From stone to screen: applying Virtual Reflectance Transformation Imaging (V-RTI) methodology to rock art in Dhofar, southern Oman

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Abstract

This paper presents an integrated methodology for the documentation and interpretation of a large, engraved boulder located in Dhofar region, southern Oman, combining traditional analytical techniques with high-resolution photogrammetric survey and the application of Virtual Reflectance Transformation Imaging (V-RTI). The outlined approach highlights the potential of combining photogrammetry and virtual imaging to document, analyse, and communicate rock art, offering new insights into both technique and meaning while supporting the preservation of and remote access to archaeological heritage.

Keywords

Rock art, Oman, photogrammetry, Virtual Reflectance Transformation Imaging, accessibility to archaeological heritage

Introduction

In recent years, scholarly interest in rock art has grown significantly, resulting in notable advancements on a global scale, including in areas where this focus has only recently developed. Within the Arabian Peninsula, attention to this field has been steadily increasing, with research expanding across various countries, following an initial surge of scholarly attention in the 2000s (Insall 1999; Al-Shahri 2000; Khan 2000; Nayeem 2000; Ziolkowski 2007). Notable efforts include recent studies in the Sultanate of Oman (Fossati 2017, 2019; Degli Esposti et al. 2020), the United Arab Emirates (Angás *et al.* 2021; Fossati 2022), and Qatar (El Menshawy 2017). Additionally, Saudi Arabia has recently witnessed a surge in archaeological initiatives - through surveys and excavations - that have both heightened interest in and expanded the understanding of the rock art of the region (see, for instance, Macdonald 2012, 2014; Khan 2013; Guagnin et al. 2015, 2016; Charloux *et al.* 2022).

Scholarly attention has intensified in recent decades, thanks in part to its compatibility with multidisciplinary investigation. This topic not only brings together archaeologists but also harnesses expertise in palaeobotany, palaeozoology, and geomorphology, while employing archaeometric techniques such as radiocarbon dating of rock varnish - a method successfully tested in recent times in various regions of the Arabian Peninsula (Andreae *et al.* 2021; Zerboni *et al.* 2021; Rowe *et al.* 2022).

Rock art also provides an ideal testing ground for the application and critical evaluation of a range of documentation techniques, including, most recently, photogrammetry, Reflectance Transformation Imaging (RTI), and its virtual counterpart, Virtual Reflectance Transformation Imaging (V-RTI). These methodologies enable the generation of highly detailed and accurate three-dimensional representations of rock surfaces, while remaining relatively accessible and cost-effective, thus making them particularly suitable for fieldwork in remote or resource-limited settings (Bosco and Minucci 2019).

Meticulous documentation is crucial in the study of rock art, but equally vital is the integration of new technologies, which not only enhance analytical capabilities but also contribute to its preservation and improve accessibility.

As a form of cultural heritage at risk, rock art faces numerous threats, ranging from natural processes of deterioration, such as the erosion of rock surfaces due to environmental exposure, to human activities, including the extraction of boulders for construction purposes or their displacement from the original context. However, the most significant threat to rock art comes from modern humans; in many unprotected sites, anthropomorphic and animal figures have often been vandalized, with incisions or spray-painted graffiti defacing or obliterating ancient inscriptions and depictions.

While carvings or paintings on stone served the purpose of marking one's passage through a place, it is equally true that, even in antiquity, the presence of such traces often encouraged others passing through the same location to leave their own marks. This phenomenon explains, for example, the coexistence of representations or inscriptions from different periods, where newer ones frequently overlap or obscure older ones.

This deeply rooted psychological impulse (for more on this topic, see Al-Ghabban 2011, Vol. 2, 497-498) - to assert one's existence by leaving a physical trace - has endured since antiquity and remains as compelling today as ever. It drives people to inscribe their names, initials, symbols or even elaborate graffiti onto rock faces, monuments, architectural elements and other surfaces, effectively staking a claim to posterity[1]. Yet this same urge, when expressed through unauthorized carving or painting, poses a serious threat to the artistic and cultural patrimony.

It is also true that, most often, rock art is located in areas that are difficult to access, such as remote cliffs, caves, or mountainous regions. This geographical isolation poses significant challenges, not only hindering the study and documentation of these sites but also limiting public accessibility to this archaeological heritage. Furthermore, the inaccessibility of these

[1] See, for example, Fossati 2019, 242, fig. 9.75. Many of these representations have been moreover recorded by one of the authors (AP) during a recent survey in NEOM region, Saudi Arabia.

sites can result in them being overlooked or under protected, leaving them vulnerable to natural degradation, environmental factors, or even potential vandalism.

(AP)

Combining Tradition and Innovation: The Study and Preservation of Oman Rock Art through Photogrammetry, RTI and Virtual-RTI Technology

This paper explores an integrated approach to the study of a large boulder from the Dhofar region, in the southwestern part of the Sultanate of Oman. The approach combines traditional methods of analysis, graphic reproduction, and photogrammetric survey with the innovative application of Virtual-RTI technology to the documentation and interpretation of rock art.

This approach builds on established documentation practices, which, until very recently, have relied primarily on traditional techniques such as rubbing or plastic tracing. Fossati's work - culminating in the first major volume on the rock art of Oman - exemplifies these methods, highlighting the value of meticulous direct tracings supported by photographic documentation with oblique lighting (Fossati 2019, 40).

While two-dimensional recording systems remain effective for the analysis of engraved motifs, they offer limited support for broader accessibility or remote study of rock art. Moreover, they are less suited to capturing subtle features - such as depth, faint engravings, pecking marks, and other microstructural elements of the carvings - which, as we will see, become more visible when the engravings are observed under varying lighting conditions.

In this case study, the traditional approach - anchored in photogrammetry as a reliable basis for the study of rock art - is enhanced by the integration of RTI technology, and more specifically, Virtual-RTI (V-RTI). This innovative method enables a more detailed examination of the engravings, contributing to a deeper understanding of the panels, and it allows users to interact with the boulder through a three-dimensional reconstruction. In essence, the technique combines real two-dimensional data with virtual three-dimensional models, effectively overcoming the limitations of even high-quality photographic documentation.

Naturally, this approach is not only instrumental in achieving a more thorough and accurate interpretation of petroglyphs - particularly in cases of faint or superimposed engravings - but it also enables both scholars and visitors to access archaeological assets that would otherwise remain inaccessible or challenging to reach.

Regarding the various stages of documentation acquisition, in October 2019, one of the authors (AP) conducted an initial photographic documentation of the boulder together with Ghanem Al-Shanfari - then serving as the Director of the Land of Frankincense Sites Department at the Salalah branch of the Office of the Adviser to His Majesty the Sultan for Cultural Affairs. This documentation occurred as part of a series of surveys conducted north of the area of Jibjat (Fig. 1) to assess the presence of endangered rock art sites and propose a strategy for their documentation, recording, and potential preservation.



Figure 1. The site of Jibjat, the focal point of the area surveyed in 2019 and the territory belonging to the Salalah plan (adapted from Google Earth by A. Pavan, 2024)

The size and shape of the boulder, located along the riverbed of a dry wadi (Fig. 2), along with the unique arrangement of the engraved motifs exclusively on the upper surface, made it challenging to document, limiting the ability to capture an overall view of the scenes and designs. During this initial phase, general photographs were taken of the surrounding context, along with detailed images and a video documenting the engraved representations. However, the results of this photographic survey were not fully satisfactory due to challenging lighting conditions and the absence of poles or supports for mounting the photographic equipment, which resulted in pronounced shadows affecting the quality of the images. As a consequence, their effective use for documentation and analysis was significantly limited.

Subsequently, in the early stages of the collaboration between the Office of the Adviser to His Majesty the Sultan for Cultural Affairs and the University of Naples L'Orientale - formalized in 2021 under the direction of Roberta Giunta and under the auspices of the current Ministry of Heritage and Tourism of the Sultanate of Oman - a more detailed close-range photogrammetric survey of the boulder was carried out by one of the authors (RV) in December 2019, leading to the creation of a 3D model of the boulder (Fig. 3)[2].

The established workflow, set based on the uniqueness of the object to be documented, the geographical context of the boulder's location, and the limited time available, led the team to include:

[2] After the documentation campaign, a video was also created by architect Carlotta Passaro, with the participation of the authors of this contribution (AP and RV), along with Sabatino Laurenza.



Figure 2. Image of the boulder located along the bed of wadi Lahjeej (photo by A. Pavan, 2019)

- Preliminary assessment of the target's dimensions and condition
- Evaluation of lighting conditions and camera-to-object distances to ensure optimal resolution. Shooting at noon in a region with consistently sunny weather is a strategic choice to minimize shadows and achieve even lighting. When the sun is at its highest, direct light reduces elongated shadows, enabling clearer and sharper surface imaging. Additionally, avoiding the operator's shadow during the acquisition of streaks is crucial to ensuring accurate and undistorted data. Shadows can compromise image quality and distort surface feature measurements, making it essential to carefully plan the position and angle of each shot. Finally, in those conditions, it was not easy to keep all the graffiti in focus
- Configuration of camera settings (ISO, white balance, focus ring lock, distortion correction, and VR)
- Planning the appropriate image overlap (>70%) (For procedure for the close-range photogrammetry see Remondino 2014 and Bosco 2022)

Image acquisition was conducted using a Nikon D750 FX DSLR camera equipped with a 24.3 MP full-frame sensor and a 35 mm focal length lens. The photographs (dimensions: 6016 × 4016mm) were processed using two photogrammetric software packages. The first dataset, comprising 274 images, was processed with Agisoft Metashape Pro, with 104 images successfully aligned. The second dataset, consisting of 207 images, was processed using Reality Capture v.1.5.1, achieving full alignment. The spatial resolution of the resulting 3D models showed minimal variation between the two workflows, with deviations remaining below one millimetre. This corresponds to a sub-millimetric ground sampling distance (GSD), meaning that each pixel

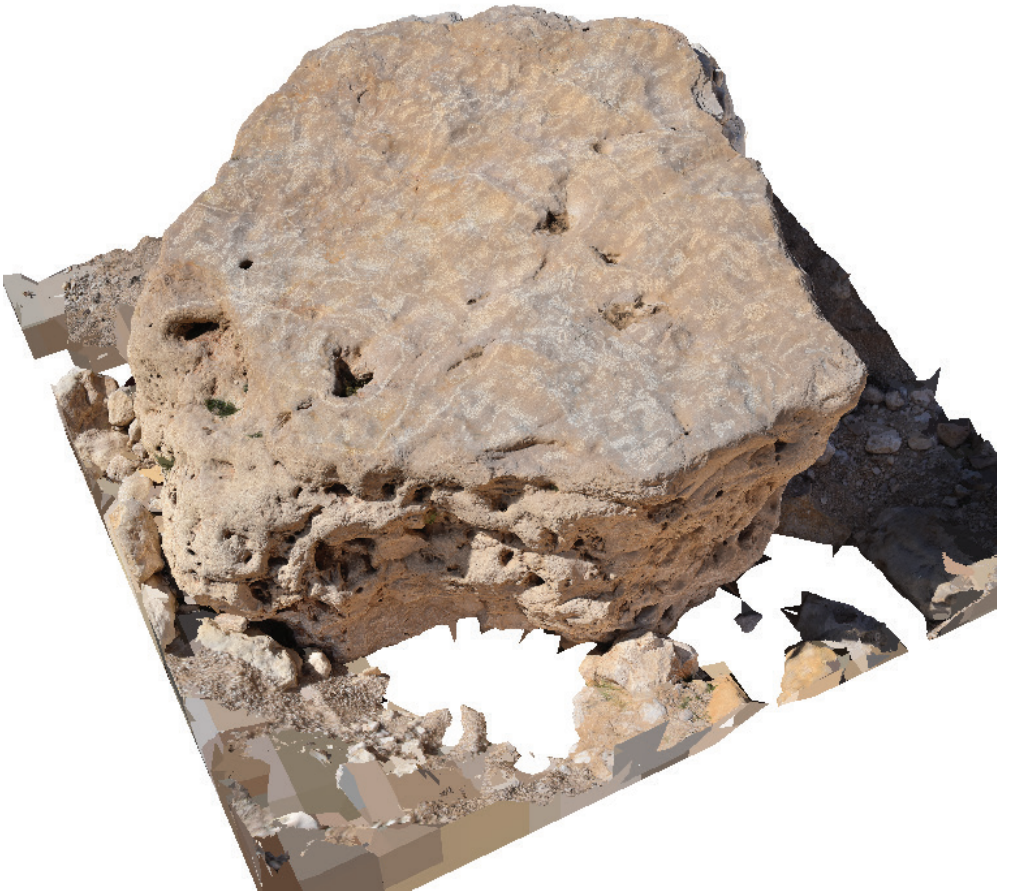


Figure 3. Digital twin of the boulder (elaboration by R. Valentini, 2025)

represents less than one millimetre of the boulder's actual surface. Such resolution enables the generation of highly detailed and metrically accurate 3D models, capable of capturing fine features and surface irregularities of the intricate graffiti etched into the boulder's surface with remarkable accuracy.

The outbreak of the pandemic subsequently led to the suspension of fieldwork, and as a result, the documentation project was put on hold. However, interest in the boulder grew when it was decided to move it, in 2023, from its original location in Dhofar to the park of the Oman Across the Ages Museum in Manah, region of Ad Dakhiliyah, in northeastern Oman (Fig. 4), where it was partially buried to ensure its upper surface remains clearly visible, highlighting it as a significant example of the country's rock art[3].

(AP, RV)

[3] See https://omanwanderlust.com/oman-across-the-ages-museum/



Figure 4. The new location of the boulder, partially buried in the park of the Oman Across the Ages Museum in Manah (photo by A. Pavan, 2024)

Reflectance Transformation Imaging - RTI

RTI is an increasingly adopted technique for the study and preservation of cultural heritage (Earl *et al.* 2011; Duffy *et al.* 2018; Fiorini 2018), as it offers innovative tools to enhance the understanding of historical and archaeological artifacts. This method is based on photography and uses open-source software developed by the non-profit organization Cultural Heritage Imaging – CHI (CHI 2011, 2013 a-b, 2014). Conveniently, on a personal computer, it allows users to relight an object from different directions, emphasizing surface features, even microscopic ones, that would otherwise be difficult to observe under natural lighting conditions (Pintus *et al.* 2019).

The computational principles underlying this technology go beyond simply capturing RGB colours in photographs; they also record the surface normals for each pixel. These data provide information on the reflectance angle of the light striking each point of the object.

This tool is highly appreciated both for its wide range of applications, from the study to the conservation of ancient artefacts of different types, and for its ease of use. The RTI method, indeed, requires the use of common and low-cost equipment, which makes it sufficiently versatile and accessible at different levels (Bosco and Minucci 2019). The preferred acquisition method in archaeology is Highlight-Based RTI (H-RTI). This approach requires a standard camera, a tripod, and an external light source, such as a wireless flash or continuous light.

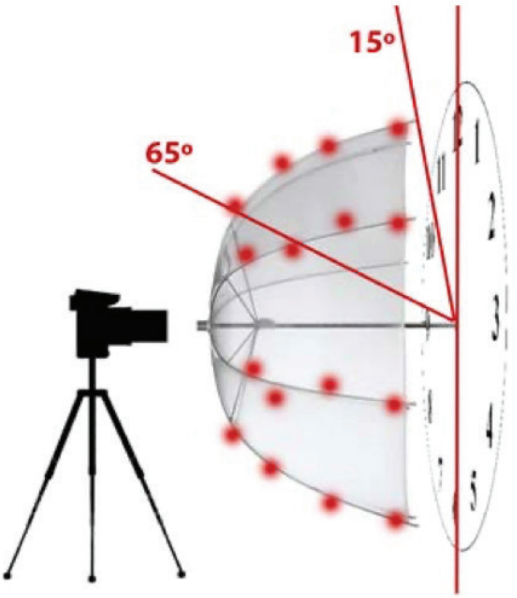


Figure 5. Representation of RTI acquisition mode, with red dots representing the light spots (Guide to Highlight Image Capture, Cultural Heritage Imaging, 2013)

A reflective target is essential for successful acquisition. This target consists of a glossy, dark-coloured sphere or hemisphere (one or two can be used), positioned near the object being recorded. The sphere must remain fixed in its position and visible in every frame.

The target's function is to capture the light source position through direct reflection on its surface. The light source should move around the area of interest at angles between 15° and 65°, forming a sort of dome (Fig. 5). Each light position corresponds to a separate camera shot, with the camera maintaining a fixed viewpoint on the object. For optimal acquisition and high-quality photographic datasets, it is crucial to avoid vibrations or movement during the capture process. Additionally, the light source should be positioned at a distance at least twice the diameter of the object being recorded.

This technique is widely applied outdoors for the acquisition of inscriptions and rock reliefs in order to improve the reading, and thus the interpretation, of the signs and to better understand the processes of their creation (Miles *et al*. 2018; Mourey 2019; Kościuk *et al*. 2020).

Another acquisition method involves the use of a light dome (D-RTI). This consists of a physical dome (Fig. 6), made of metal or plastic, with an upper opening for the camera and internally mounted LEDs placed at predefined distances to illuminate the object from multiple equidistant points. The LEDs are synchronized with the camera shots, maximizing automation and minimizing direct handling of the camera. This method is particularly suited for small objects, and it is generally used in laboratory settings. The dome's inherent stability and semi-automated capture process eliminate the risk of motion, ensuring sharp, high-quality images free from blur-related artifacts, which could otherwise compromise the final data processing.



Figure 6. Image of the D-RTI dome from CISA laboratory, University of Naples L'Orientale (photo by A. Bosco, 2025)

Both acquisition techniques, however, have limitations, as they can only be applied to objects or surface sections of medium to small size. This restriction arises either from the physical capacity of the dome (D-RTI) or from resolution issues when it is acquired at an excessive camera-object distances (H-RTI). Additionally, RTI requires ample manoeuvring space to allow for regular movement while keeping a consistent distance from the object. This requirement is not always possible in archaeological sites or historic monuments. Even when working with objects in museum collections, relocating artifacts to sufficiently spacious environments may not always be possible.

The RTI methodology, as mentioned, is highly appreciated for its ability to bring out the depth of the engravings by manipulating light. This expedient, also aided by the various renderings available in visualisation software, is often referred to as 2.5D. However, several studies feel the need to supplement the information from this methodology with 3D acquisitions of the objects/surfaces being analysed (Min *et al.* 2020). This makes it possible to observe anomalies on surfaces from different angles.

The rapid evolution of three-dimensional acquisition and visualisation systems has made it possible for most scientific research to take advantage of very high-resolution 3D resources. Such resources have many times provided key information and data for archaeological research, in many cases revolutionising (without necessarily replacing) traditional procedures.

(AB)

The Virtual RTI

The Virtual RTI (V-RTI) methodology was developed to overcome the acquisition challenges encountered in traditional RTI, leveraging the increasingly widespread and well-structured 3D surveying workflow used in archaeology (Bosco *et al.* 2023; Di Iorio *et al.* 2024).

V-RTI involves the creation of a virtual dome within the open-source software Blender, simulating the technical characteristics of a real dome while allowing for adaptable dimensions depending on the object being acquired. The object itself is placed in the virtual environment as a 3D replica, obtained through photogrammetric surveying or laser scanning, and imported in OBJ format.

Next to the object, a virtual reflective sphere is positioned, created by generating a primitive UV Sphere with a high number of geometry subdivisions to ensure maximum smoothness, complemented by smooth-shaded normals. Additionally, the sphere's shadow can be disabled, preventing it from being projected onto the object's surface. The entire setup accurately replicates a real-world RTI acquisition, with the camera positioned at the top of the dome, near the uppermost ring of lights. Each light position corresponds to a captured image, and the final dataset can be processed as usual using RTI software such as RelightLab.

This virtual methodology combines the geometric detail of high-resolution 3D models with the micro-relief analysis capabilities of RTI, providing a powerful tool for archaeological research.

However, it is essential to note that the quality of the results depends strictly on the resolution of the 3D replica being used. The 3D mesh must have a high level of geometric detail to ensure that the light projection and subsequent application of filters linked to specific fitting algorithms - such as PTM (Polynomial Texture Mapping) or HSH (Hemispherical Harmonics) - yield relevant and accurate results.

(AB)

Acquisition Parameters in the Virtual Dome for the Rock Art Case Study

Rock art represents an ideal case study for the application of Virtual RTI, given its complexity as an archaeological artefact: the boulder comprises numerous representations executed with different techniques, likely produced in distinct chronological phases, with varying depths and frequent superimpositions. The surface area covered by the petroglyphs is quite large (approximately 3.8x3.6m) and the rock is elevated by approximately 1.70m above ground level.

The combination of these physical features and the environmental context - an originally isolated element situated along the riverbed of a wadi, with constant sun exposure throughout

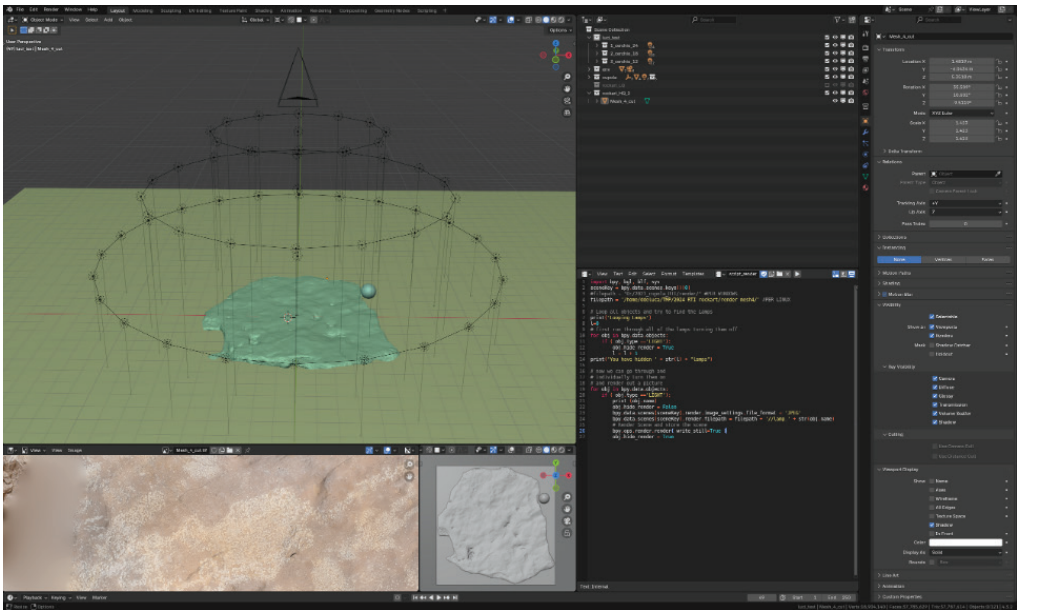


Figure 7. View of the virtual dome in Blender software.

the day - renders the application of a traditional RTI acquisition method across the entire surface of the artefact virtually unfeasible.

The original mesh, obtained by photogrammetric elaboration, had a total vertex count of ~43 million vertices and at first, to be handled better for the V-RTI, it was processed inside Metashape by manually trimming faces and vertices that were outside the rock art area and still preserving the whole upper surface. That result of the cleaning process was a mesh with ~19 million vertices, so much easier to manage.

The virtual boulder was then exported from the Metashape software and imported into Blender as an .obj file with the UvMap and the associated texture.

The dome of the V-RTI uses three "rings" of virtual lamps, composed respectively of 24, 18 and 12 point lamps, with a small radius to replicate the real dome with led lamps (Fig. 7).

The Cycles engine of Blender was used to render the model and, because of the high level of detail of the rock surface, hi-res images were necessary. The resulting renderings are 4320 × 4320 Mpx and, with this resolution, every mesh detail present into the photogrammetry was retained.

Because the engravings on the rock are, sometimes, extremely fine and shallow and superimpositions occur as well, the virtual lighting and rendering settings were carefully adjusted to enhance and preserve the details in the final digital model. We experimented with the standard parameters and we found an overall lighting improvement by using a colour management that uses the display space "Khronos PBR Neutral". The rock was still very bright and contrasted, so we used a "Very Low Contrast" transformation curve and also, we modified

the exposure to -1.0 to avoid over-exposed areas and calibrated the gamma to 1.2 to get a good final light of the rock.

To better clarify the method, we think it's worth taking a closer look at the resolution aspects related to this approach.

In this procedure, resolution has a linear effect, but only in terms of geometry and not texture. If a model doubles its geometric resolution, it means that where there was previously one square, there are now four smaller squares; if it is doubled again, there are 16 even smaller squares. In this way, every time the resolution increases, the model gains a proportionally finer level of detail.

For example, a shadow that appears coarse, blurred, or poorly defined at low resolution becomes progressively more precise and detailed at higher resolutions. The increase in resolution allows us to distinguish increasingly finer features, where before we could only see an approximate shape. In other words, what was previously rendered as a single indistinct blur is, at higher resolution broken down into more complex lines and shades that better describe the surface features – "shadow" here referring to light-simulation output of the RTI process.

All this applies when considering only the geometric resolution. However, if we also take into account the rendering resolution within Blender or that of the RTI output, then additional factors are involved. In practice, if the rendering is of low quality, even a high-resolution model will lose precision and detail: the final quality of the image will therefore depend on both the resolution of the model and that of the rendering.

A possible rule of thumb is this: if we want to achieve high-resolution rendering, the pixel density of the image should be consistent with the density of the polygons in the mesh.

In other words, each triangle (or square) of the mesh should be represented by at least one pixel in the rendering. Ideally, however, it would be better to have about 9 pixels per triangle in order to properly handle anti-aliasing, shading, and visual details.

For example: if a 3D model is composed of about 1000 triangles per side (roughly 1 million triangles in total, as a projection of planar vertices onto the camera's field of view), a 3000×3000 pixel rendering would be a good choice. This is a very rough estimate, but it gives a rough sense of the relationship: the rendering must have a resolution that is a multiple of the mesh density.

If, on the other hand, the model has about 4 million triangles, a rendering of around 6000×6000 pixels would be needed to represent it at its best. However, such high resolutions become impractical; in fact, values of approximately 4000×4000 pixels are often adopted, which still offer a good compromise between quality and resource management.

In summary, we can say that the rendering resolution should be about thrice (or more) the "average size" of the mesh triangles, to avoid losing the details of the model.

(AB, DDL)

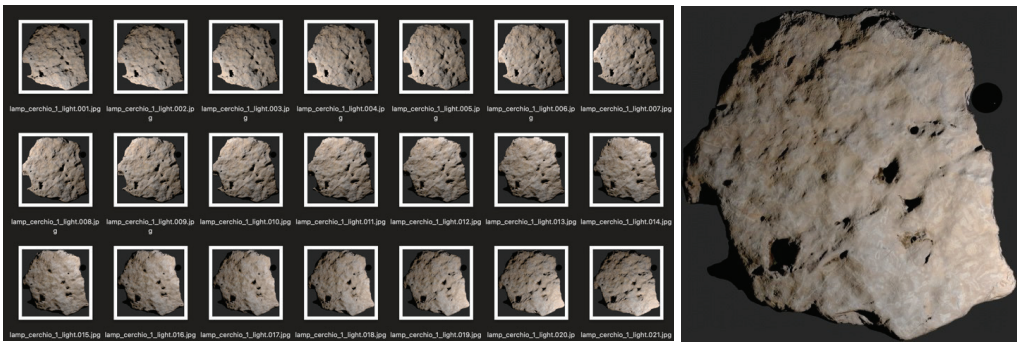


Figure 8. Left: a selection of renders taken in Blender software; right: a render in which the virtual reflecting sphere is clearly visible in the top right

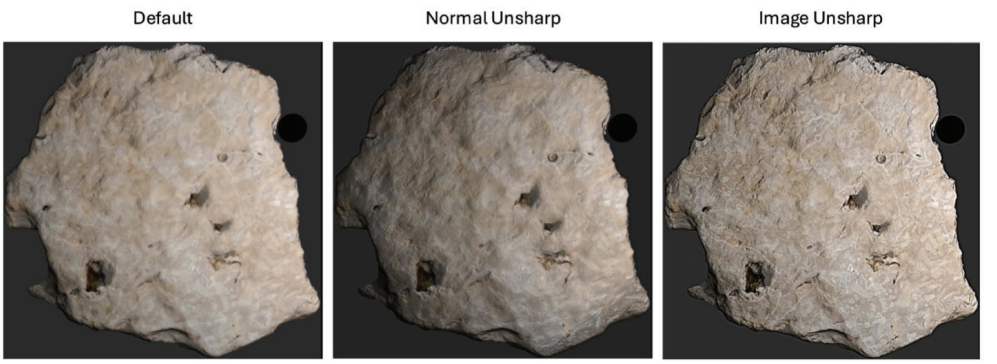


Figure 9. Images of the rock surface with different rendering modes applied with the same angle of light

The Advantages of Using V-RTI for the Study of Rock Art in Dhofar

Virtual processing produced 54 shots, saved in .JPG format (Fig. 8), which were loaded into the RelightLab software in order to generate the dynamic RTI file. As previously mentioned, the software uses algorithms to calculate surface reflectance based on variations in light. During the process, a normal map and polynomial coefficients are generated to simulate the interaction of light with the surface. The resulting product can be read using a dedicated open-source viewer, RTIViewer, or through a web-based viewer.

The user can dynamically adjust the light direction to examine surface details and apply enhancement filters such as Specular Enhancement, which enhances reflections, Normal Unsharp and Image Unsharp, which increases the sharpness of the object's surface details by applying a filter to the surface normals, or Diffuse Gain which increases contrast (Fig. 9). Additionally, and this is a recent innovation of the software, there is now the possibility to insert metric values, making the generated products measurable and compatible with other documentation tools, such as GIS.

(AB)

The location of the boulder

The boulder under investigation was originally located in the Governorate of Dhofar, in the pre-desert region of Nejd (literally "*plateau*"), an area situated between the escarpment to the south, which rises sharply from the coastal plain, and the dunes of the Empty Quarter desert to the north. This plateau is a relatively flat area, characterized by numerous northward-flowing wadis, which are seasonal rivers that drain towards the desert and not to the sea.

The boulder was located along the bed of wadi Lahjeej (see above Fig. 2), a seasonal river that forms part of the intricate water systems of wadi Dhahabun and wadi Salafan. These wadis meander through numerous bends of varying sizes as they flow toward the desert, ultimately converging south of Thumrait[4].

The boulder, made of limestone typical of the area, is in an isolated position along the riverbed. Apparently, though this aspect would require further verification through a more detailed survey, there are no other examples of rock art nearby, except further north in the wadi Jazeel area, sometimes referred to as wadi Jeez Leet (Fossati 2019).

(AP)

Archaeological background

Nejd, and particularly the area of wadi Dhahabun, has been the focus of numerous surveys since the 2000s. In 2004, it was mapped as part of the Central Oman Pleistocene Research (COPR Project), led by Jeffrey Rose (Rose *et al.* 2019) who was able to identify a few assemblages dated to the Palaeolithic, though most accessible shelters were attributed to the Holocene.

During the same period, the area was included in the Dhofar Archaeological Survey Project (DS), conducted between 2008 and 2009 by Juris Zarins and Lynne Newton under the Office of the Adviser to HM the Sultan for Cultural Affairs (Zarins and Newton 2013). A Neolithic site (DS-08-088) rich in lithic material (Newton and Zarins 2017, fig. 2.5, 1-16), was discovered, as well as several Iron Age sites, including shelters and graves (DS-08-082; Zarins and Newton 2013, 58), cliffside graves (DS-08-087), and notably, triliths (DS-08-081; DS-08-090-095).

Research by Ohio University, headed by Joy McCorriston, focused on the archaeology and lives of pastoralists, carried out targeted investigations of small-scale monuments through the whole Dhofar (McCorriston *et al.* 2020) and, specifically, in the area of wadi Dhahabun (McCorriston 2023, 33, table 3.1).

As part of this work, the boulder was documented using an orthophoto[5] after being identified through satellite imagery during a survey of the complex system formed by wadi Dhahabun and its tributaries (McCorriston 2023, 32, 34-35, fig. 3.9). To the authors' knowledge, this

[4] Unfortunately, during neither of the two visits made by the authors to the area, was it possible to obtain the precise GPS coordinates of the location.

[5] The boulder has been catalogued within the framework of the Arabian Human Social Dynamics Project (AHDS) under the designation D113.

is the only complete image of the boulder published to date, apart from the photographs available online on the Oman Across the Ages Museum webpage[6].

(AP)

Description and Interpretation

The boulder has an irregular quadrilateral shape with substantial dimensions (3.8x3.6m) and rises to a height of approximately 1.70m. The only engraved surface is the upper one, which is predominantly flat but features some natural fractures and a couple of cupmarks with a diameter of about 10cm[7].

The upper surface of the boulder is extensively covered with a dense array of engravings, many of which are superimposed (Fig. 10).



Figure 10. Orthophoto obtained through photogrammetric survey (Orthophoto by R. Valentini, 2025)

[6] https://omanwanderlust.com/oman-across-the-ages-museum/. A graphic reproduction of a portion of the boulder's decoration is published in Al-Shahri 2000, 138.

[7] These typical semi-spherical, cup-shaped depressions commonly found in rock art worldwide, often associated with various purposes are differently named in the Arabian Peninsula as cupules (see, for example, Khan 2013) or receptacles (see Fossati 2017, 31).

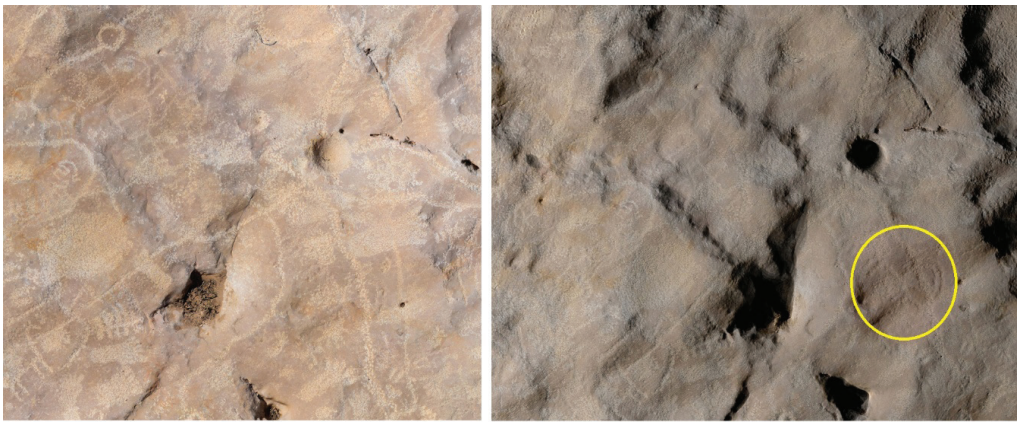


Figure 11. The ibex figure is not discernible through photogrammetry, but is clearly visible using Virtual RTI

Although this superimposition might suggest different phases of execution, an initial photogrammetric analysis revealed no clear evidence of separate chronological layers. A subsequent re-examination using V-RTI technology, however, revealed that some motifs bear shallower pecking marks, likely due to surface wear, and become perceptible only through variations in shading. This is the case, for instance, of the ibex figure in the northernmost section of the boulder which is barely perceptible in the photogrammetric model but appears far more clearly under V-RTI (Fig. 11).

The petroglyphs feature anthropomorphic figures, animal representations, and - most notably - non-figurative motifs and abstract symbols, whose interpretation remains, however, speculative.

Rather than providing a detailed iconographic analysis, this study adopts a methodological approach to present a case study aimed at illustrating the potential of new tools for documenting, promoting, and enhancing access to the rock art heritage of the Sultanate of Oman. However, a brief analysis and description of the figurative and abstract motifs identified on the boulder will follow. Additionally, an attempt will be made to offer a comprehensive interpretation, though it will remain hypothetical.

The most commonly depicted motif on the panel is that of a bare foot, shown in various sizes, all smaller than life-size and typically featuring five toes. Rarely, footprints with four or three toes are observed. In two instances, the foot is enclosed within a rectangular shape (Fig. 12, left). Occasionally, footprints of different sizes, sometimes partially overlapping, can be seen, possibly symbolizing the movement of family groups. The footprints are oriented in various directions and are often, though not always, associated with faint linear engravings, to be possibly interpreted as wadis or pathways (Fig. 12, right).

Footprints are relatively uncommon in Oman's rock art (Fossati 2019, 119), with a higher concentration in the northern regions of Musandam and Shenah, where they possibly symbolized territorial control and the delineation of boundaries (Al-Jawhari and ElMahi 2013). Their presence is nonetheless documented in Dhofar, albeit sporadically, while handprints are



Figure 12. Footprints engraved on the boulder

decidedly more common (Zimmerle 2017, fig. 27). On the boulder in question, handprints occur in two instances, one of which features six fingers[8].

In addition to body elements like hands and feet, the boulder displays two anthropomorphic figures that differ significantly in style, despite being created using the same pecking technique. Neither figure exhibits identifiable sexual characteristics.

One example (Fig. 13, left) represents a stick-figure human composed of simple lines schematically indicating body parts (arms, torso, and legs), with a rhomboid-shaped head that appears hypertrophic and disproportionate to the rest of the body.

The second figure (Fig. 13, right), in contrast, is more realistic, with a fluid design that conveys a sense of dynamism. The posture suggests the body's weight is resting on one leg, while the other remains slightly bent. The head, round and proportionate to the body, creates a silhouette that is relatively rare among petroglyphs. The fact that the figure has been depicted wearing a garment is a rarity among the representations in Dhofar and might suggest a particular status of the depicted character (Zimmerle 2017).

Zoomorphic elements are also present, including two horned animals (Fig. 14) with prominently emphasized long horns, identifiable as ibexes or possibly as depictions of Nubian ibexes (*Capra nubiana*), the latter commonly characterized in rock art by a long pair of curved horns (See Fossati 2017, 49; Angás *et al*. 2021, 8). Representations of ibexes are widespread throughout the Arabian Peninsula and are rendered in various stylistic forms. In nearly all cases, their curved horns are deliberately accentuated, underscoring the animal's symbolic significance[9]. On the

[8] Footprints and handprints are one of the oldest rock art motifs, occurring in Arabia from the Neolithic to the Islamic Period, see Khan 2007.

[9] In southern Arabia the ibex held strong associations with important deities in the South Arabian pantheon, such as Almaqah and Athar, see Avanzini 2005.



Figure 13. Anthropomorphic figures engraved on the boulder



Figure 14. Horned animals with prominently emphasized long horns, possibly ibexes or Nubian ibexes

panel, the animals are depicted in isolation or in connection with footprints, possibly hinting at a ritual significance.

A dromedary is also present on the panel, represented in a schematic form. The dromedary is one of the most iconic motifs in the rock art of Dhofar (Elmahi 2015), in the whole Oman (Fossati 2017, 72), and the entire Arabian Peninsula, where it reflects the daily life of desert societies, serves as an expression of ownership, and symbolizes sacrificial offerings[10]. In the panel under study, the camel appears in association with the recurring footprints.

[10] For an in-depth discussion of camel depictions, particularly in northern Arabia, see Brusgaard 2020.



Figure 15. Donkey or onager's footprints as appeared with V-RTI

The category of zoomorphic representations also includes a series of hoof or footprint engravings (Fig. 15), created using the same pecking technique but executed with greater depth (as clearly shown by the V-RTI). These are arranged in various directions and can possibly be attributed to a donkey or an onager.

A number of non-figurative abstract/symbolic motifs are also visible, with geometric designs prevailing (Fig. 16), although they were representational to those who created them, but their meaning is largely elusive to us today. It is plausible that, in some cases, they could represent landscapes, roads, or architectural structures or be tribal/ethnic marks (*wusum*)[11]. On the boulder they include radiating shapes, such as a potential solar figure formed by a circle with long rays extending outward and a central dot, as well as spiral patterns. Additionally, there are semi-circular and straight lines from which vertical elements extend on one side.

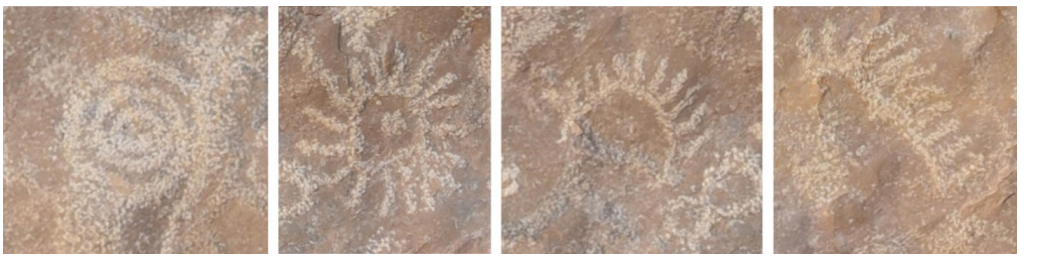


Figure 16. Examples of non-figurative abstract or symbolic motifs engraved on the boulder

T-shaped figures also appear, grouped in clusters and partially obliterated by subsequent engravings. This type of representation is also found among the petroglyphs of northern Oman (Fossati 2017, 23, 39, fig. 3.27) and in the rock art of the Al-Hajar mountains in the Emirate of Sharjah, where they have been dated to between the 3rd and 2nd millennia BCE and assigned a variety of interpretations[12].

The analysis of the boulder under different lighting conditions also revealed a series of square figures forming a sort of checkerboard pattern.

[11] While non-representational to us, these motifs indicated territorial or animal ownership for the Bedouins and are often, but not always, associated with the depiction of horses and/or camels, see Khan 2000.
[12] See, for example, https://whc.unesco.org/en/tentativelists/6642/

The panel also includes motifs such as a circle with a horizontal appendage or two interconnected circles, which could be interpreted as representations of dwellings, cairns, or platforms connected by pathways essential for linking them - features typical of the archaeological landscape of the area, which has been recently described as characterized by "persistent pastoralism" (McCorriston 2023).

The engravings were made using the pecking technique, the most frequently documented method for rock art in Oman (Fossati 2019, 28). This technique involves systematically striking the surface of the boulder with a harder stone, creating a series of closely spaced depressions that together form the depicted motifs. However, there are also lines created using deep incisions.

While the scene cannot be fully understood or interpreted, certain elements - such as the lines covering the flat surface, the circles connected by these lines, and the significant number of footprints - suggest that the panel might represent a stone transcription of the surrounding landscape, potentially serving as a sort of map. This map would include various motifs often referred to as "topographics" which, typically, include square and rectangular engravings, beside circular motifs.

This interpretation is supported by the fact that topographics are often associated with scenes featuring cupmarks, dwellings, human figures and single-engraved line pathways (Nash 2021). Such a map might also have served as a guide to a specific location, now obscure to us. This hypothesis is further reinforced by the panel's position on a boulder within the wadi bed, likely a major route for communication and exchange.

The central placement of the boulder along the wadi could indicate its potential role as a "public panel" for travellers navigating the route. However, the engravings are located on the flat, smoothed upper surface of the boulder, which was ideal for carving but would not have been visible to passersby at ground level, complicating interpretations of its intended function or audience.

(AP)

Bridging the Gap: Digital Strategies for the Preservation and Interpretation of Rock Art

The relocation of the boulder from its original site to the park of Oman Across the Ages Museum in Manah was motivated by the entirely legitimate desire to ensure the preservation of the integrity of this extraordinary example of rock art. The move also allowed for enhanced visibility and public appreciation of the panel. However, such intervention inevitably resulted in a caesura between the object and its original context, which is integral to its historical and cultural value. This disjunction severs the relationship between the boulder and the landscape in which it was originally situated. It detaches the panel from its geo-cultural setting, obscuring clues about why this particular outcrop was chosen and how it related to ancient travel routes, ritual pathways, or local topography. In essence, the boulder's original "stage" - its position, orientation, and surrounding environment - formed part of the narrative the engravings were meant to convey. By relocating it, the stone was safeguarded but much of the experiential and contextual information that gave the rock art its full meaning was sacrificed.

In this scenario, advanced digital technologies could offer significant opportunities for the valorisation and enjoyment of the work, bridging, at least in part, the gap created with physical removal. By installing simple touchscreen displays in museums or visitor centres, rock art becomes immediately and universally accessible - no specialist equipment or site access permits required. These screens can present high-resolution photogrammetric 3D models and Virtual RTI renderings, allowing users to rotate, zoom, and interactively illuminate the engraved surfaces. Layered annotations, photographic close-ups, and guided audio or video tours can be overlaid on the digital twin to explain individual motifs, techniques, and cultural contexts. Such an installation not only brings remote or fragile panels "within reach" of all visitors - including those with mobility or visual impairments - but also preserves the original site by reducing physical contact. Moreover, these digital displays can be updated with new findings, comparative examples, or multilingual content, transforming static exhibits into dynamic learning environments and ensuring that the story of the rock art continues to evolve alongside ongoing research.

At the same time, Virtual RTI acquisitions prove fundamental for a more precise reading of stone engravings, making visible details that would escape direct observation or traditional photography. Such technologies not only advance the study of engraving techniques and the artefact's conservation state, but also help unlock its symbolic and aesthetic meanings, making them accessible to a broader audience through captivating digital experiences.

(AP, AB, RV)

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