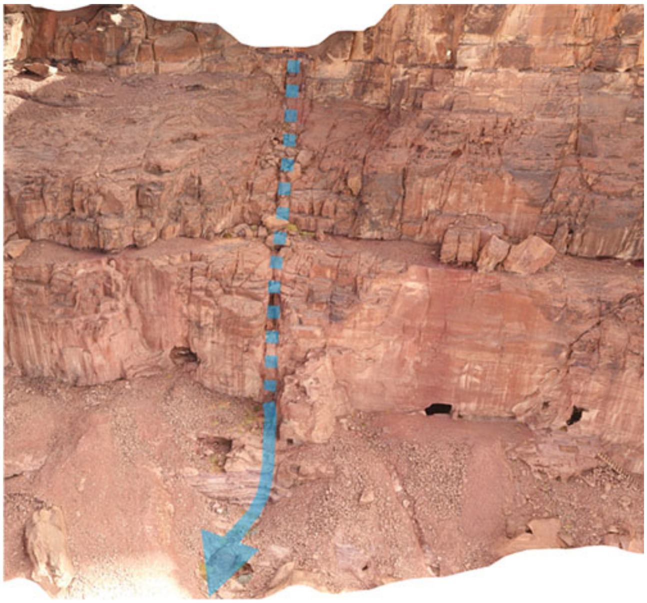


Fig. 19 Rill erosion (dashed line) occurring at the medium Siq formation (inclined strata) in occasion of heavy rainfall, damaging the archaeological remains

data computing along specific trajectories or imposing predetermined fall direction.

Hy-STONE incorporates both kinematic (lumped mass) and hybrid (mixed kinematic-dynamic) algorithms, allowing to model free fall, impact and rolling. Different damping relationships are available to simulate energy loss at impact or by rolling. The topography is described by a raster DEM, which is converted in a vector topographic model (Triangulate Regular Network, Guzzetti et al. 2002) for the solution of impact and rolling.

The stochastic nature of rockfall processes is introduced as a function of model spatial resolution and by random sampling most parameters from different PDFs (e.g. uniform,

Fig. 20 Potential collapse in the quarried part of the slope and involving archaeological remains

Fig. 21 Collapsed blocks at the toe of the cliff with the pedestrian pathway passing through. This is a clear example of a pathway standing too close to the cliff and exposing visitors to a potential risk of being involved in a rockfall

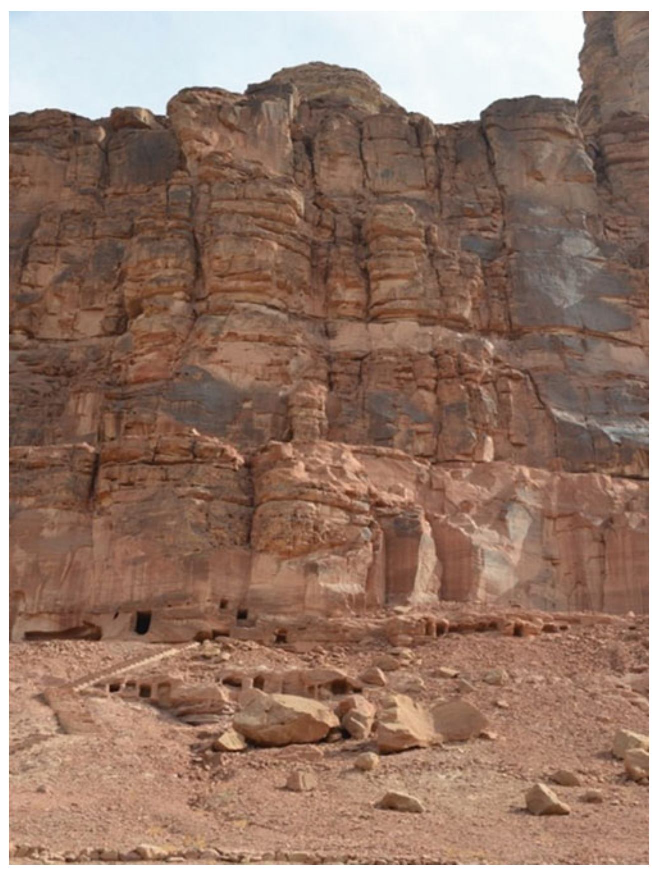


Fig. 22 Tombs located in the intermediate Siq formation and damaged by the runout of collapsed blocks

Fig. 23 General view of AlUla Old Town and the dangerous Western cliff

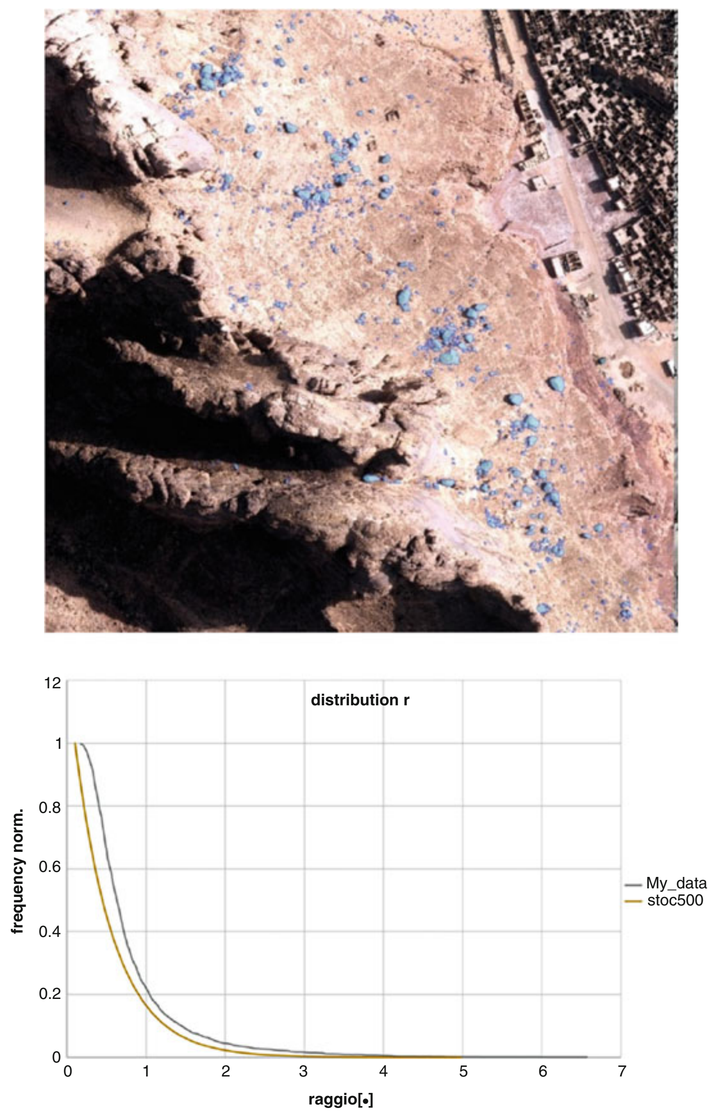


Fig. 24 Rock block inventory along the Western cliff and frequency/distance distribution from origin source

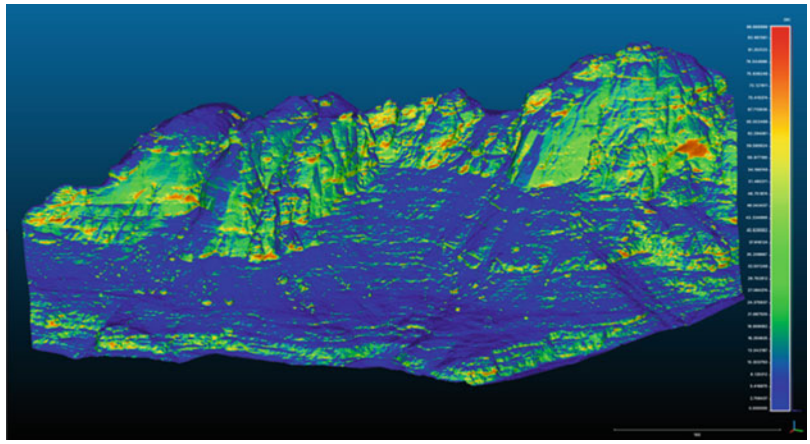


Fig. 25 Global kinematic index for the Western cliff of AlUla

normal, lognormal, exponential). The capability to simulate the effect of passive countermeasures, dynamics of "flying rocks" and the effect of vegetation were implemented and tested against real events (Frattini et al. 2012). A special elasto-viscoplastic strain hardening model for impact on soft ground (Di Prisco and Vecchiotti 2006) was also implemented. Model results are provided in both raster and vector formats and these include rockfall frequency, density of arrest points, critical sources area, fly height, rotational and translational velocity and kinetic energy, as well as information about motion type, and impact locations.

The following Fig. 26 shows the result of the 3D modelling, highlighting that the possibility that some trajectories of falling boulders are arriving till the border of Old Town is not negligible.

6 Conclusion

The AlUla oasis covers a wide archaeological area where it is possible to visit ancient heritage sites in a rock cut landscape shaped over thousand years. In addition to its best-known World Heritage site of Hegra, the region hosts a number of fascinating historical and archaeological sites such as its Old Town; Dadan and many ancient rock-art sites.

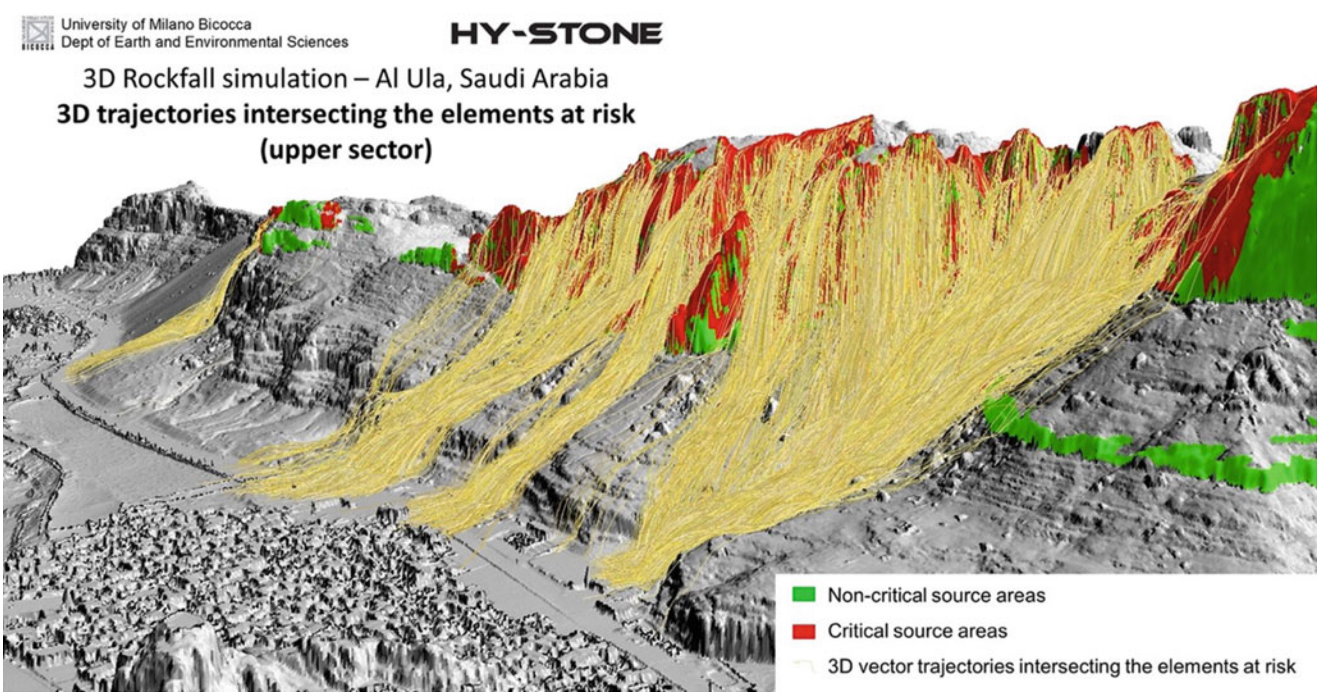


Fig. 26 3D trajectories intersecting the elements at risk in AlUla Old Town. In this simulation the source for falling boulders is the upper part of the Western cliff

The entire area is characterized by the presence of low to medium strength sandstone formations. More in detail, the north area shows the outcropping of the Quweira Yellowish sandstone unit while in the central and Southern area (Old Town and Dadan) and further south the Siq Red Sandstone appears, divided into three main sub-units (Lower, Middle and Upper). The poor geological and geomechanical characteristics of these two formations affect the potential instability and weathering of the cultural heritage sites carved into them.

The geological formations are characterized by a significant internal variability, both vertical and lateral. The Quweira Yellowish Sandstone, of interest for the site of Hegra, is mainly interested by diffused weathering and erosional phenomena as well as rockfall connected to internal structural asset. The archaeological areas in the Siq Red Sandstone, i.e. Dadan and Old Town, are mainly affected by rockfall and slides as a consequence of the local discontinuities pattern.

Acknowledgments The reported activities were carried out thanks to the collaboration between the UNESCO Chair on Prevention and Sustainable Management of Geo-Hydrological Hazards of the University of Florence, the Italian Institute for Environmental Protection and Research (ISPRA), the Sapienza University of Rome and the University of Milano Bicocca, coordinated by the Royal commission for AlUla (RCU) and the French Agency for AlUla Development (AFALULA), in the framework of the International Programme on Landlsides IPL-259 project "Landslide Risk assessment in AlUla Archaeological sites—Kingdom of Saudi Arabia". LAGIRN laboratory of the University of Bologna, in the person of Dr. Fausto Peddis and Dr. Barbara Ravaglia, is highly acknowledged for the activity of laboratory testing. Jhaed Kamuzaman Abul provided also his help in this stage of the research.

References

Agliardi F, Crosta G (2003) High resolution three-dimensional numerical modelling of rockfalls. Int J Rock Mech Min Sci 40:455–471

Boldini D, Guido GL, Margottini C, Spizzichino D (2017) Stability analysis of a large-volume block in the historical rock-Cut City of Vardzia (Georgia). Rock Mech Rock Eng 51:341–349. https://doi.org/10.1007/s00603-017-1299-7

Crosta GB, Agliardi F (2003) A methodology for physically based rockfall hazard assessment. Nat Hazards Earth Syst Sci 3:407–422

Descoeudres F, Zimmermann TH (1987) Three dimensional dynamic calculation of rockfalls. In: Proceedings 5th international congress on rock mechanics, Montreal (Canada), vol I, pp 337–342

Di Prisco C, Vecchiotti M (2006) A rheological model for the description of boulder impacts on granular strata. Geotechnique 56(7): 469–482

Donald G, Hadly G (1987) Explanatory notes to the geological map of the Sahl Al Matran Quadrangle, sheet 26 C, Kingdom of Saudi Arabia, pp 1–24

Dorren LKA, Berger F, Putters US (2006) Real-size experiments and 3-D simulation of rockfall on forested and non-forested slopes. Nat Hazards Earth Syst Sci 6:145–153. https://doi.org/10.5194/nhess-6-145

Ferrari F, Giacomini A, Thoeni K (2016) Qualitative rockfall hazard assessment: a comprehensive review of current practices. Rock Mech Rock Eng 49:2865–2922. https://doi.org/10.1007/s00603-016-0918-z

Frattini P, Crosta GB, Lari S, Agliardi F (2012) Probabilistic rockfall hazard analysis (Prha). Landslides and engineered slopes: protecting society through improved understanding - proceedings of the 11th international and 2nd north American symposium on landslides and engineered slopes, 2012, 2, pp 1145–1151

Gallego JI, Margottini C, Spizzichino D, Boldini D, Abul JK (2022) Geomorphological processes and rock slope instabilities affecting the AlUla archaeological region. In: Lancellotta R, Viggiani C, Flora A, de Silva F, Mele L (eds) Geotechnical engineering for the preservation of monuments and historic sites III. Proceedings of the third international ISSMGE TC301 symposium, Napoli, 22–24 June 2022

Gerber W (2019) Naturgefahr Steinschlag – Erfahrungen und Erkenntnisse. Eidg. Forschungsanstalt für Wald, Schnee und Landschaft WSL, Birmensdorf. WSL Berichte 74:149

Gigli G, Casagli N (2011) Semiautomatic extraction of rock mass structural data from high resolution LIDAR point clouds. Int J Rock Mech Min Sci 48(2):187–198

Guzzetti F, Crosta GB, Detti R, Agliardi F (2002) STONE: a computer program for the three-dimensional simulation of rockfalls. Comput Geosci 28(9):1081–1095

ISRM (1978a) Suggested methods for the quantitative description of discontinuities in rock masses. Int J Rock Mech Min Sci Geomech

ISRM (1978b) Suggested methods for determining hardness and abrasiveness of rocks. Int Rock Mech Min Sci Geomech

ISRM (1978c) International society for rock mechanics commission on standardization of laboratory and field tests. Int J Rock Mech Min Sci Geomech Abstr 15:319–368. https://doi.org/10.1016/0148-9062(78)91472-9

ISRM (1981) Suggested methods for determining tensile strength of rock materials. In: Brown ET (ed) Suggested method: rock characterization, testing and monitoring. Pergamon Press, Oxford, p 211

Loew S, Hantz D, Gerber W (2021) Rockfall causes and transport mechanisms: a review. In: Treatise of geomorphology, 2nd edn. Elsevier. https://doi.org/10.1016/B978-0-12-818234-5.00066-3

Margottini C, Spizzichino D (2021) Traditional knowledge and local expertise in landslide risk mitigation of world heritages sites. In: Sassa K, Mikoš M, Sassa S, Bobrowsky PT, Takara K, Dang K (eds) Understanding and reducing landslide disaster risk. WLF 2020. ICL contribution to landslide disaster risk reduction. Springer, Cham. https://doi.org/10.1007/978-3-030-60196-6_34

Margottini C, Spizzichino D (2022) Weak rocks in the Mediterranean region and surroundings: threats and mitigation strategies for selected rock-cut heritage sites. Eng Geol 297:106511. ISSN 0013-7952. https://doi.org/10.1016/j.enggeo.2021.106511

Marija L, Martin Z, Jordan A et al (2022) Rockfall susceptibility and runout in the valley of the kings. Nat Hazards 110:451–485. https://doi.org/10.1007/s11069-021-04954-9

Moriset S, Gandreau D (2022) Dadan 2022–2030. Conservation Management Plan. AFALULA and RCU

Ramsey BC (2020) OxCal. Available at: https://c14.arch.ox.ac.uk/oxcal.html. Accessed 29 Mar 2021

Reimer P, Austin W, Bard E, Bayliss A, Blackwell P, Bronk Ramsey C, Talamo S (2020) The IntCal20 northern hemisphere radiocarbon age calibration curve (0–55 cal kBP). Radiocarbon 62(4):725–757. https://doi.org/10.1017/RDC.2020.41

Spizzichino D, Margottini C, Chiessi V, Boldini D (2016) Assessment of the stability conditions of a large-volume sandstone block in the northern sector of the Siq of Petra. Landslides and engineered slopes. Experience, theory and practice, pp 1851–1858

Thomas H, Kennedy M, Dalton M, McMahon J, Boyer D, Repper R (2021) The mustatils: cult and monumentality in Neolithic North-Western Arabia. Antiquity 95(381):605–626. https://doi.org/10.15184/aqy.2021.51

Varnes DJ (1978) Slope movement types and processes. In: Schuster RL, Krizek RJ (eds) Landslide analysis and control. Transportation Research Board, Special report 176. National Academy Sciences, Washington, DC, pp 11–33

Wahbi AM (2014) Sedimentological and stratigraphic studies of the cambro-ordovician succession in Northwest Saudi Arabia. Master Thesis of King Fahd University of Petroleum & Minerals. Dhahran

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.