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Research Article

Documentation and Condition Assessment of the Sasanian Shapur I Rock Relief at Naqsh-e Rostam and Presentation of Emergency Conservation Strategies

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Abstract: The Shapur I rock relief at Naqsh-e Rostam is one of the most prominent stone monuments of the Sasanian period. Owing to its prolonged exposure to outdoor environmental conditions and the inherent properties of its stone substrate, the relief has undergone various forms of weathering and deterioration. Identifying the factors contributing to its deterioration and developing scientifically informed conservation measures are essential for its sustainable protection. This study aims to identify the factors affecting the deterioration of the relief, assess the properties of its stone substrate, and develop emergency conservation strategies based on condition assessment. Detailed documentation was first undertaken using terrestrial laser scanning and digital photogrammetry, resulting in a three-dimensional model, orthophotos, and damage maps. Stone substrate samples were then examined through petrographic studies, physical tests, and XRD and XRF analyses. Regional climatic data were also evaluated and the results were analysed in conjunction with systematic field-based damage mapping. The findings indicate that the stone substrate is limestone with a predominantly calcitic composition and a small proportion of clay minerals. Its marked reduction in compressive strength under saturated conditions indicates considerable vulnerability to moisture penetration and chemical dissolution. Climatic investigations further identified precipitation, surface runoff, freeze–thaw cycles, temperature fluctuations, biological agents, and environmental pollutants as the principal factors contributing to the intensification of weathering processes. Based on the condition assessment, an emergency conservation programme following the principle of minimum intervention is proposed. The programme includes surface cleaning, consolidation of friable areas, injection of natural hydraulic lime grouts, stabilisation of microcracks using micro-acrylic resin, and mortar repairs in deteriorated areas. The integration of digital documentation, laboratory investigations, and systematic damage mapping enables a more precise understanding of deterioration mechanisms and supports the selection of conservation measures compatible with the properties of the stone. This approach provides a scientific basis for stabilising unstable areas, reducing factors contributing to the progression of deterioration, and establishing a framework for long-term monitoring and conservation management of the monument.

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1. Introduction

Stone deterioration is a major challenge in the conservation of historical and cultural heritage. It results from the interaction between environmental conditions and the intrinsic properties of stone, with its type and severity influenced by climatic conditions, geological characteristics, mineralogical composition, and physical structure. Temperature fluctuations, freeze–thaw cycles, moisture, precipitation, solar radiation, atmospheric pollutants, and biological activity are among the principal external agents, while porosity, grain size, cementation, chemical composition, and mechanical strength determine the stone's susceptibility to deterioration.

Stone deterioration can broadly be classified as physical or chemical weathering (Saba et al., 2018). Physical weathering includes cracking, fracturing, scaling, delamination, and disintegration caused by processes such as thermal stress, freezing, salt crystallisation, and mechanical pressure. Chemical weathering results from reactions between minerals and environmental agents, leading to dissolution, secondary mineral formation, discoloration, loss of cohesion, and progressive disintegration (Parvin, 1996: 6). These processes commonly operate simultaneously, reducing structural cohesion, increasing effective porosity, and weakening the mechanical properties of stone (Benavente et al., 2008). The heterogeneous nature of stone further contributes to differential deterioration, as variations in mineralogy, porosity, grain structure, veins, and natural fractures can cause different parts of a monument to respond differently to environmental conditions.

Accurate identification and assessment of deterioration are fundamental to effective conservation planning. Such assessment requires more than visual observation and should integrate field examination, photographic documentation, damage mapping, sampling, laboratory analysis, and monitoring (Fitzner, 2014). Integrating these data enables the interpretation of deterioration mechanisms, identification of contributing factors, assessment of the monument's condition, and selection of compatible conservation measures while supporting long-term monitoring and preventive conservation.

The Shapur I rock relief at Naqsh-e Rostam has been exposed to environmental weathering for centuries, making systematic documentation and condition assessment essential for its conservation. Its complex surface, heterogeneous stone substrate, and overlapping deterioration features require accurate recording of the location, extent, and severity of damage. Digital documentation, photogrammetry, and precise geometric surveying provide a reliable basis for condition recording, damage mapping, change detection, and monitoring. The novelty of this study lies in presenting the first published documentation of the physical and conservation condition of the Shapur I rock relief at Naqsh-e Rostam, together with a systematic assessment of its deterioration. The resulting documentation and condition assessment provide an evidence base for understanding the present condition of the relief, prioritising conservation measures, and developing appropriate strategies for its long-term conservation, monitoring, and management.

Research Questions

-What is the relationship between the intrinsic properties of the stone substrate, environmental conditions, and the spatial distribution pattern of deterioration observed on the Shapur I rock relief?

-How can understanding this relationship contribute to prioritising emergency conservation measures?

2. Background

2.1. The Shapur I Rock Relief

Shapur I, the Sasanian king, was trained in warfare, state administration, and kingship under his father, Ardashir I. He became an active military commander from the early years of the Sasanian state and participated in major campaigns against Rome. In 243 CE, he defeated the army of Gordian III, who was subsequently killed, and in 260 CE he conquered parts of eastern

Mesopotamia and Syria and captured the Roman emperor Valerian and his entourage (Daryaei, 2004: 19–20; Shapur Shahbazi, 1986; Huyse, 1999: 33–43; Back, 1978: 306–329). These victories are commemorated in several rock reliefs in Fars, including three at Bishapur, one at Darab, and the most prominent example at Naqsh-e Rostam, adjacent to the tomb of Darius the Great (Fig. 1). Here, Shapur I is depicted mounted on an approximately life-sized horse on a relatively smooth rectangular rock surface measuring approximately 13 m in length and 8 m in height (Table 1).



Figure 1. Oblique aerial photograph of the Naqsh-e Rostam site showing the location of the Shapur I rock relief (Source: Deylami Pour, 2018)

Table 1. Dimensions of the Shapur I rock relief at Naqsh-e Rostam, including the Kartir relief.

Dimension	Measurement
Width	7.69 m
Length	13.19 m

The relief depicts Shapur wearing a crenellated crown, royal globe, diadem with long ribbons, curled beard, and royal attire. He holds the hilt of his sheathed sword with his left hand and points towards two Roman figures with his right hand, while his elaborately harnessed horse occupies the centre of the composition (Fig. 2). A kneeling figure extends his hands towards Shapur, while a standing figure beside him has his hand held by the king. Their clothing, swords, and laurel crowns identify them as Roman figures (Shahbazi, 1978: 108; Lukonin, 1971; Sami, 2010). Their identities, however, have long been debated. Earlier interpretations identified the kneeling figure as Valerian and the standing figure as Cyriades (Ker Porter, 1822: 543; Sarre & Herzfeld, 1910: 79), while later scholars questioned this identification. Sprengling regarded the standing figure as a Roman commander, whereas Herzfeld considered his identity uncertain (Sprengling, 1953: 372; Herzfeld, 1941: 315).

McDermot's 1954 study proposed that the two figures represented Valerian and Philip the Arab, based on Shapur's inscription on the Ka'ba-ye Zartosht, which names Gordian III, Philip, and Valerian. Since the inscription states that Shapur personally captured Valerian, McDermot identified the standing figure as Valerian and the kneeling figure as Philip, while Gordian was represented separately at Darab (McDermot, 1954: 76–80). This interpretation was supported by Ghirshman and Porada (Ghirshman, 1971: 151). Hintze later reversed the identification, interpreting the standing figure as Philip the Arab and the kneeling figure as Valerian, based on the latter's humiliating posture, the peace settlement between Philip and Shapur, and comparison with a statue of Philip in the Vatican (Hintze, 2006: 243–244).

Although the identities of the two Roman figures remain debated, the Naqsh-e Rostam relief is one of the most important visual statements of Sasanian political power and Shapur I's victory over Rome. The associated Greek and Middle Persian inscriptions further enhance its historical significance (Herzfeld, 1926: 244; Hintze, 2006: 327–328).

2.2. The Kartir Rock Relief and Inscription

Behind the Shapur I rock relief at Naqsh-e Rostam, a bust of Kartir, the prominent Sasanian high priest, and a Middle Persian inscription were carved during the reign of Bahram II (276–293 CE). The location of the relief reflects Kartir's important position within the political and religious structure of the Sasanian state. During Bahram II's reign, he played a major role in consolidating and expanding the Zoroastrian religious–state institution and maintained his influence across the reigns of seven Sasanian kings (Hintze, 2006: 251; Sprengling, 1953: 248).

Kartir is depicted beardless and facing right, wearing a tall semi-cylindrical cap with a distinctive emblem, which Hintze interpreted as a symbol of his authority and judicial power (Hintze, 2006: 262). He raises the index finger of his right hand towards Shapur as a gesture of respect. Beneath the figure is a 38-line Middle Persian inscription, parts of which, particularly lines 20–29, are severely damaged and illegible. The relief and inscription are generally dated to around 280 CE (Shahbazi, 1978: 118). The inscription is an important source for understanding the religious and political structure of the Sasanian period. First introduced by Niebuhr in the eighteenth century, it was subsequently studied, transliterated, and translated by other scholars (Niebuhr, 1975).



Figure 2. Top: Orthophoto showing details of the victory relief of Shapur I at Naqsh-e Rostam, together with the Kartir inscription (Source: Zia Deylami Pour, 2018); bottom: Line drawing of details of the relief (Source: Mostafa Rakhshandeh Khoo, 2020)

2.3. Conservation and Restoration Measures

Given the historical and artistic significance of the Shapur I rock relief, several conservation interventions have been undertaken over the past decades, primarily to control crack propagation, stabilise deteriorated areas, and improve the monument's overall stability. Reviewing these interventions is important for understanding changes in the monument's condition and evaluating the effectiveness and consequences of previous treatments.

The earliest documented intervention dates to 1953, during the tenure of Ali Sami at Persepolis. A longitudinal fissure on the eastern side of the relief, probably associated with natural weathering, geological stresses, or pre-existing fractures in the rock mass, was filled with plaster and brick fragments to reduce water ingress and further deterioration. Although appropriate within the technical context of the period, the differences between these materials and the stone substrate in thermal expansion, porosity, and moisture behavior subsequently led to their reassessment and removal. The second major intervention began in April 2007 on the eastern face of the relief under the supervision of Professor Hassan Rahsaz. Its objectives were to rectify previous treatments, strengthen deteriorated areas, and reduce the risk of further crack propagation while preserving the authenticity of the monument. The main measures included:

– Removal of the earlier repair materials using hand tools.

– Cleaning and refilling the existing fissure with a sand–cement–lime mortar to improve cohesion and resistance to environmental factors.

– Consolidation of the Kartir relief and adjacent inscription through lime-slurry injection and application of Paraloid resin to stabilise friable areas (Fig. 3).

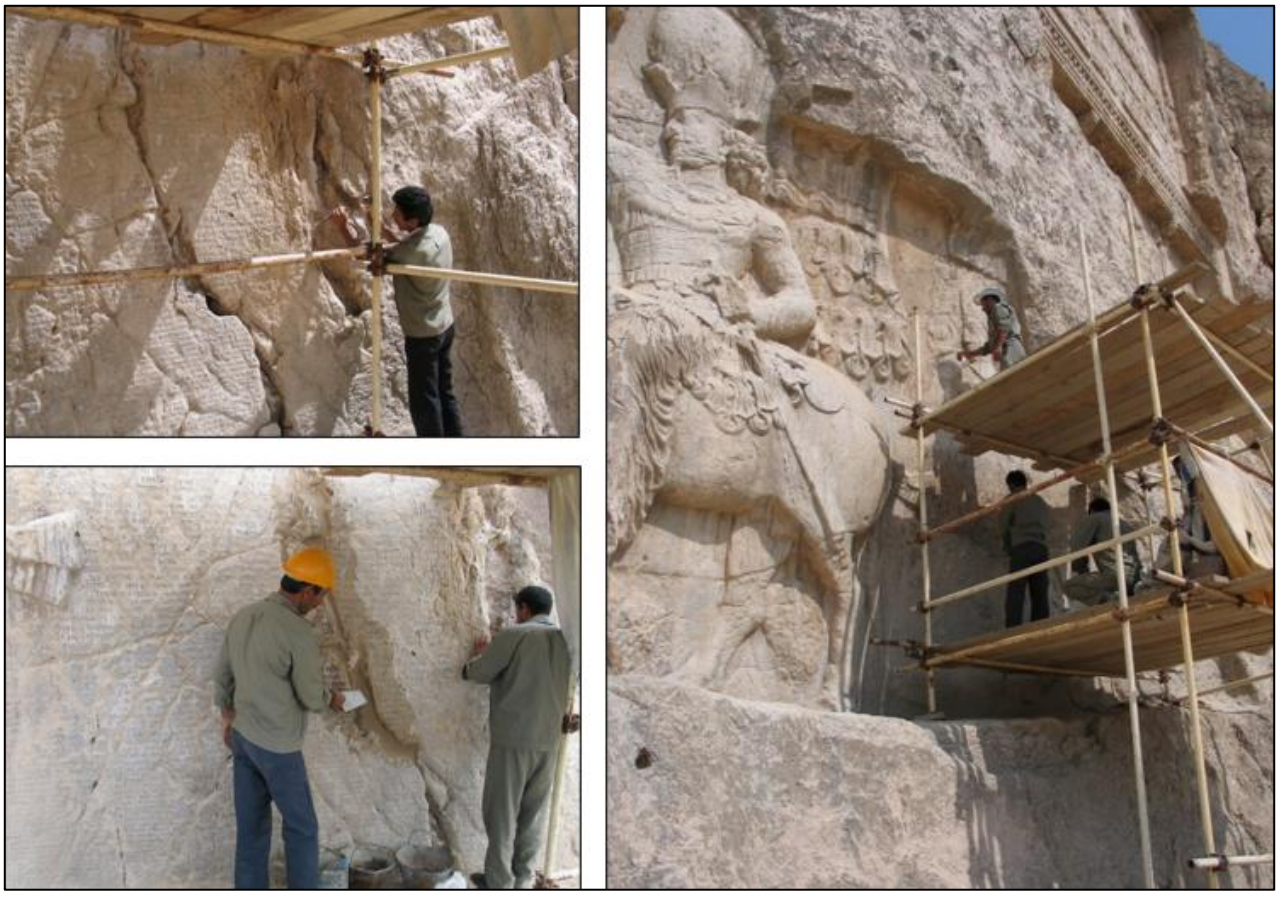


Figure 3. The second phase of conservation measures undertaken in 2007 in the eastern section of the Shapur relief, aimed at reviewing and correcting previous repairs and conserving and consolidating the Kartir inscription (Source: Documentation Centre of the Persepolis World Heritage Site, 2007)

3. Materials and Methods

3.1. Documentation and Damage Mapping

The Shapur I rock relief was documented in collaboration with Farnagar Peymayesh Surveying Company using terrestrial three-dimensional laser scanning and digital photogrammetry. The integrated data were processed to generate a three-dimensional point cloud and colourised, textured models (Fig. 4), from which a high-accuracy orthophoto was produced as the geometric and visual basis for damage mapping (Fig. 2). The documentation established a baseline record of the conservation condition before intervention and enabled the precise recording and comparison of the location, dimensions, and extent of deterioration. To facilitate close examination of the relief, a protective working platform and scaffolding system was installed (Fig. 5). This allowed deterioration features not clearly visible from ground level to be identified and recorded by correlating field observations with digital imagery (Fig. 6).

Deterioration features were classified according to the ICOMOS–ISCS International Scientific Committee for Stone system into five principal groups: discoloration and deposits, material loss, detachment, cracks and deformation, and biological colonisation (ICOMOS–ISCS, 2008; Table 2). The features were delineated on orthophotos using AutoCAD, with separate spatial layers created for each damage group. These layers were subsequently combined to produce digital damage maps showing the distribution, extent, and spatial overlap of deterioration features. The integration of digital documentation and detailed field examination provided an accurate and traceable record of the relief's conservation condition and established a reliable basis for spatial analysis, long-term monitoring, change detection, and evaluation of conservation interventions.



Figure 4. Three-dimensional point-cloud model of the Shapur I rock relief without texture and after integration with the natural texture (Source: Documentation Centre of the Persepolis World Heritage Site; prepared by Zia Deylami Pour, Farangar Survey Engineering Company)



Figure 5. Establishment of a safe working platform and provision of access to different sections of the relief for detailed surface examination and condition mapping



Figure 6. Use of the orthophoto for damage mapping of the Shapur I rock relief: image gridding (right) and transfer and recording of damage areas on the image (left)

3.2. Sampling and Laboratory Studies

Petrographic, mineralogical, and chemical analyses were conducted on three small stone samples collected from the rock mass outside the main frame of the relief to avoid damage to significant carved areas. Thin sections were examined using a polarising light microscope to determine texture, grain size, mineralogical composition, cementation, and microstructural characteristics, providing a basis for assessing the stone's response to weathering and deterioration.

The physical and mechanical properties of the stone were evaluated under dry and saturated conditions using five larger samples collected away from the carved figures. Density was determined from specimen dimensions, volume, and weight, while uniaxial compressive strength was measured in accordance with ASTM C170 using cylindrical specimens measuring 5 × 5 cm. The specimens were loaded axially to failure, and the mean strength of the five specimens under each condition was used to assess the effect of saturation on mechanical properties.

X-ray fluorescence (XRF) and X-ray diffraction (XRD) analyses were conducted to determine the stone's chemical and mineralogical composition and identify phases and products potentially associated with weathering. XRF analysis was performed at the Research Institute for Conservation and Restoration of Historical and Cultural Artefacts using an ARL 8420 spectrometer and UniQuant software. XRD analysis was carried out using a SIEFERT T2T powder diffractometer at 30 mA and 40 kV over a 2θ range of 6–60°. Samples were prepared using the Plexiglas pellet method.

4. Results and Discussion

4.1. Petrography of Thin Sections

Petrographic and mineralogical examinations showed that the stone samples from Naqsh-e Rostam are broadly similar in composition and texture. Thin-section analysis indicates that the stone consists predominantly of micritic and sparitic calcite, intraclasts, minor fossil remains, iron oxides, and a small amount of dolomite. Intraclasts comprise approximately 40–50% of the rock fabric and are cemented by sparitic calcite, while many voids, veins, and microfractures are secondarily filled with calcite (Fig. 7).

A dissolved sample collected near openings in the rock surface was predominantly micritic, with local recrystallisation of micrite into sparite (Fig. 8). The presence of secondary calcite associated with moisture penetration and weathering is a notable feature. In addition, the moisture-retention capacity of iron oxides and the solubility of micrite may contribute to the intensification of deterioration and surface alteration.

Table 2. Guide to the damage mapping of the Shapur I rock relief (based on the standard patterns proposed by the ICOMOS International Scientific Committee for Stone)

Damage form	Damage group	Description	Causes of formation
Discoloration and deposits	Encrustation	Formation of a hard, adherent mineral layer on the stone surface, usually differing in colour and morphology from the underlying stone.	Materials transported and deposited by seepage water and internal processes within the monument.
	Moist area	Darkening of the surface caused by moisture, with a pattern and extent corresponding to its source.	Rising moisture, moisture absorption in the presence of salts, and condensation.
	Deposit	Accumulation of crust-like materials of variable thickness, with low or no adhesion to the stone surface.	Soot and dust, paint and mortar drips, salt aerosols, splashed materials, and bird and bat droppings.
Material loss	Missing part	Formation of a void where material has been lost, usually occurring in projecting or prominent parts.	Human activities and physical and chemical deterioration processes.
	Differential Erosion	Uneven erosion of the stone surface resulting from differences in the resistance or porosity of different parts.	Stone heterogeneity and selective deterioration, including lichen activity.
Detachment	Delamination	Physical separation of the stone into one or more layers of variable thickness and shape.	Weathering of layered stones, particularly sedimentary rocks and some metamorphic rocks.
	Peeling	Detachment of thin layers parallel to the stone surface, which may be curved or warped.	Weathering of layered stones, particularly sedimentary rocks and some metamorphic rocks.
	Fragmentation	Complete or partial breakage of the stone into fragments of irregular shape and size.	Applied stresses, discontinuities, and structural weakness of the stone.
Crack and deformation	Fracture	A crack or rupture extending through the entire stone element.	Weathering and the presence of discontinuities in the stone.
	Splitting	Rupture of the stone along weak planes, microcracks, or clay- and silt-rich layers.	Movements and applied stresses, and weakness along planes of discontinuity.
	Crack	A visible fissure or rupture indicating the separation of part of the stone.	Weathering, discontinuities in the stone, structural instability, corrosion of metal fixings, hard pointing, earthquakes, fire, and freezing.
Biological colonisation	Lichen	Growth of crustose or foliose lichen coverings on the stone surface, usually grey, yellow, orange, or black in colour.	Persistent moisture and suitable environmental conditions for biological growth.
	Plant	Vegetation with roots, stems, leaves, or parts thereof.	Presence of moisture and suitable substrates for root growth, such as cavities and fissures in the stone.

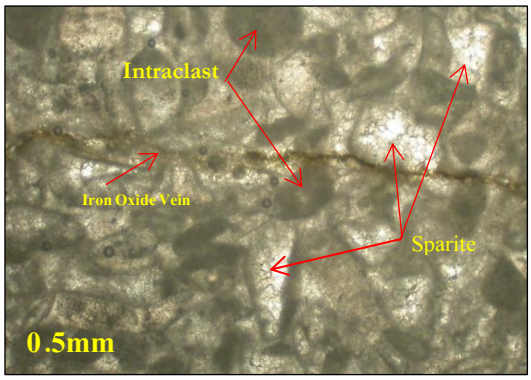


Figure 7. Photomicrograph at 4× magnification. Numerous dark cream-coloured intraclasts are visible, within which sparitic calcite occurs as light-coloured mineral phases. Iron oxides are also visible as red spots and veins.

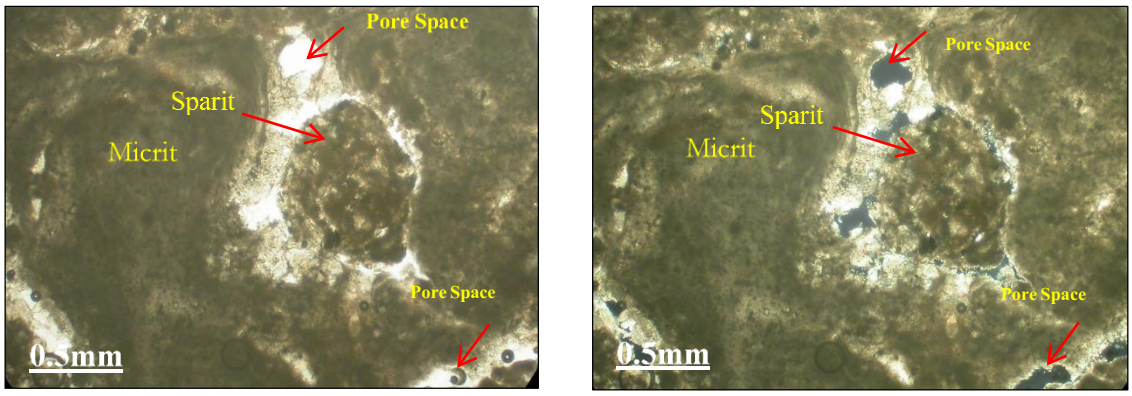


Figure 8. Photomicrograph of a deposit formed within the stone structure in the presence of moisture, at 4× magnification. The deposit consists mainly of calcareous mud (Micrite), with recrystallisation to sparite visible in some areas. In the left image (PPL), the voids appear bright, whereas in the right image (XPL), the same voids appear dark.

4.2. Physical Properties of the Stone

To assess the mechanical behaviour of the stone substrate and the effect of moisture on its strength, density and uniaxial compressive strength were measured on samples collected from the rock mass at Naqsh-e Rostam. Five specimens were tested under dry conditions and five after complete water saturation (Table 3). Saturation produced a slight increase in density but reduced compressive strength by approximately 29.5%. This substantial reduction indicates the sensitivity of the stone to moisture and is consistent with the petrographic observations. Thin-section analysis revealed numerous microfractures, many of which are filled with secondary calcitic cement. These discontinuities provide pathways for water penetration, which can weaken intergranular bonds, reduce internal cohesion, and promote microcrack propagation and mechanical weakening.

From a conservation perspective, the reduction in strength under saturated conditions highlights the importance of controlling moisture ingress. Water entering through rainfall, surface runoff, or the rock mass may simultaneously weaken the stone and intensify chemical weathering, salt crystallisation, and wetting–drying cycles, increasing the risk of cracking, grain detachment, and surface scaling. Although the stone has adequate strength under dry conditions, its marked loss of strength upon saturation demonstrates its vulnerability to moisture-related deterioration and underscores the need for surface-water management, moisture control, and continuous environmental monitoring.

Table 3. Bulk density and compressive strength of the stone samples at the Naqsh-e Rostam historical site

Material type and test condition	Number and dimensions of specimens	Bulk density (g/cm^3)	Compressive strength (kg/cm^2)
Stone sample, dry condition	5 specimens, 5 × 5 cm	2.521	637.8
Stone, saturated condition	5 specimens, 5 × 5 cm	2.572	449.6

4.3. Mineralogical and Chemical Composition of the Stone

Three samples from the rock mass were analysed by X-ray diffraction (XRD) and X-ray fluorescence (XRF) to determine the mineralogical and chemical composition of the stone substrate (Table 4). The results show that the substrate is a limestone with a very high calcite content, with CaO exceeding 95% of the oxide composition. The low concentrations of Al_2O_3, SiO_2, SO_3, K_2O, and Fe_2O_3 indicate a limited contribution of clay, silicate, and other accessory phases. Although relatively elevated P_2O_5 was detected in some samples, no distinct phosphate phase such as apatite was identified by XRD. Phosphorus may therefore occur within carbonate or poorly crystalline secondary phases, although its precise source requires further investigation. Its possible association with atmospheric pollutants and agricultural activities may also be considered (Fadaei et al., 2024).

Overall, the results indicate that the Shapur I rock relief is composed predominantly of high-purity calcitic limestone. While this composition contributes to the relative uniformity of the stone, it also increases its susceptibility to chemical weathering, particularly dissolution associated with acidic precipitation.

Table 4. Results of the chemical and mineralogical composition analyses of stone samples using XRF and XRD at the Naqsh-e Rostam site

Sampling location	Mineralogical composition (XRD)	Fe_2O_3 (%)	CaO (%)	K_2O (%)	SO_3 (%)	P_2O_5 (%)	SiO_2 (%)	Al_2O_3 (%)	MgO (%)
Naqsh-e Rostam, Xerxes' Tomb area, rock substrate	Calcite (high), clay minerals (low)	0.29	95.80	0.02	0.17	3.30	0.26	0.15	–
Naqsh-e Rostam, Xerxes' Tomb area, rock substrate	Calcite	0.26	96.70	0.02	0.13	2.70	–	–	–
Naqsh-e Rostam, Elamite relief area, rock substrate	Calcite	0.31	98.60	–	0.05	0.95	–	–	–

4.4. Documentation and Damage Mapping

The integration of terrestrial laser scanning and digital photogrammetry provided an accurate geometric and conservation record of the Shapur I rock relief, including a three-dimensional model and spatially referenced orthophotos. These orthophotos enabled the location, extent, and boundaries of deterioration to be recorded and compared. Protective scaffolding also allowed close examination of areas that were not clearly distinguishable from ground level, improving the identification of cracks, surface fractures, textural alterations, and biological deterioration. The observed features were classified according to the ICOMOS–ISCS system into five principal groups: discoloration and deposits, material loss, detachment, cracks and deformation, and biological colonisation (Vergès-Belmin, 2011; ICOMOS–ISCS, 2008). The resulting damage maps

documented their spatial distribution and overlap across the relief (Table 2; Figs. 9, 10, 11, 12, 13 & 14).

The damage maps show that deterioration is spatially heterogeneous, with some features concentrated in specific areas and others distributed more broadly. Their spatial overlap suggests the interaction of multiple deterioration processes. Cracks and discontinuities may facilitate water penetration, while wetting–drying and freeze–thaw cycles can promote detachment and material loss; surface depressions may also favour moisture and sediment accumulation and biological colonisation. Recording these features on a fixed geometric reference provides baseline data for monitoring changes, identifying vulnerable areas, prioritising conservation measures, and evaluating intervention outcomes.

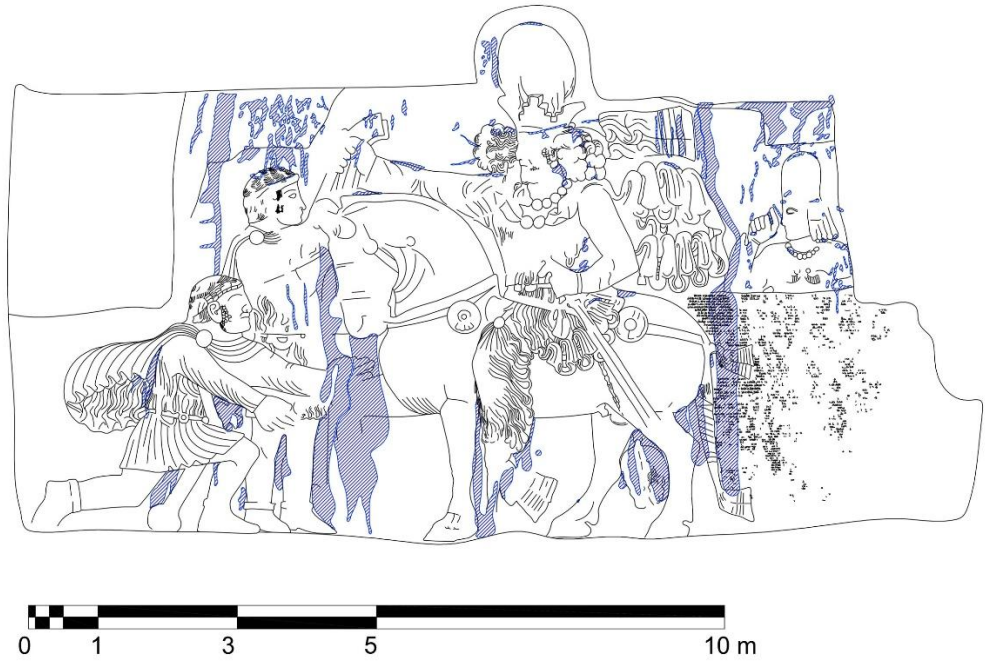
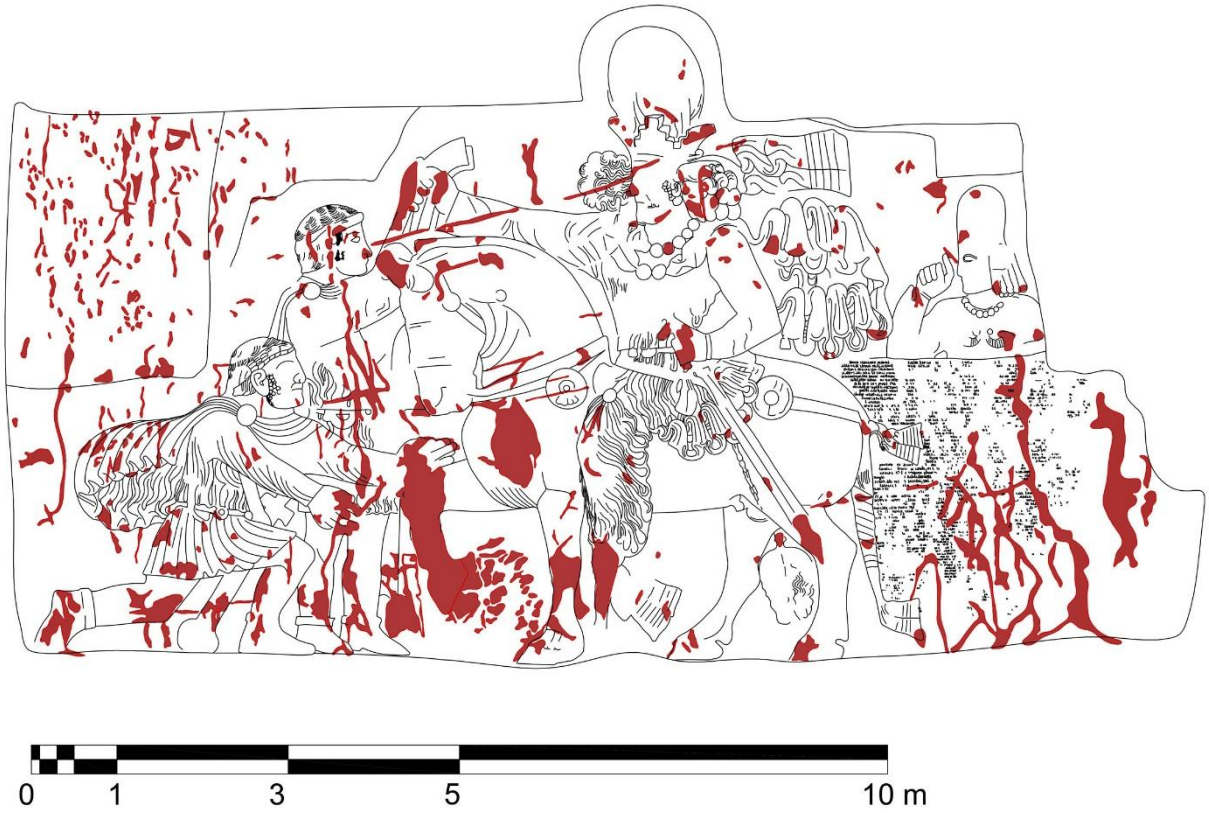


Figure 9. Documentation of “deposit” on the Shapur I rock relief, classified as “discolouration and deposit” damage (description and deterioration factors are provided in Table 2)





Figure 10. Documentation of a “moist area” on the Shapur I rock relief, classified as “discolouration and deposit” damage (description and deterioration factors are provided in Table 2)



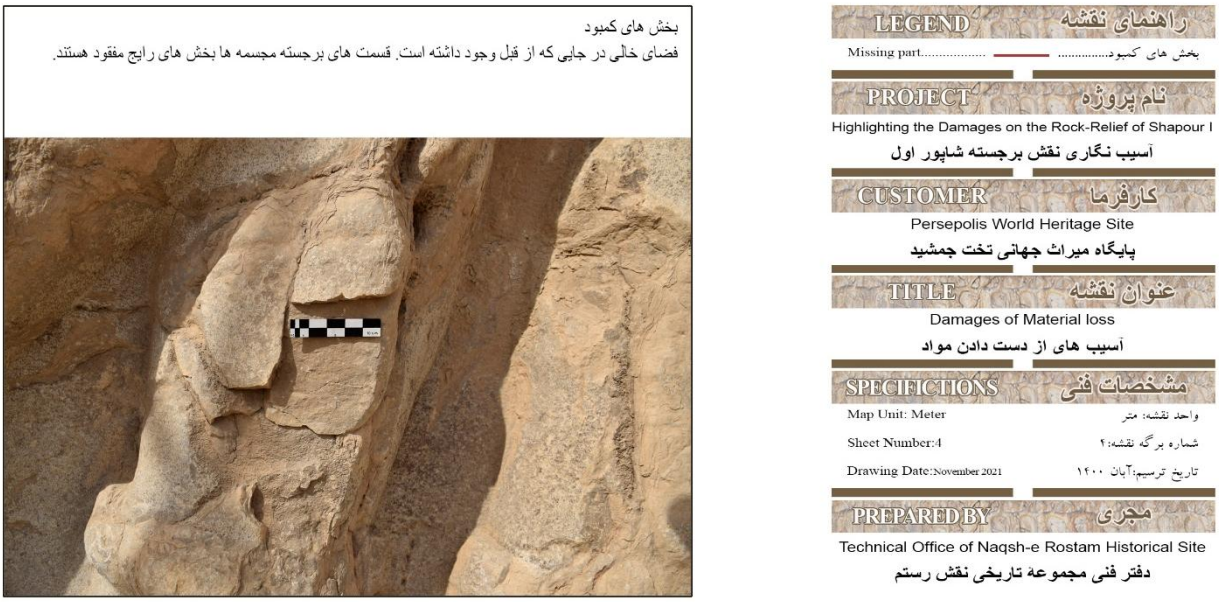


Figure 11. Documentation of “missing parts” on the Shapur I rock relief, classified as “material loss” damage (description and deterioration factors are provided in Table 2)

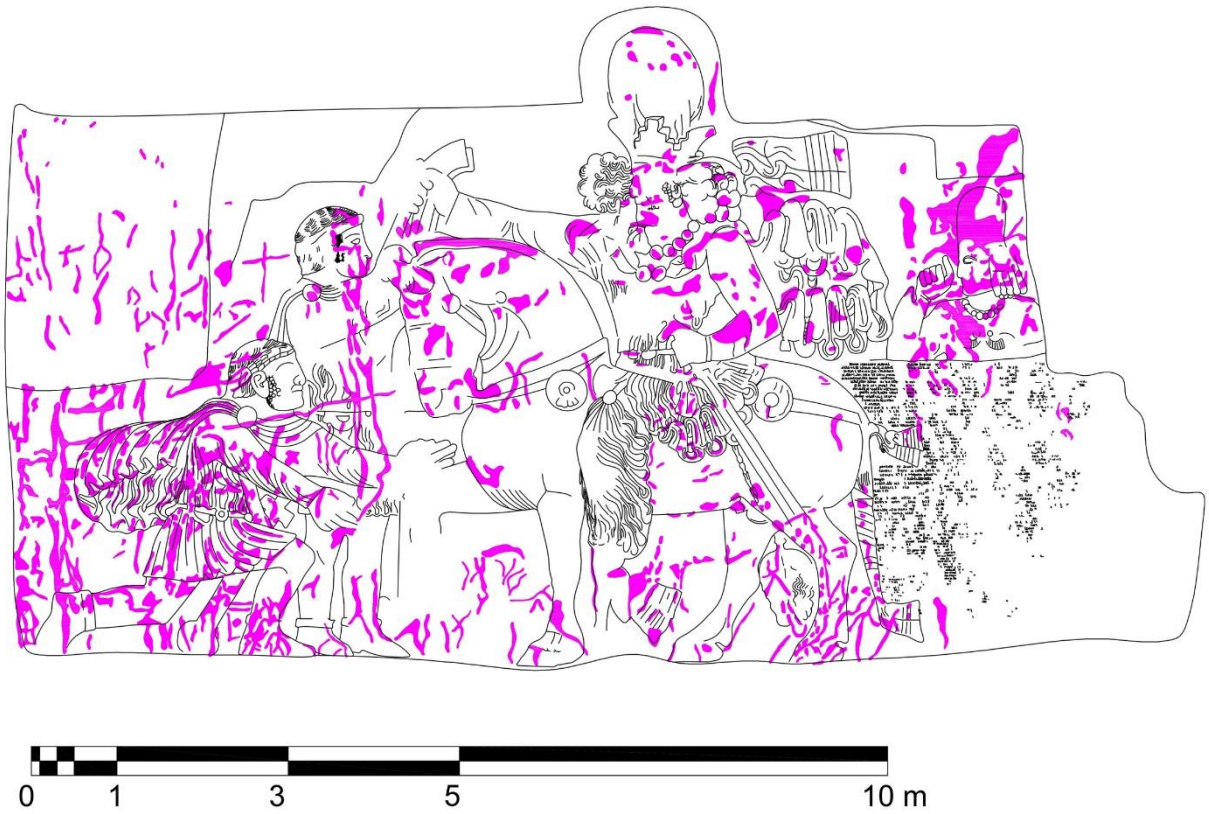


Figure 12. Documentation of “delamination” on the Shapur I rock relief, classified as “detachment” damage (description and deterioration factors are provided in Table 2)



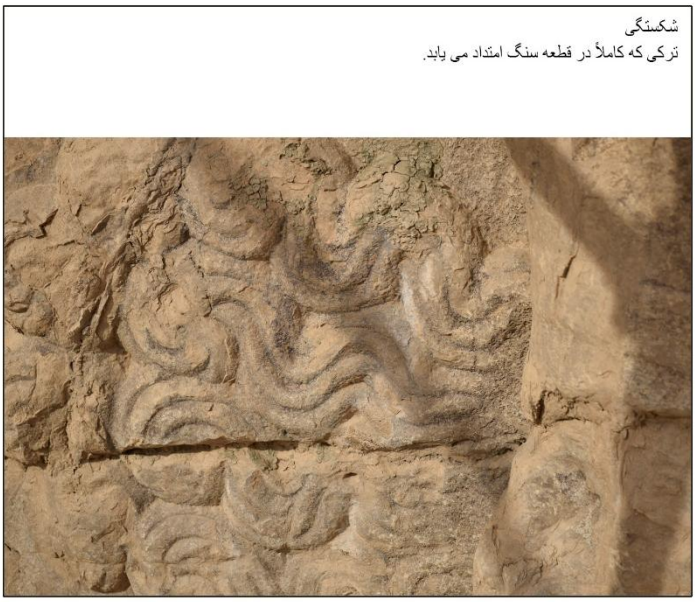




Figure 13. Documentation of “Fracture” on the Shapur I rock relief, classified as “crack and deformation” damage (description and deterioration factors are provided in Table 2)





Figure 14. Documentation of “lichen” on the Shapur I rock relief, classified as “biological colonization” damage (description and deterioration factors are provided in Table 2)

4.5. Analysis of Climatic Components and Their Effects on the Weathering of the Shapur I Rock Relief

Climatic data from the Takht-e Jamshid synoptic station, the nearest station to Naqsh-e Rostam, indicate that the region's hot and dry climate, marked by temperature fluctuations, seasonal precipitation, variable humidity, and high evaporation, provides favourable conditions for stone weathering and deterioration (Table 5). These factors act in combination through moisture, thermal, and freeze–thaw cycles.

Table 5. Summary of climatic data for the Naqsh-e Rostam region (Persepolis synoptic station, 1974–2017 statistical period)

Climatic parameter	Value
Total number of rainy days	38 days
Maximum daily precipitation	2.76 mm
Total number of frost days	54 days
Mean minimum temperature	9 °C
Mean maximum temperature	25.6 °C
Mean temperature	17.3 °C
Mean relative humidity	49%
Mean annual precipitation	302.6 mm
Mean daily sunshine duration	9.4 h
Mean daily evaporation	5.4 mm

The station recorded 38 rainy days, with most precipitation concentrated in the colder months, particularly December, January, and February (Fig. 15). Although annual precipitation is relatively low, its seasonal concentration and runoff across the upper parts of the relief and adjacent surfaces may promote surface erosion, water penetration into cracks and discontinuities, and increased moisture within the stone.

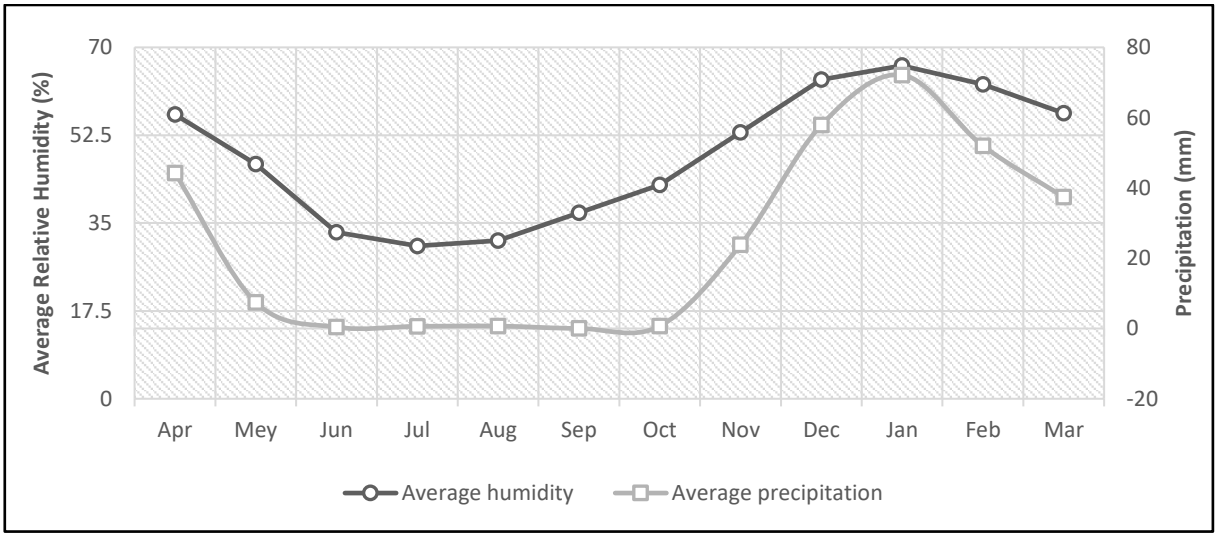


Figure 15. Long-term humidity and precipitation graph at the Takht-e Jamshid synoptic station during the 1973–2017 statistical period (Fadaei & Hosseini, 2017)

Repeated wetting–drying cycles can contribute to microcrack propagation and loss of surface cohesion. The presence of clay minerals may further increase sensitivity to moisture through swelling and associated internal stresses (Delgado Rodrigues, 2001; Veniale et al., 2001). The concentration of precipitation and increased relative humidity during the colder months may also intensify chemical weathering. Atmospheric pollutants, particularly during winter temperature inversions, can increase the concentration of reactive gases near the stone surface. In the

presence of precipitation and moisture, these gases may promote mineral dissolution and chemical alteration (Fadaei et al., 2024). Moreover, the combination of winter moisture and low temperatures increases the potential for frost-related deterioration where water penetrates pores and discontinuities.

Temperature fluctuations are important contributors to the physical weathering of the stone. During the statistical period, January was the coldest month, with a mean temperature of −0.5°C, while July was the warmest, at 38°C; the largest monthly temperature range occurred in summer, reaching approximately 19°C (Fig. 16). Such fluctuations, particularly on surfaces exposed to solar radiation, can produce differential thermal expansion and contraction. Given the structural heterogeneity of the stone (Ündül et al., 2016), repeated thermal stresses may promote microcracking, loss of cohesion, scaling, and particle detachment (Waqas and Ahmed, 2020; Weiss et al., 2004).

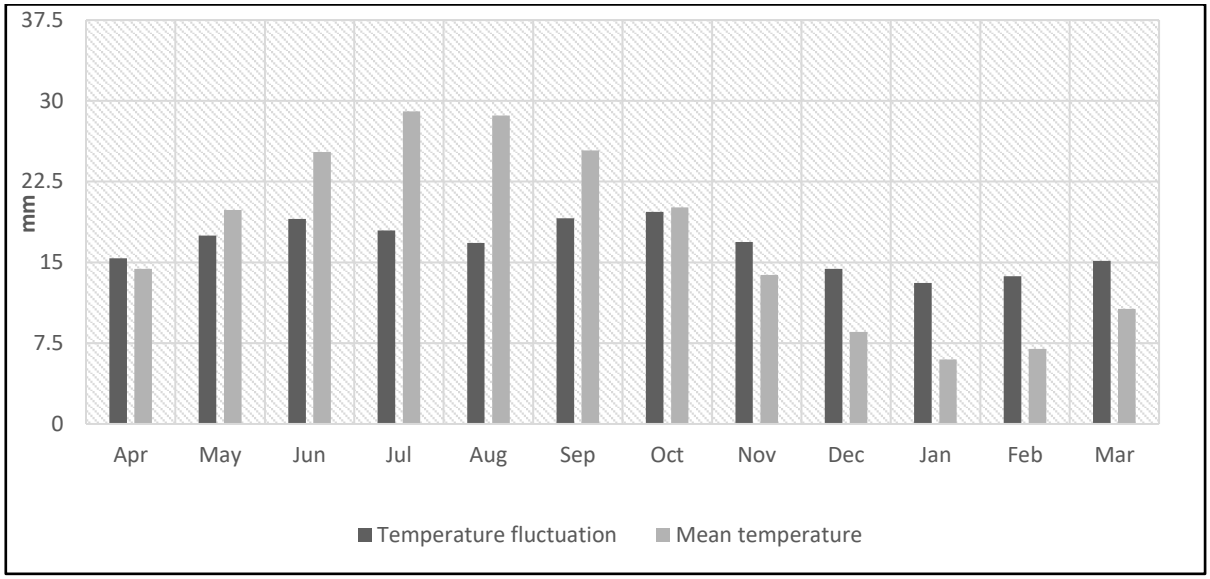


Figure 16. Long-term temperature fluctuation and mean temperature graph at the Takht-e Jamshid synoptic station during the 1973–2017 statistical period (Fadaei & Hosseini, 2017)

Temperature fluctuations may also affect evaporation, salt migration, and salt crystallization. The concentration of soluble salts within pores and at the surface, followed by repeated crystallization and associated pressures, can generate internal stresses and accelerate deterioration (Rodriguez-Navarro and Doehne, 1999; Ruedrich et al., 2007; Buj and Gisbert, 2010; Coussy, 2006).

The 54 recorded frost days' further highlight the importance of freeze–thaw processes. January had the highest frequency, averaging 19 frost days per month, coinciding with the highest precipitation, number of rainy days, and relative humidity (Fig. 17). Water entering pores and microcracks expands upon freezing, and repeated freeze–thaw cycles may widen discontinuities and cause particle and fragment detachment (Ruedrich et al., 2011; Bayram, 2012). Overall, wetting–drying cycles, thermal fluctuations, salt crystallization, and freeze–thaw cycles constitute the principal climatic mechanisms of deterioration, although their effects depend on the stone's porosity, microstructure, existing discontinuities, and pre-existing condition.

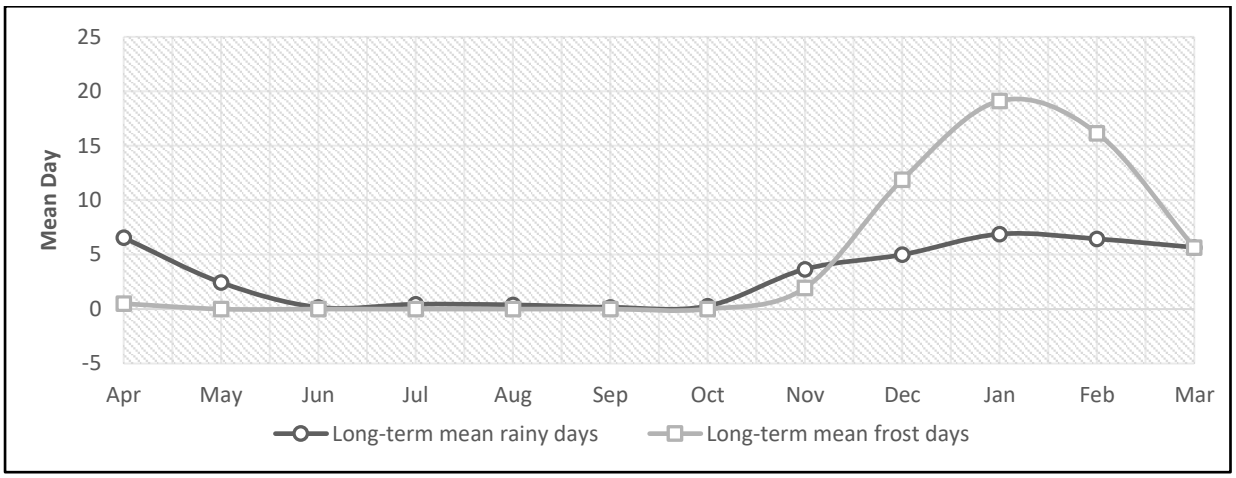


Figure 17. Long-term graph of the number of rainy days and frost days at the Takht-e Jamshid synoptic station during the 1973–2017 statistical period (Fadaei & Hosseini, 2017)

4.6. Intrinsic Properties of the Stone

Climatic factors alone cannot explain the deterioration pattern of the Shapur I rock relief; the intrinsic physical, chemical, and microstructural properties of its stone substrate must also be considered. Texture, mineralogical composition, porosity, microfractures, mechanical strength, and intergranular cementation influence the stone's response to weathering (Amoroso & Fassina, 1983; Moropoulou et al., 2003).

Petrographic studies showed that the substrate is a predominantly calcitic limestone affected by diagenetic processes, including cementation, micritisation, compaction, and microfracturing. Although calcitic cement contributes to stone cohesion, microcracks and discontinuities provide pathways for water and chemical solutions, increasing susceptibility to wetting–drying cycles, freezing, and chemical dissolution (Liu et al., 2021). This interpretation is supported by the approximately 30% reduction in compressive strength under saturated conditions, indicating that moisture penetration can reduce internal cohesion and mechanical resistance.

The high calcite content also makes the stone susceptible to dissolution by carbonated water and acidic precipitation. Field observations at Naqsh-e Rostam, including pores, dissolution cavities, and moisture-drainage channels in the rock mass and around the reliefs, indicate the movement of water through natural discontinuities. Progressive calcite dissolution may enlarge these pathways, increase porosity, and contribute to mechanical weakening and surface deterioration (Amoroso & Fassina, 1983).

Potential atmospheric pollutants may further intensify these processes. The proximity of the Marvdasht petrochemical complex, industrial activities, vehicular traffic, agricultural practices, and burning of agricultural residues represents potential sources of sulphur- and nitrogen-bearing pollutants. In combination with moisture and precipitation, these pollutants may promote acidification and calcite dissolution, contributing to micropore enlargement, loss of mechanical strength, and surface deterioration (Fadaei, 2024).

Overall, the deterioration of the Shapur I rock relief results from the interaction of intrinsic stone properties and environmental factors. Its predominantly calcitic composition, microfractures, moisture-related loss of strength, and susceptibility to chemical dissolution, combined with climatic conditions and potential pollutant sources, contribute to the progression of weathering and deterioration.

5. Emergency Conservation Plan for the Shapur I Rock Relief

Based on the documentation, condition assessment, and investigation of deterioration factors, an emergency conservation plan was developed to stabilise vulnerable areas, reduce the progression of deterioration, and prevent the detachment or collapse of original material. The presence of reduced stone cohesion, cracks and microcracks, delamination, granular erosion, powdering, and

localised detachment requires targeted intervention focused on stabilisation rather than reconstruction. The plan follows the principles of minimum intervention, preservation of authenticity, material compatibility, and relative reversibility (Nezarati Zadeh, 2024). Lost or missing portions will therefore not be reconstructed, except where limited filling is necessary to ensure stability, prevent water penetration, or protect historic edges.

Table 6. Strategies in the emergency conservation plan for the Shapur I rock relief

Damage group	Proposed conservation and treatment strategy
Discoloration and deposits	For inactive encrustation, preserve the existing condition and prevent further deterioration. In moist areas, identify and control the moisture source before intervention. Active deposits should be assessed for adhesion before cleaning. Removable contaminants may be cleaned using controlled, low-risk methods such as distilled water and alcohol.
Material loss	Lost material should not be reconstructed. Protective filling should be limited to cavities or losses that compromise stability, facilitate water penetration, or accelerate deterioration. Ledan C30 or Ledan MTX with compatible mineral fillers may be used. Intervention in areas of differential erosion should be limited to essential stabilisation.
Detachment	Delaminated and peeling layers should be stabilised and reattached using micro-acrylic resin. Voids behind detached layers may be consolidated by injecting permeable lime-based mortar, particularly Ledan TA1. Partially detached fragments may be treated using a combination of micro-acrylic resin and TA1 injection mortar.
Cracks and deformation	The activity, depth, and structural significance of fractures, splitting, and cracks should first be assessed. Significant discontinuities should be stabilised and filled with compatible lime-based mortars. Coarser mortar may be used internally and finer mortar near the surface. The objective is stabilisation and reduction of water ingress, not reconstruction.
Biological colonisation	Lichens should be removed mechanically using preferably wooden tools, with suction to collect detached particles and minimise dispersal. Plants should be physically removed, followed by cleaning and filling of the resulting cavity where necessary. Periodic monitoring should be undertaken to prevent regrowth.

The proposed interventions include controlled cleaning, consolidation of friable areas, reattachment of partially detached layers, stabilisation of structurally significant cracks, and limited filling of essential voids and losses. Materials should be compatible with the calcitic limestone in terms of physical and chemical properties, permeability, vapour exchange, and durability. Accordingly, hydraulic-lime mortars such as Ledan C30, MTX, and TA1 are proposed, based on their previous use in conservation projects at Pasargadae and Persepolis (Fadaei & Prosperi Porta, 2024; Rakhshandeh Khoo et al., 2023). These mortars can be adjusted using compatible mineral fillers and used for crack filling, localised repairs, and injection behind detached stone layers (Vintzileou, 2006).

For partially detached layers, Ledan TA1 is proposed as an injection mortar for consolidating cracks, cavities, and voids up to approximately 5 mm in width. Micro-acrylic resin (Microacril CV40), at approximately 5–10%, may be used to consolidate microcracked and superficially delaminated areas (I.M.A.R. Italia, n.d.). Ledan C30 and MTX, combined with compatible fillers such as white Majdabad stone powder and Sivand sand, are proposed for filling essential fractures and localised losses (Fadaei & Naseri, 2022). Final formulations should be established through preliminary tests of colour, texture, strength, and workability.

All interventions should be localised and manually applied following careful surface preparation and removal of deposits and biological growth. Finishing and curing should preserve the legibility of the relief, minimise visual contrast, and prevent shrinkage or secondary cracking. As summarised in Table 6, the overall strategy is to stabilise historic material, reduce moisture ingress and deterioration, and prevent further loss while avoiding formal reconstruction. All interventions should be documented and implemented following approval of the technical documentation and damage maps, providing a basis for subsequent monitoring and long-term conservation management.

6. Conclusion

The Shapur I rock relief at Naqsh-e Rostam has undergone prolonged physical, chemical, and biological weathering as a result of its exposure to environmental conditions in an open-air setting. The findings of this study demonstrate that its deterioration pattern results from the interaction of climatic conditions, the intrinsic properties of the stone substrate, and potential anthropogenic influences rather than from a single damaging factor. Seasonal precipitation, frost periods, temperature fluctuations, and variations in relative humidity are among the principal environmental factors contributing to the progression of deterioration. In particular, the coincidence of winter precipitation with sub-zero temperatures may promote repeated freeze–thaw cycles within pores and microcracks, contributing to cracking, delamination, and loss of mechanical strength (Benavente et al., 2008). The location of the relief along potential runoff pathways may further increase moisture penetration and prolong contact between water and the stone surface.

Petrographic, mineralogical, and chemical investigations identified the substrate as a predominantly calcitic limestone containing diagenetic microfractures. The approximately 29.5% reduction in compressive strength under saturated conditions confirms the sensitivity of the stone to moisture and demonstrates the significance of water-related processes in its deterioration. Potential pollutant sources associated with industrial activities, transportation, and agriculture may further contribute to chemical weathering and changes in precipitation acidity (Fadaei et al., 2024; Fadaei, 2024). Digital documentation through terrestrial laser scanning and digital photogrammetry provided an accurate geometric record of the relief and enabled the production of orthophotos and spatially referenced damage maps. These records established a reliable basis for condition assessment, deterioration analysis, future monitoring, and evaluation of conservation interventions.

The condition assessment provided the basis for an emergency conservation programme founded on minimum intervention and preservation of authenticity. The proposed measures prioritise the stabilisation of unstable areas, consolidation of friable stone, treatment of cracks and partially detached layers, and control of factors contributing to further deterioration, while avoiding reconstruction of lost material. The proposed use of natural hydraulic-lime mortars (Ledan) for injection and mortar repairs, together with micro-acrylic resin for the stabilisation of microcracks and delaminated layers, is intended to provide targeted and compatible interventions. Overall, the study demonstrates that effective conservation of open-air stone monuments requires an integrated understanding of the relationships among stone properties, environmental conditions, and deterioration patterns. The combination of scientific investigation, digital documentation, damage mapping, and targeted conservation measures provides a practical framework for risk reduction, long-term monitoring, and sustainable conservation management of the Shapur I rock relief.

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Conflict of Interest

The authors declare that there is no conflict of interest associated with this article.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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