Article

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Digital Technology: A Step to Protect Cave Art of Indian Subcontinent as National Heritage – A Review

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Abstract: The integration of digital technology, particularly virtual reality, is proving to be a pivotal tool in preserving and sharing the rich cultural heritage found within Cave art sites. This article deliberates on the use and application of digital technology in the field of cave painting conservation that provides an authentic and effective method of Cave art preservation for the future. Employing advanced techniques of photogrammetry, terrestrial laser scanning, structured light scanning, and high-resolution photography can digitally preserve the intricate details of Cave art, while the utilization of humidity, temperature, and CO_2 sensors may provide a comprehensive digital monitoring system to track the condition of Cave art over time. This paper deals with the evolving landscape of technologies and their application to safeguard Cave art from environmental degradation and anthropogenic factors. The digitization of cave art has the potential to accurately conserve a site if used in an effective manner while also allowing visitors to experience this art form in ways never before feasible. The application of advanced digital technology in cave art conservation is not merely a choice but a necessity, considering the impermanent nature of these paintings in their natural environment. This paper underscores the urgency and significance of leveraging digital tools to ensure the enduring legacy of Cave art, an example of how digital technologies, as they evolve, will play an increasingly essential role in the conservation and dissemination of our world's extraordinary cultural heritage.

Keywords: Cave art; conservation; 3D imaging; digital technology; tourism; dunhuang art caves

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1 Introduction

The preservation of cave art has entered a new era, one driven by advancing technologies (Cipresso et al. 2018). These innovations, encompassing online databases, virtual tours, film, and more, offer fresh opportunities to augment existing conservation methodologies. Through these technological advancements, recording the intricate details of cave art has achieved an unparalleled level of precision, paving the way for the creation of digital archives, websites, and high-quality images (Valdez-Tullett and Figueiredo Persson 2023). The advent of digital imagery and reconstruction techniques represents a substantial leap forward, surpassing the limitations of static replicas. It now grants audiences and researchers the immersive experience of interacting with digital representations, far beyond the confines of static displays (Whitworth 2001).

However, a significant debate arises regarding the digital image's capacity to capture the "aura" of an original artwork (Rose 2022). Critics scrutinize whether these representations can preserve the essence of the original. However, the digital image, involving rigorous scholarly analysis, possesses the unique ability to encapsulate the original work's aura, delivering it to viewers through rich visual information. Digital images thus have the potential not only to capture the aura but also to engender distinct, individual meanings, open to appreciation and analysis by those who engage with them (Edwards 2021).

Caves and rock-cut structures, with their unique environmental conditions, have served as sanctuaries for paintings, preserving them for not just centuries but millennia. These ancient artworks, found on natural rock surfaces, offer a priceless glimpse into the vibrant lives of our ancestors, akin to keyholes into history (Fogelin 2006; Thomas 2001). India stands as a global treasure trove of ancient rock-cut cave temples, with a geological landscape, primarily the Deccan Plateau, teeming with suitable cliff faces and domes for rock-cut architecture. With over 1500 known rock-cut caves and ongoing discoveries, India's wealth in this regard is unparalleled (Singh 2018). The prevalence of durable rocks like basalt,

diorite, and granite in the Deccan Plateau forms the perfect canvas for these paintings, with the sheltered cave environment shielding them from seeping water and erosion.

India's vast expanse and diverse cultures promise a rich tapestry of artistic styles. The country boasts a rich tapestry of rock art, categorized into three distinct forms: petroglyphs, pictographs, and petro forms. These artworks span a wide range of styles and themes, with a chronology stretching from the Upper Palaeolithic era to historic times (Painting 2016), offering glimpses into the lives of contemporary tribal communities. These rock art treasures are found in various states across India, including Madhya Pradesh, Uttar Pradesh, Andhra Pradesh, Telangana, Kerala, Uttarakhand, Bihar, and Karnataka, with Central India, characterized by sandstone hills in regions like Kaimur, Satpura, and Vindhyas, standing out as the most prolific area (Sandhu, Sonika. 2021). These rock shelters, ecologically ideal for occupation, have yielded paintings reminiscent of styles in far-flung places like Rhodesia, Eastern Spain, South Africa, and Australia. Such artworks offer vivid portrayals of hunting, battles, dancing scenes, human figures, and animals (Tripathi 2017).

Understanding the structural intricacies of mural paintings is a pivotal endeavour in documenting the diverse modes of deterioration and the factors influencing them. Typically, mural paintings exhibit a layered composition, comprising a support structure, often brick or stone walls. This is followed by a ground layer, usually consisting of coarse and fine lime or mud plaster. Subsequently, a lime wash layer and the paint layer itself form additional strata (Singh 2014). However, each of these layers is susceptible to various factors that may lead to alterations or decay. With this in mind, a meticulous study of these components is indispensable for accurately assessing the state of preservation and implementing necessary corrective measures.

The murals at Ajanta present a distinctive preservation structure. These paintings are upheld by a substantial layer of coarse and fine mud plaster, with thickness varying from 2.5 to 5 cm, contingent upon the inner support basaltic stone wall's roughness (Singh 2014; Singh and Arbad 2014; Singh and Arbad 2015). The composition of this mud plaster encompasses clay, sand, silt, vegetal fibers, lime, and aggregate grains derived from basaltic rock, featuring minerals such as quartz, feldspar, pyroxene, olivine, and iron oxide; this layered foundation serves as the canvas for the intricate mural artwork. Above the mud plaster, a delicate lime wash layer, measuring between 80 and 200 μm in thickness, was meticulously applied. This layer likely served multiple purposes, including providing a flat and uniform surface for painting, enhancing color consistency, and improving the adherence of the subsequent pigment layers. The outcome is a robust yet fragile surface that hosts the mural art. Over time, the painted surface has accrued a layer of dirt, dust, soot, and traces of altered shellac, natural resins, and, in some instances, polyvinyl acetate used as a coating material during chemical conservation.

2 A Short Story of Indian Cave Paintings

2.1 Prehistoric Times

In prehistoric times, India's natural caves and smaller shelters were adorned with remarkable paintings. One outstanding site is the Bhimbetka Rock Shelters, where over 500 caves and smaller rock shelters house thousands of these ancient artworks (Figure 1). The oldest paintings here date back to around 15,000 years ago and may even stretch as far back as 30,000 years, making Bhimbetka a repository of some of the earliest human-made paintings (Selvakumar and Kois 2019). Prehistoric art adorns various regions of India, spanning from the southern state of Tamil Nadu to the snow-covered Himalayas.

2.2 Ancient Paintings: Second Century B.C. – Seventh Century A.D.

The rich legacy of Indian art finds its earliest well-preserved cave paintings within the depths of history. Inside Cave 10 of the Ajanta Caves, we encounter a remarkable treasure,

Figure 1: Prehistoric cave paintings at Bhimbetka Caves, Bhopal, India (source: www.traveldine.com).

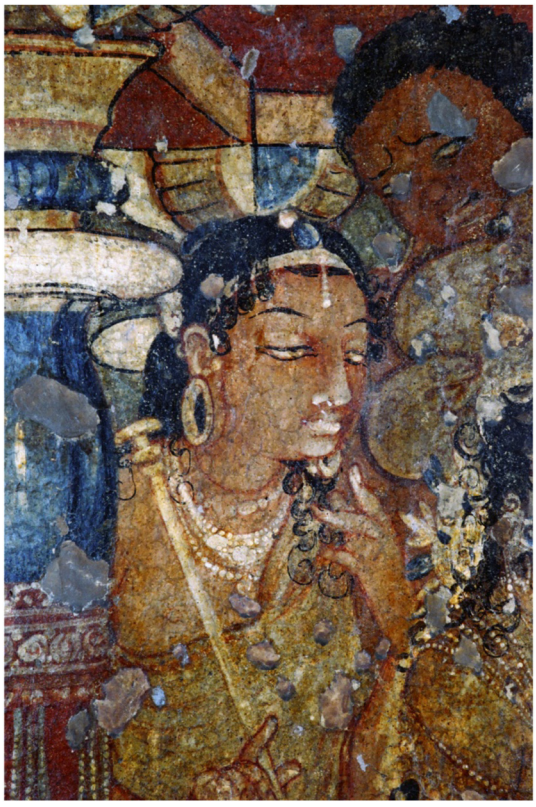

Figure 2: Cave painting at Ajanta Caves, Aurangabad, India.

paintings dating back to around the second century B.C. (Oza 2022). These are no mere primitive renderings but the work of seasoned, professional artists. Although the majority of Ajanta's murals hail from a later period, primarily between 460 and 480 AD, they are globally renowned and narrate tales of Buddha's life and other themes typical of Buddhist art. Among these intricate artworks, the depictions of women are nothing short of breathtaking (Figure 2). Many of these paintings and sculptures portray mythical beings such as yakshas, nagas, vrikshikas, and river goddesses Ganga and Yamuna, who possess a supernatural beauty that is integral to their essence (Gandhimathi and ArulMary 2017).

In the realm of art and history, the Jogimara Cave paintings in Chhattisgarh, created around the first century B.C., stand as unique treasures, not only for India but for the entire world. Unlike their religiously inspired counterparts, these drawings adorn a rock-cut cave, offering a glimpse into an intriguing facet of ancient life, as if this cave once served as a dressing room for actresses from a nearby open-air theater. The paintings capture a dancing couple, figures of fish and elephants, and an enigmatic chariot depiction (Sharma and Singh 2021).

Further afield, the Pitalkhora Caves in Maharashtra, adorned with beautiful fourth century A.D. paintings (Agnew et al. 2015), have preserved their artistry on the columns of Cave three and other chambers, bearing witness to history. For the connoisseurs of ancient Indian cave art, the Bagh Caves in Madhya Pradesh shine as masterpieces created around the fourth to sixth century A.D. (Li 2018). These sites embody the brilliance and sophistication of ancient Indian artistic endeavors, offering a rich tapestry of heritage.

The grandeur of ancient Indian cave art is further showcased in the regal Badami Cave Temples in Karnataka, dating back to the late sixth to seventh century AD. A jewel within these caves, the splendid artwork on the ceiling of Cave three portrays the four-armed Brahma atop his swan (Sharma 2007). Elsewhere, in a truly unique testament to artistry, a tempera painting graces the Ravan Chhaya rock shelter near Sitabinji, Odisha, harkening back to the seventh century. This site presents a royal procession, suggesting its potential use as a royal hunting lodge (Nayak 2017). Concluding this journey through ancient Indian cave paintings takes us to the pinnacle of rock-cut architecture, the Ellora Caves in Maharashtra. Here, five caves reveal traces of remarkable artwork, most notably the Buddhist and Hindu temple, Kailas (Cave 16, constructed between 760 and 860 A.D., Figure 3), which houses paintings that have been painstakingly repainted at least three times (Somathilake 2016). The subsequent Jain temples, Cave 32 (Indra Sabha) and Cave 33, crafted between the ninth and eleventh centuries, carry remnants of exquisite murals, showcasing the artistic transition into the medieval period of Indian painting (Sohoni 2017).

More subdued yet significant vestiges of ancient Indian cave paintings from the third to the eighth centuries A.D. are discovered in a multitude of cave temples scattered across Maharashtra. These include sites like Karsamble, Thanale, Kuda, Lenyadri, Shivneri, Tulja, Lena, and Manmod, along with the renowned Elephanta Caves and Bhaja Caves. These temples offer intriguing glimpses into the artistic endeavors of their time (Ray 2022).

2.3 Medieval Paintings After the Seventh Century A.D.

In the early medieval times, the most beautiful Indian cave paintings were created in Southern India. Exceptional – but still comparatively little known – monuments of Indian art are paintings in Sittanavasal Cave (Tamil Nadu). Here, in the seventh to ninth century A.D. was the rock-cut Jain temple named Arivar-Koil, and most paintings here were made in the ninth century A.D. and still cover the ceiling and upper part of columns (Figure 4). The central element of these marvelous paintings in Sittanavasal is a pond with lotuses (Seastrand 2022); flowers in this pond are collected by

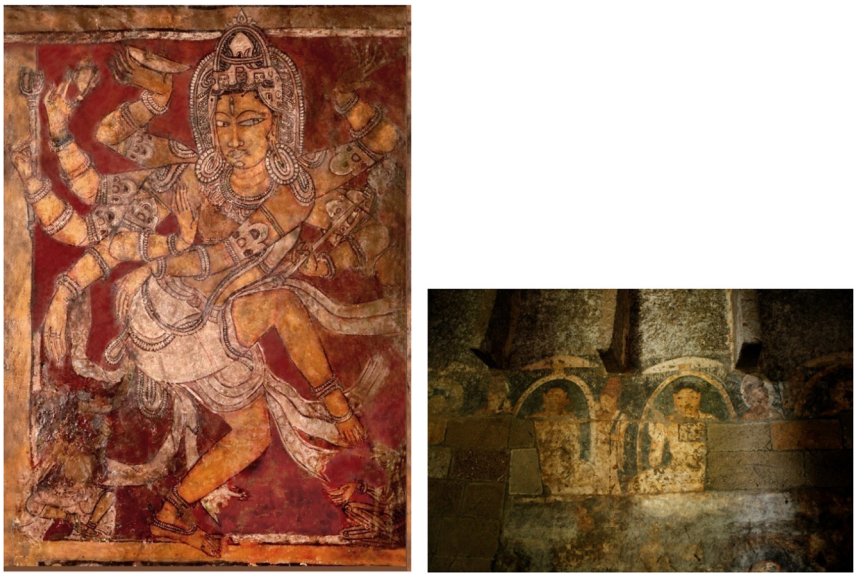

Figure 3: Cave painting at Ellora Caves, Aurangabad, India.

monks, with ducks, swans, fishes, and other animals also shown. This scene shows Samava-sarana – an important scene in Jain religion. Samava-sarvana is a special, beautiful audience hall where Tirthankaras (great liberated souls in Jain religion) delivered sermons after they reached realization (kevala-gnana). Bulls, elephants, apsaras, and gods gathered in this audience hall to witness this grand scene (Kumar and Das 2018).

Armamalai Cave (Tamil Nadu) is a natural cave that served as a Jain sanctuary around the eighth century A.D. Beautiful color paintings are still on the ceiling and walls, such as the standing lady with people, lotuses, and other floral motives (Painting 1978).

Thirunadhikkara Cave Temple (Tamil Nadu) is a rock-cut Jain temple from the seventh to eighth century A. D, which in the ninth to 10th centuries A.D. was converted into a Hindu shrine and decorated with beautiful paintings. Now only hazy outlines remain, but once upon a time these were colorful depictions of the stories from Ramayana and Mahabharata. The style of these paintings later evolved into the Kerala style of painting frequently used in constructed temples (Kumar 2016).

Olipathivishnu Vishnugraham is a Vishnu temple, one of the Malayadipatti rock-cut Hindu temples (Tamil Nadu). The oldest part of this temple is a rock-cut structure from the eighth to ninth century A.D. Much of this temple – sculptures and walls – are covered with stucco and paintings. Most likely these paintings are much younger – from the 16–17th centuries. Drawings show 10 incarnations of Vishnu–Dashavatara and other motives of religious nature (Saxena 2011).

Rock-cut cave temples and dwellings for monks were also made in the far north of India – Himalaya. There are

Figure 4: Cave paintings at Sittanavasal Caves, Tamil Nadu, India.

several cave temples with beautiful paintings in Tibet and Nepal, while at least one is located also in India. Saspol Caves (Jammu and Kashmir) are amazing rock-cut temples from the 13th to the 15th century A.D., with four of these caves lavishly adorned with paintings of the Buddhist pantheon. The dominant color here is bright blue, but the paintings themselves represent an exciting fusion of Tibetan and Indian Buddhist art (Pinto et al. 2018). Certain information about faint traces of paintings have also been found in Tabo caves (Himachal Pradesh), and there are further beautiful wall paintings in the nearby Tabo Monastery (Verma 2016).

3 Ancient Indian Painting Techniques

Preserving ancient and medieval Indian cave paintings relies significantly on the techniques used in their creation. Notably, the Ajanta Caves' paintings were executed with meticulous preparation. The process commenced by chiseling the basalt stone surface to create a rough texture, facilitating plaster adhesion (Sharma and Singh 2022). Then, skilled artisans meticulously applied plaster made from clay, lime, plant seeds, and basaltic aggregates. Sculptures were often plastered to achieve a smooth appearance and the application of powdered conches and seashells lent a distinct shine, resulting in a glossy surface. This technique allowed the paintings in Ajanta to retain much of their original brilliance even after over 1500 years of abandonment in the tropical climate (Somathilake 2007).

In Armamalai Cave (Tamil Nadu), two distinct techniques were employed. In the "Northern style", brick walls within the shrine were adorned using the tempera technique, akin to the approach taken in Bagh Caves. A thick layer of mud was first applied to the brick structure, followed by a lime covering bound with animal gum. The light lime surface proved conducive to vibrant paintings, although these have regrettably not endured (Paramasivan 1939). In contrast, the "Southern technique" was employed in Armamalai Cave, offering better-preserved paintings. This method was also used for the artwork in Sittanavasal Cave, where the uneven walls resulted in plaster layers of varying thickness. The pigments were mixed with lime and potentially some gum, particularly in the black pigment, with the color then applied to the dry plaster, forming an exceptionally durable bond (Burrafato et al. 2004). Jogimara Cave (Chhattisgarh) utilized white base plaster for painting, albeit some areas featured paint directly applied to an unprepared base (Nordmark 2011). Kuda Caves and Manmod Caves (both in Maharashtra) were plastered with a mixture of earth and rice-chaff. Ancient and medieval artists possessed a deep understanding of natural pigments, a knowledge that has regrettably faded with time; these mineral-derived colors, when mixed with lime, exhibited exceptional resistance to fading and endured the test of time (Thompson 1956). These artists skillfully mastered various colors, including black, green, yellow, orange, blue, and white pigments in Sittanavasal (Set 2004). While these practices may seem straightforward today, they required meticulous testing to understand their compatibility with plaster, interactions with each other, responses to water and adhesive substances, and alterations upon the plaster's complete drying.

4 Protecting Cave Painting

Cave art, serving as an illustrative language on cave surfaces, represents a historical archive spanning 50 millennia, from the dawn of visual art to the advent of modern writing (Anati 1993). Unfortunately, like many forms of cultural heritage, cave art is in a continual state of decay due to time, natural erosion, human interference, animal damage, looting, vandalism, and conflict-related harm (Blum 2020; Singh 2011). Conservation efforts vary worldwide, with India often using physical barriers to deter intruders and Africa increasing local enforcement to combat vandalism. This lack of uniformity in cultural heritage preservation approaches has led to diverse methods, including digital technology and site closure (Messenger and Smith 2010). Cave art preservation has generally involved five key strategies:

- Governments and international organizations enacting heritage protection laws.
- Restricting access to the public while permitting scholars and experts.
- Creating replicas of closed sites to promote and preserve cave art.
- Disseminating knowledge through books and peer-reviewed articles.
- Utilizing technology, such as websites and digital restoration, to safeguard and showcase cave art.

Cave art conservation has evolved through various means, including legislation and policy creation. Nations have enacted heritage management laws to protect their cave art sites, while international organizations, like the 1972 Convention Concerning the Protection of the World Cultural and Natural Heritage, have influenced global heritage preservation policies. Replicas of cave art have been produced as responses to site closures, offering the public access without endangering original sites (Clottes 2008). Elsewhere, scholarly work, such as books and peer-reviewed articles, has significantly contributed to cave art preservation (Coles

1969). Over the years, researchers have documented their findings in comprehensive volumes, aiding the expansion of cave art studies from various angles and fostering broader perspectives (Singh 2013).

Modern technology also plays a crucial role in conservation efforts. It allows for extensive recording of cave art and the presentation of sites through websites, virtual tours, and online databases (McKercher and Du Cros 2002). These digital tools enhance access and interaction with art, moving beyond static replicas. Recent advancements in technology have also provided new opportunities to conserve art in formats that have not previously been available (Porr and Bell 2012). Digital technology is not merely about access; it provides a means of restoring deteriorating sites. By using past visual records, researchers have digitally resurrected sites invisible to the naked eye (Darvill and Fernandes 2014), an approach which overcomes preservation challenges in the original setting (Bednarik and Seshadri 1995). However, in the quest for cave art preservation, various methods have faced challenges. Digital technology offers innovative ways to overcome these obstacles, ensuring that this invaluable heritage endures for future generations (Bednarik and Seshadri 1995).

In recent years, the preservation and protection of cultural heritage sites have become topics of significant debate. Challenges are arising regarding the ongoing threats to these sites and the most effective strategies for safeguarding them for future generations (Feilden 2007). The literature review primarily focuses on the current conservation methods employed to protect these sites. The field of conservation can be categorized into five distinct areas: heritage management and cultural policy, individual site management, the creation of replicas, the publication of books and articles, and the contemporary approach of digital technology and screen media for conservation (Porr and Bell 2012).

5 Materials and Methods for Digital Preservation

5.1 Photogrammetry

This is a powerful tool in documenting, monitoring, and preserving cave art, leveraging digital technology for comprehensive conservation efforts (Tucci et al. 2023). Photogrammetry involves capturing multiple high-resolution photographs of an object or a scene from various angles (Robert et al. 2016). Specialized software then processes these images to generate accurate 3D models of the cave art, capturing intricate details. The 3D models obtained through photogrammetry serve as digital replicas of the cave art, ensuring a high-fidelity representation of the original artwork (Büyüksalih et al. 2020). This digital preservation is crucial for safeguarding the art against physical deterioration, environmental factors, or human activities.

Once a 3D model is created, it can be used for remote monitoring of the cave art. This is particularly beneficial for caves that are difficult to access or are sensitive to human presence (Wang et al. 2019) as changes over time, such as degradation or damage, can be monitored without direct physical inspection. Photogrammetry is a non-invasive technique, as it doesn't require physical contact with the artwork, which is essential for preserving the delicate nature of cave paintings that can be easily damaged by direct touch. Digital 3D models enable in-depth analysis and research, letting scholars and conservationists study the art without being physically present, allowing for detailed examinations of pigments, brush strokes, and other artistic elements. Digital replicas obtained through photogrammetry can also be used for educational purposes. Virtual tours, interactive exhibits, and educational programs can be developed, allowing a broader audience to experience and learn about the cave art.

Photogrammetry can also be integrated into broader conservation strategies. For example, conservationists can use the 3D models to plan and execute targeted restoration efforts while minimizing impact on the original artwork. Digital 3D models also serve as part of a comprehensive archive for cave art (Lesvignes et al. 2019), with this documentation valuable for future generations and able to assist in restoration efforts if the need arises. By leveraging the capabilities of photogrammetry, cave art can be effectively documented, monitored, and preserved in a digital format, ensuring its cultural and historical significance endures for the future.

5.2 Terrestrial Laser Scanning (TLS)

Terrestrial laser scanning captures precise 3D coordinates of surfaces using laser beams. In cave art preservation, TLS can provide highly detailed and accurate 3D models of cave surfaces and paintings, and periodic TLS scans can be used to monitor changes in the cave environment and detect alterations or deterioration of the art over time (Bayarri et al. 2023). The detailed point cloud data generated by TLS serves as a valuable record for preservation efforts, aiding in restoration and conservation of planning.

5.3 Laser Scanning

Laser scanning, similar to TLS, uses laser beams to measure distances and create detailed 3D models. It is particularly

effective for capturing intricate details of cave art. Continuous laser scanning can be employed for real-time monitoring of cave conditions, helping conservationists respond promptly to any threats or changes. Laser scanning also contributes to the preservation of cave art by creating accurate digital replicas, enabling conservationists to study and plan interventions without direct contact with the art.

5.4 Structured Light Scanning

Structured light scanning involves projecting light patterns onto a surface and capturing the deformations to create a 3D model. This is useful for capturing surface details in cave paintings. Regular scans using structured light can provide detailed insights into the condition of the art, helping conservationists identify and address issues early (Carrero-Pazos, Vilas-Estévez, and Vázquez-Martínez 2018). The high-resolution 3D models produced by structured light scanning serve as valuable resources for preservation initiatives, allowing for digital archiving and restoration planning.

5.5 Advantages of 3D Scanning for Cave Art

All three scanning methods are non-invasive, ensuring that the delicate nature of cave art is preserved during documentation. These technologies offer high precision, capturing details at a level that is essential for studying pigments, brush strokes, and surface characteristics. The 3D models produced can serve as a comprehensive digital archive, ensuring that a detailed record of the cave art is preserved for future generations. The digital replicas enable researchers and conservationists to study and monitor cave art remotely, reducing the need for physical presence in sensitive environments. The 3D models can also be integrated into broader conservation strategies, facilitating targeted restoration efforts and aiding in decision-making (Salagean-Mohora et al. 2023). By leveraging these 3D scanning technologies, cave art can be thoroughly documented, continuously monitored, and effectively preserved, ensuring its cultural and historical significance endures.

5.6 High-Resolution Photography for Cave Art Documentation and Preservation

High-resolution photography excels at capturing intricate details of cave art, including pigments, brush strokes, and surface textures. It provides accurate color representation, crucial for preserving the aesthetic qualities of the art. Monitoring high-resolution images serve as baseline records, enabling experts to monitor changes over time. Regular photography sessions can be conducted remotely to track alterations or degradation without physical presence.

High-resolution photographs create a comprehensive digital archive of cave art, serving as a valuable resource for future research. Detailed images aid in planning and executing restoration efforts, allowing conservators to work with precision. Photography is a non-invasive method, ensuring that the delicate nature of cave art is preserved during documentation. Compared to some advanced technologies, high-resolution photography is a cost-effective solution for capturing detailed images of cave art; it is versatile and can be employed in various lighting conditions, adapting to the unique challenges of cave environments. Digital images facilitate cultural accessibility, allowing a broader audience to engage with and appreciate cave art without direct physical exposure.

For digital photography it is essential to use professional-grade cameras and lenses capable of capturing high-resolution images with minimal distortion. It is recommended to photograph the cave art from multiple angles to create a comprehensive visual record. The time-lapse photography should be implemented to track changes over extended periods and identify trends in degradation; this also includes metadata such as date, time, and conditions during photography to enhance the contextual information associated with the images.

5.7 Monitoring Cave Art with Humidity, Temperature, and CO_2 Sensors

5.7.1 Humidity Sensors

Humidity is a critical factor influencing the preservation of cave art. Humidity sensors help monitor moisture levels in the cave environment, to prevent excessive humidity which can lead to mould growth and degradation of pigments due to adsorption/desorption of moisture from the plaster support. Moisture can also dissolve the organic binder used in Indian artworks causing loss of decorative surfaces. Seasonal variations of humidity need regular monitoring for preventive measure; regular monitoring of humidity allows conservators to take preventive measures. Strategically placed sensors near vulnerable art sections or in areas prone to moisture accumulation is an essential component of digital preservation.

5.7.2 Temperature Sensors

Temperature variations can impact the stability of cave environments. Temperature sensors provide insights into

the thermal conditions; fluctuations in temperature can cause expansion and contraction of surfaces, affecting the structural integrity of the cave art. The thermal degradation due to increased footfalls in poorly ventilated caves are an important parameter of loss of artworks. It is essential to position sensors in areas susceptible to temperature changes, such as entrances or sections exposed to external elements.

5.7.3 CO_2 Sensors

CO_2 levels can indicate the presence of organic materials or the influence of external factors like visitors. In the cave murals of Ajanta, the high CO_2 concentration due to enhanced tourist flow is causing loosening and falling of white calcium carbonate due to formation of calcium bicarbonate in high humidity. The elevated CO_2 levels may indicate increased human traffic, potentially leading to physical damage or introduction of contaminants. It is essential to strategically install CO_2 sensors as a tool for digital preservation, considering areas with frequent visitor interaction or potential sources of external contamination.

5.7.4 Integration and Data Analysis

Integrating data from humidity, temperature, and CO_2 sensors provides a holistic view of the cave environment. It is imperative to set predefined thresholds for each sensor that can trigger alarms if conditions exceed acceptable ranges, prompting immediate attention. Regular monitoring establishes historical data, enabling trend analysis for conservationists to identify patterns and correlations over time. Implementing sensors with remote monitoring capabilities allows conservationists to receive real-time data, facilitating prompt responses to anomalies.

5.7.5 Benefits of Monitoring Environmental Parameters

Early detection through sensor data allows for proactive conservation measures, minimizing potential damage to cave art (Lacanette et al. 2023). This digital monitoring ensures the long-term preservation of cultural heritage by mitigating environmental risks. Data collected from sensors contributes to scientific research, enhancing the understanding of cave ecosystems and aiding conservation practices. By leveraging humidity, temperature, and CO_2 sensors, cave art conservationists can implement a comprehensive digital monitoring system that contributes to the sustainable preservation of these invaluable cultural artefacts.

6 Discussion

6.1 Digital Technology

Digital technology and virtual reality in the context of cultural heritage have received limited attention in early publications. Earlier works primarily revolved around concepts like “virtuality”, examining the relationship between the real and virtual worlds, interactivity, and the emerging Internet landscape (Robertson 2001). Notably, specific aspects related to cultural heritage, such as digital objects, interactions with virtual audiences, and the potential cultural transformations induced by communication technologies like the Internet, remain relatively underexplored (Anstey and Pape 2009). Delving deeper into this domain involves considering diverse subjects, including artificial intelligence, visual art history, cultural communication, social research, information technology, cultural studies, museum studies, conservation, and cognitive processes (Pujol-Tost 2011).

While recent research has started to describe individual projects and their practical implications, it has yet to fully stimulate critical discourse on the meanings, implications, and challenges posed by digital communication in the realm of cultural heritage (Brown 2007). Although the cultural heritage sector acknowledges the significance of digital technologies, many issues warrant further investigation. Several sites have undertaken experimentation with digital imagery and the restoration of cave art, demonstrating the potential for digital technology in this domain (Poll 2010). As the broader application of digital technology within cave art is ongoing, the possibilities for virtual reconstructions are immense. To advance our understanding of how virtual reality can be applied in cultural heritage and cave art contexts, research should further contextualize it within the realms of sensitivity, cognition, and realism. This approach can provide insights into potential future applications within the field (Chen 2020).

6.2 Current Threats to Cave Art

Cave art sites face ongoing threats, with common challenges including deforestation, pollution, urban expansion, vandalism, and human interference (Van Beynen and Townsend 2005). The extent to which these threats affect individual sites depends on their specific location, the type of cave paintings they house, and their positioning. Running in parallel with these enduring challenges, the issue of site management plays a pivotal role in the preservation of these sites (Deacon 2006).

Site management is particularly complex in the context of the recent surge in cultural tourism. The effective management of these sites hinges on several critical aspects,

including site preservation, controlling access and information, educating and shaping the perspective of visitors, utilizing site museums, exploring the role of replicas and technology, and developing a comprehensive, long-term conservation strategy (Alberts and Hazen 2010).

Researching Cave art begins with site recording, a process that has gained particular significance in the context of digital technology. While numerous countries have recorded various sites, the challenge lies in the vast number of unrecorded and vulnerable sites. The primary concern regarding recording is the lack of a universal approach; given the inherent diversity in recording sites due to their locations, the need for a standardized approach becomes essential. This standardization enables researchers to foster mutual understanding, compare results, and identify common elements that can be prioritized for further study in the digital age (Marhavilas et al. 2011).

In the era of digital technology, the constant deterioration of Cave art often results in the loss of sites before they can be recorded. However, detailed recording of significant Cave art sites, especially when done digitally, offers a wealth of information that empowers researchers to gain deeper insights into the origins and techniques employed in the creation of these sites (Elliott 2004). In addition, efforts to conserve and mitigate the effects of degradation often necessitate significant human intervention. Within caves, we can observe profound human interventions, such as the removal of Cave art and the application of extreme conservation treatments to renowned sites (MacLeod 2000). Exploring conservation approaches through significant human intervention involves examining case studies from numerous sites in India; these caves serve as effective demonstrations of the substantial human interventions employed to conserve them and counteract rapid degradation. At the same time, exploring the conservation of Cave art through their removal reveals alternative approaches within the field of conservation.

6.3 Cave Art Removal: The Context of the Environment

While scientific intervention has been used to conserve some Caves, others have favored different methods to address art deterioration. As such, the removal of Cave art from its original setting has been practiced since the early nineteenth century. This practice has been motivated by three separate reasons throughout history: collecting for curiosity, collecting for conservation, and collecting to "rescue" damaged Cave art (Lewis-Williams 1983).

Collecting for curiosity occurred from the eighteenth century and was performed by many researchers who had a passion for collecting archaeological objects. At the time of this destructive and seemingly common custom, primitive Cave art was fashionable among society's elite and many collectors paid high prices for people to remove it. Elsewhere, even when collecting Cave art in an attempt to understand and preserve it, the process of removing art panels from a site was commonly a violent and destructive practice (Arthur et al. 2021). Despite the violent removal process, museums and collectors were motivated by the belief that they were saving rapidly deteriorating panels from destruction caused by weathering in the natural environment (Cameron 2007). The impact from using dynamite resulted in the site often being destroyed all together or a portion of Cave panels at the site destroyed in favor of "saving" others (Henry 2007).

From the late twentieth century, the previous common practice by museums to remove cave art shifted from a preferred choice to one undertaken as a last resort. This view dramatically changed due to the understanding that removing Cave art from its original setting also removed its context and the ability to interpret the images (Hollmann and Msimanga 2008). An effect of this realization is that Cave art removal is now rarely practiced and the conservation has shifted to alternative methods. However, despite Cave art removal being rarely undertaken at present, the remnants of the practice can be witnessed in cultural heritage collections all over the world, allowing Cave art to be viewed yet devoid of context, limiting the ability of the audience to interpret the image (Henry 2007).

6.4 Replica

Replicas in museums and art galleries have occupied a significant place alongside expertly crafted artifacts and art objects (Foster and Curtis 2016). In recent years, replicas have emerged as a solution for making Cave art sites accessible to viewing audiences, recognizing the rising popularity of cultural tourism and the understanding that people will still be drawn to replicas of significant cultural heritage sites (Yang et al. 2008). The increase in cultural tourism, coupled with technological advancements, has underscored the necessity for creating replicas, with case studies demonstrating their successful implementation. Replicas enhance the Cave art site visit experience, incorporating educational tools such as site museums and interactive digital media (Stogner 2016). These replicas have several advantages, such as providing economic benefits to local communities by opening closed sites, with the cost of creating the replica recouped within the initial few years. Digital technology facilitates an exact, highly detailed reproduction of artworks and allows viewers to examine them more closely than they would in the original form

(Brady et al. 2018). A 3D high-resolution scanner plays a crucial role in generating full-scale digital reproductions of the caves, while experienced artists recreate the paintings using natural pigments and charcoal coated in resin (Kenderdine, Chan, and Shaw 2014).

Replicas aim to faithfully recreate the original cave, immersing audiences in a sensory experience that encompasses temperature, smell, humidity, darkness, and silence as essential components of its authentic reconstruction (Susie 2012). The technology for producing such replicas and copies of original paintings is continually advancing. Replicas have been developed for many significant Cave art sites to meet visitor demands while protecting art from additional damage (Hughes et al. 2021). Technological advancements now enable the creation of replicas that provide an immersive experience for viewers, shedding light on the challenges facing Cave art and its long-term survival. However, while the implementation of replicas has been successful in safeguarding significant sites, the abundance of Cave art in natural environments exposes less renowned sites to continuous deterioration and threats to their preservation (Gireesh Kumar 2021).

6.5 Digital Technology as a Method to Conserve Cave Art

The number of known Cave art sites does not account for undiscovered sites and painted figures. Considering the extensive worldwide presence of Cave art, it is evident that not every figure or site can be saved from human or environmental destruction. Preserving this art for the future necessitates a balanced approach that combines conservation, reproduction, restoration, management, and research (MacLeod 2000).

In preserving Cave art through enhanced conservation and management, the development and implementation of policies are pivotal. Current efforts to conserve cultural heritage for future generations involve resource allocation and funding. Although international organizations and national governments allocate funding for preserving significant cultural heritage sites, these funds often represent a small fraction of their overall budgets. The international policy landscape plays a crucial role in shaping the development and direction of cultural heritage management and preservation (Edgell et al. 2008).

UNESCO has significantly influenced the direction of cultural heritage preservation in international policy. The 1972 World Heritage Convention linked nature conservation with cultural property preservation and has guided policy discussions on cultural heritage worldwide. UNESCO established the World Heritage Centre in 1992 to coordinate the World Heritage Convention (Gfeller 2013). The Centre, through its role in organizing World Heritage Committee sessions and maintaining the World Heritage List, actively participates in determining policy issues related to heritage preservation. The World Heritage List and UNESCO draw attention from national governments and impact the creation of heritage legislation at the national level. Given the substantial financial resources available to these organizations, analyzing the allocation of funds for cultural heritage conservation serves as an indisputable method for gauging organizational priorities (Messenger and Smith 2010).

Due to insufficient funding from major international organizations and the resulting impact on national governments, preserving Cave art for the future necessitates exploring alternative avenues. The lack of economic resources severely constrains the fieldwork that can be undertaken to actively preserve these sites. While each individual site's level of deterioration and potential conservation treatments is assessed on a case-by-case basis, it is reasonable to assume that each site will require funding and resources not currently available (Wright 2018).

The challenges in preserving and documenting Cave art are compounded by the proliferation and diverse locations of these sites (Sanz, Fiore, and May 2016). In the absence of sufficient funding and resources, researchers are compelled to seek alternative methods for documenting and protecting Cave art before it succumbs to the effects of deterioration (Anderson et al. 2018). In the past, researchers have documented Cave art through pictorial means, typically in the form of books and peer-reviewed articles. However, with technological advancements, digital preservation allows scholars and scientists to expand their research and build upon the prior pictorial record, which was primarily presented in two-dimensional formats (Kuzminsky and Gardiner 2012).

6.6 Individual Site Approaches to Digital Technology

In recent times, cultural heritage professionals have increasingly recognized the potential of utilizing digital technology. Within the field of Cave art, digital technology is emerging as an efficient, cost-effective, and dependable method for preserving a multitude of sites for future investigations (Mudge et al. 2008).

The wider application of digital technology faces certain limitations, with concerns raised that digital images, virtual tours, websites, or virtual reality constructions may fail to capture the aura of an original, resulting in a loss of meaning within the Cave art. However, by examining past debates surrounding copies or replicas of original artworks, it

becomes clear that this concern is unfounded. Digital technology and the creation of digital images allow researchers to faithfully represent the original site and artwork, preserving the essence of the original (Stanco, Battiato, and Giovanni Gallo 2017).

The evolution of digital technology has enabled the creation of digital images. Recently, the generation and utilization of digital images to represent original artworks have sparked extensive debates (Pearson 1978). These discussions revolve around the digital image's capacity to faithfully and accurately convey the essence of an original artwork. Despite ongoing debates and recent investigations, the fundamental question at the heart of this discussion remains: can virtual reality and digital images capture the intrinsic qualities or "aura" of an original object that imbues an artwork with its meaning and significance (Kuzminsky and Gardiner 2012)?

An essential question when considering this topic is whether the intrinsic qualities that confer meaning to an object can be effectively transferred to its digital counterpart (Mayer 2020). Ongoing discussions regarding the status of digital copies often label them as inferior replicas of their non-digital counterparts, based on the belief that non-digital copies alter the values and meanings attributed to the original (Jeffrey 2018). Consequently, digital historical objects, such as Cave art, can be regarded as distinct from the originals, fostering different relationships between viewers and the artifacts. The creation of a digital image requires scholars and researchers to carefully curate an object's representation, determining what to include and what to extend within the digital record. This process entails a critical evaluation of the aura of the original object and facilitates viewers' understanding of the object's significance, cultural symbolism, and value. However, the extent to which the aura of an original artwork or object is transferred through digital image replication can vary depending on the specific context. As digital imagery and virtual reality continue to advance, digital technologies will become increasingly prevalent and be viewed as cultural treasures imbued with their own meaning and significance. This perspective extends from the idea that objects, replicas, 2D and 3D representations of original artifacts in cultural institutions possess their own value and exert a distinct impact on viewers' interpretation (Clogg, Díaz-Andreu, and Larkman 2000).

The digitization of cultural heritage should be regarded as a valuable educational resource for viewers rather than merely a conservation method. The debate surrounding the creation of digital images and their capacity to faithfully convey the "aura" of an original object has been extensive (Turner et al. 2018). When crafting a digital image of an original object, the intrinsic qualities of the original can be preserved through the careful assessment of its "aura" by scholars and researchers, resulting in a faithful representation. While the digital image functions as a representation of the original, it generates a lifelike impression that can be valued and imbued with its own meanings, enabling viewers to learn about Cave art and its cultural significance. The ongoing debates and discussions about the digital image notwithstanding, its ability to expand the pictorial record provides an unprecedented opportunity within an authentic and realistic framework. As the creation of digital images advances, the applications of virtual reality in the cultural heritage sector are emerging as a means to replicate objects for remote study, curatorial research, and conservation (Yung and Khoo-Lattimore 2019).

6.7 Combating Cultural Tourism and Visitor Related Damage

Mogao Grotto in China has successfully integrated virtual reality with other digital technologies, offering tourists and researchers the opportunity for immersive visits to the caves. To construct this virtual reality experience, researchers developed 3D models based on the existing pictorial record, consulted site plans, analyzed interior photographs, delved into historical information, and even made on-site visits to gain a personal impression. By drawing from this diverse range of sources, those involved in creating the virtual reality experience aimed to provide virtual visitors with an authentic and realistic impression of the original site while safeguarding it from potential damage (Lutz and Weintke 1999).

The creation of the Virtual Dunhuang Art Caves followed a systematic series of phases. It commenced with the research team developing 3D geometric models of the original cave site (Agnew, Reed, and Ball 2016). Once the basic model with accurate dimensions was established, the researchers proceeded to integrate three-dimensional representations of objects. This addition aimed to achieve realistic illumination, generate shadows for a sense of depth, and incorporate finer details such as wall textures and statues, like the Buddha, found within the original site. The final step in this process, which served as the foundational stage for subsequent design work, involved converting the models into a data format compatible with specialized software designed for crafting a virtual reality experience (Lu et al. 2012). After completing this rendering process and crafting the Virtual Dunhuang Art Caves, the researchers then focused on ensuring that the Caves could be displayed across a variety of output devices.

The Virtual Dunhuang Art Caves offer versatile display options, adaptable to different environments. These images can be presented on large-screen studio projections within exhibition or museum spaces, as well as on monitors or advanced five-sided CAVE displays. This flexibility ensures

that the Virtual Dunhuang Art Caves can reach a diverse audience in various settings. Furthermore, the researchers incorporated interactive elements into the experience; viewers can utilize a virtual flashlight to explore the virtual reality cave images and access a virtual tour guide, mirroring the way original site visitors would navigate the caves (Lutz and Weintke 1999).

The experience of visiting the original Mogao Grottoes involves navigating through total darkness, akin to an archaeologist exploring dark caves with only a flashlight, in search of hidden treasures (Lutz et al. 2004). This concept was translated into the Virtual Dunhuang Art Cave through the creation of a virtual flashlight, providing visitors with the sensation of exploring the caves much like an original site visitor. In addition to the flashlight, the researchers developed a virtual tour guide to convey the site's significance and the meanings of the artworks. To enable the audience to focus on the intricate imagery within the virtual scenes, the tour guide was seamlessly integrated into the imagery and communicates through speech rather than relying on text-based panels (Purnomo et al. 2018). This approach allows viewers to observe a scene while listening to information delivered by the virtual voice, akin to how visitors engage with tour guides at the original site. By incorporating a virtual flashlight and tour guide, the researchers offered an experience in the Virtual Dunhuang Art Caves that mirrors what a visitor might encounter at the actual site while safeguarding the site from potential damage (Han et al. 2019).

7 Conclusions

The ability to explore rock art treasures in a virtual realm provides an accessible, dynamic, and educational experience for scholars and the general public alike. The ability to replicate these intricate and delicate environments, such as the Mogao Grottoes and the Dunhuang Art Caves, allows for an authentic and immersive experience for viewers, all while safeguarding the original sites from potential harm. Digital technology's capacity to capture the essence, or "aura," of these artifacts and transmit it to viewers is a topic of ongoing debate, but it undoubtedly serves as a valuable educational resource for understanding and appreciating the cultural significance of Cave art. As funding constraints and the challenges of documenting, conserving, and protecting these sites continue, the digital representation of Cave art is a beacon of hope. It offers a means to engage a global audience in appreciating the beauty and historical value of these sites without physically compromising them.

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