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SYSTEMATIC CONSTRUCTION OF THE ROCK ART HERITAGE ARCHIVE DATABASE FROM THE PERSPECTIVE OF DIGITAL HUMANITIES

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Abstract. As a core heritage carrying the memory of early human civilisation, rock art faces multiple challenges, including scattered sites, vulnerability to damage and limitations in interpretation. Against the backdrop of the vigorous development of digital humanities technology, constructing a systematic rock art heritage archive database has become a key path to address these dilemmas. By sorting out international practices in rock art digitalisation and mature cases of cultural heritage digitalisation in China, combined with the distribution characteristics and research status of China's rock art resources, this study proposes a four-stage systematic framework: *data collection, database construction, function expansion and public application*. Based on the *IFRAO Rock Art Glossary*, the framework integrates rock art ontology information, associated background and multimedia resources, builds a four-tier platform covering resource *foundation construction, management, opening and application*, and is supported by multiple functions such as multilingual consultation, virtual exhibition halls, immersive experiences, and cultural and creative co-creation. The research clarifies that database construction must address core challenges, including data integration heterogeneity, lack of unified standards, and insufficient cross-entity collaboration. Through technical adaptation, professional collaboration, and full-life-cycle quality control, it realises the permanent preservation, academic research innovation and global dissemination of rock art heritage, injecting lasting vitality into the digital transformation of cultural heritage and the development of the creative industry.

Introduction

Digital humanities is an interdisciplinary field that integrates traditional humanities disciplines such as history, literature, archaeology and art history with digital technologies, including big data analytics, artificial intelligence, virtual reality and database construction. Rather than merely digitising the content of humanities research, it takes digital tools and methods as its core to reshape the thinking, processes and outcomes of humanities research. It retains the profound concern of the humanities for *people, culture and history*, while using digital technologies to overcome the limitations of traditional research, such as low efficiency in data acquisition, single-dimensional analysis and narrow dissemination of results. In recent years, the digital wave has impacted every industry. Rock art represents an important cultural heritage of humanity and constitutes the most numerous, content-rich, and truly global art form in the field of pre-Historic art. Since the beginning of the new century, with the deepening of cultural heritage research by scholars worldwide, academic attention to rock art has extended far beyond pure

research fields such as aesthetics, archaeology or ethnology. Rock art has become an important resource for local cultural industries from the perspectives of knowledge sharing, cultural exploration, cultural tourism, and even the development of cultural and creative industries.

To address the crisis of rock art conservation and promote its dissemination, the application of linked data, knowledge graphs, artificial intelligence and other technologies to the construction of online databases represents an emerging model for rock art digital resource services. It can facilitate the transformation of traditional rock art resources from a model centred on research and conservation by experts and scholars to a public-centred model of personalised knowledge services, so as to meet diverse needs. At present, as a methodology for interdisciplinary research, digital humanities can not only enable rock art heritage to achieve entirely new forms of presentation and expression through the media provided by digital technologies, but also contribute to new advances of digital technologies in the field of human pre-Historic art. In view of this, the comprehensive and systematic

recording, organisation, preservation, exhibition, dissemination and interaction of rock art heritage archives from the perspective of digital humanities has become an urgent task. This urgency lies in the fact that, without public understanding, support, and participation, existing rock art resources in academic and cultural resource management sectors will remain underutilised and fail to demonstrate their precious value in the conservation of numerous cultural heritage sites. In addition, it should be emphasised that digital research on rock art should pay greater attention to cooperation with Indigenous communities. Through the collection and sharing of database information, the dissemination of rock art-related research results among Indigenous peoples, granting Indigenous people the right to expression, respecting their worldviews, and involving them in rock art research and dissemination, the public can gain a clearer understanding of the historical context and core values of these cultural heritages.

Experience in the digitalisation of cultural heritage

In the early 1990s, with the global rise of the Internet, developed countries in Europe and the United States took the lead in exploring the digitalisation of cultural heritage conservation. In 1992, UNESCO launched the *Memory of the World* program, which collects digital information on important cultural heritage around the world in the form of documents, music, images, and establishes websites and databases for online retrieval. The Library of Congress launched the *American Memory project*, which digitised numerous precious collections and documents (Ma 2019).

The digitalisation of cultural heritage in China also began in this period. The Dunhuang Academy carried out early experiments on mural digitisation in cooperation with several universities. By the late 1990s, it had initially developed a mural digitisation method based on orbital parallel photography and a VR virtual roaming full-cave acquisition method (Fan 2023). Today, through *digital photography acquisition*, *3D cave reconstruction*, *cave panoramic roaming*, and other technologies, the Dunhuang Academy has built the *Digital Dunhuang* resource platform. It has realised the global sharing of high-definition digital images and panoramic roaming for 30 classic caves, enabling users worldwide to remotely appreciate the exquisite Dunhuang murals and grotto art (Yu et al. 2020). The Palace Museum has carried out digital construction since 1999 by establishing a *Digital Cultural Relics* repository and conducting digital mapping (Zou 2022). The Emperor Qinshihuang's Mausoleum Site Museum has applied panoramic photography, virtual reality and other technologies to provide digital information for public visits and academic research and used computer restoration technology to solve difficult problems in cultural relics conservation (Feng 2018).

The *World Heritage List* database maintained by

UNESCO is one of the most authoritative international databases on cultural heritage. Established in accordance with the *Convention Concerning the Protection of the World Cultural and Natural Heritage*, the database contains cultural and natural heritage sites of outstanding universal value around the globe. It lists 1248 heritage sites across 170 State Parties and 51 transboundary heritage sites across 75 State Parties, making it the most comprehensive cultural heritage database (UNESCO 2026). The database includes detailed information on each heritage site, such as its name, location, historical background, cultural value and conservation status. It is updated regularly and provides an important reference for the conservation and research of cultural heritage worldwide. Thus, digitalisation has become one of the fundamental means of cultural heritage conservation. The more distinctive the local knowledge graphs are, the greater the need to adopt a mechanism for cross-cultural narrative coordination. Standards and norms guarantee data consistency. Following consistent data specifications to ensure the standardisation and comparability of rock art information within the database is the foundation for the integration of multi-source data across regions and institutions. Rock art data collection, including the definition of data field formats, naming conventions and terminological standards, shall conform to common international rock art norms.

With the global spread of COVID-19 in 2020, countries implemented corresponding prevention and control measures advocating reduced travel and gatherings. This directly changed people's museum visiting patterns, triggering a major *Revolution in Exhibition Modes* across the museum sector, accelerating the digital development of museums and stimulating the application of a range of new technologies. For history, culture and art museums, one of the most effective ways to achieve digitalisation is to offer virtual tours. As a world-leading search engine, *Google Arts & Culture* has cooperated with more than 2000 cultural institutions worldwide, building a platform that provides free virtual access to over 7 million archived cultural relics. It aims to digitise global cultural heritage and present it to the public through advanced technologies (Google 2026).

Numerous other cultural organisations have used social media and live streaming to attract, engage and educate their audiences. The *Smithsonian Institution*, which manages major museum clusters in the United States, has released 2.8 million high-resolution 2D and 3D collection images on the *Smithsonian Open Access* (SOA) online platform for free public use. These images originate from 19 Smithsonian museums, 9 research centres, libraries, archives and other units, covering a wide variety of content. The public can view, download, edit, transform, re-create and share them online (SOA 2026). These well-funded museums are particularly active in exploring digital technologies —

such as *virtual reality* (VR) and *augmented reality* (AR) experiences—and thematic exhibitions, providing the public with interactive 3D objects. These resources can be accessed in homes via desktops, VR and AR devices, offering an additional channel for remote engagement.

The digital development of modern museums requires a strong, comprehensive institutional capacity. The ideal outcome of museum digitalisation is a cycle in which visitors browse the digital museum, then visit the physical museum, and return to the digital museum to supplement their knowledge of cultural relics. This constitutes an optimised visiting experience. By presenting cultural relics in digital form, digital museums enable visitors to tour physical museums with targeted questions in mind. This forms a virtuous cycle and represents the true significance of digital museums. In Europe and the United States, such a virtuous cycle has already taken shape. Browsing cultural relics and related information online is highly convenient. Although most relics are not displayed from multiple perspectives online, and some images are unavailable due to copyright restrictions, museums have opened channels for further information access. Typically, users can submit requests via email or dedicated applications, with professional staff providing specialised services (Wang et al. 2013).

Chinese archaeologists and academics have been actively organising archaeological findings and research results since the early 20th century, striving to promote the investigation, documentation and conservation of cultural heritage. From the beginning of the 21st century, research institutions and social groups have aligned with the digital trend of the cultural industry strategy and actively advanced digital pilot initiatives. Through scientific and rigorous investigation, measurement, recording, and depiction, many have established digital virtual display platforms based on the collections and exhibitions of physical museums.

At present, the Palace Museum has opened its *digital cultural relics repository* to the public, with its official website integrating comprehensive functions of exhibition, education, academic research and cultural creativity. As important products of the Palace Museum's cultural and creative industry, its mobile apps, such as *Daily Palace Museum*, *Palace Museum Exhibitions* and *Forbidden City 365*, serve as key platforms for knowledge sharing. The museum has also launched thematic content on *the Imperial Ceramics*, *the Daily Life of Emperors* and *Costumes of Qing Emperors*, making them essential tools for *cloud touring* the Palace Museum. In addition, the National Museum of China and almost all provincial-level museums have completed the construction of digital museum websites, providing digital channels for public viewing, academic research, educational study tours and knowledge sharing. The popularity of museum-themed programs such as *National Treasure* and

Shangxin! The Palace Museum has attracted growing numbers of visitors for in-depth and thematic museum tourism. These practical experiences have laid a solid foundation for the application of rock art heritage in the field of digital humanities.

Research and digital development status of rock art heritage archives

As a widespread cultural heritage around the world, rock art represents a precious legacy left by our ancestors. Through various analyses and studies of rock art, interpreting the clues that embody human wisdom and spiritual needs helps us decode the material and spiritual worlds of humanity's early childhood. Since the 21st century, governments worldwide have emphasised the conservation of cultural heritage and the development of cultural industries, making rock art heritage distributed across the globe a unique historical and cultural resource that has gradually received greater attention.

As early as after World War II, the international community successively established numerous institutions for rock art research and conservation. Under the *International Council on Monuments and Sites* (ICOMOS), UNESCO hosts the *International Committee of Rock Art* (CAR), which promotes international cooperation in rock art and raises conservation awareness, and develops new and traditional methods for recording and protecting rock art (ICOMOS 2026). The *International Federation of Rock Art Organisations* (IFRAO), headquartered in Australia, was founded in September 1988. After more than 30 years of growth, it now has 60 member organisations covering most regions of the world, making it one of the most influential international rock art bodies (IFRAO 2026). In addition, Africa, Europe, Australia, Central Asia and the Americas host considerable numbers of rock art research and conservation institutions, which have greatly promoted local rock art studies, heritage protection and cultural industry development.

In terms of digital technologies for rock art heritage archives, South Africa and northern Europe provided early and excellent models. The *African Rock Art Digital Archive* (ARADA) offers comprehensive digital educational functions and brings together rock art collections from more than 30 research institutions and individuals, including extensive rock art data such as historical documents, photographs, rubbings, copies, and slides (ARADA 2026). The *Swedish Rock Art Research Archives* (SHFA) is a research infrastructure at the University of Gothenburg established in 2017. Its rock art data supports online zooming and 3D visualisation, and visitors can freely download high-precision images for appreciation and research, laying a solid foundation for Scandinavian rock art to become a major research hub in Europe (SHFA 2026). The *Bradshaw Foundation*, based in Geneva, Switzerland, with the mission *Exploring our past – Informing our future*, has built the world's

largest pre-Historic rock art database, dedicated to collecting the most comprehensive international rock art materials, and has made remarkable contributions to the conservation, research, exchange, and sharing of international rock art (Bradshaw 2026). Professor Emmanuel Anati of Italy was one of the earliest scholars to develop standards for rock art documentation and has actively promoted the *World Rock Art Archive* worldwide. According to the website of the *Centro Camuno di Studi Preistorici (CCSP)* at Capo di Ponte in Valcamonica, Italy, the collection houses over 115,000 visual materials, including films, slides, and digital photographs. Supported by projects under *Italy's National Recovery and Resilience Plan (PNRR)*, the centre is advancing the digitisation and informatisation of its collections. So far, more than 14,700 traced documents, including nylon tracings, historical rubbings, field sketches and thin-paper copies, have been basically digitised (CCSP 2026). Although the centre's research is widely recognised globally, it has not yet provided public access to a database platform, and the progress of its digitisation and database input remains unclear.

Since the 1960s, China has discovered a large number of rock art sites distributed across 29 provinces. The main work of archaeological departments has included the survey and documentation of newly discovered rock art sites, as well as the implementation of conservation measures. At the local government level, the Huashan Rock Art in Guangxi, in southwest China, was successfully inscribed on the *World Heritage List* in 2016. The Helan Mountain Rock Art in Ningxia and the Yinshan Rock Art in Inner Mongolia, both in northern China, are actively seeking World Heritage inscription. Success would represent a major boost to China's cultural sector. However, in sharp contrast to China's enormous rock art resources, so far only a very small number of heritage institutions, such as those in Guangxi Huashan and Ningxia Helan Mountain, have established regional rock art databases. No authoritative national institution in China has yet effectively collected, organised, promoted and disseminated nationwide rock art resources through digital educational systems. In 2019, Zhu Lifeng proposed an initial framework for the construction of a *Chinese rock art database*, exploring directions for sustainable public education and cultural and creative industry development for Chinese rock art (Zhu 2019). In July 2023, the *China Rock Art Academy (CARA)* proposed in Chongzuo, Guangxi, to cooperate with the *China Cultural Heritage Exchange Centre* to build a high-quality national-level rock art museum, and to jointly promote the development of the *China Rock Art Database* with *China Digital Culture Group Co., Ltd.* Through basic data mapping, data management system development, 3D display system development and other approaches, the project aims to construct a knowledge graph of Chinese rock art image archives, build a Chinese rock art database and digital cultural asset library, advance intelligent management and

dynamic efficient inspection of rock art conservation, and improve the standardisation of scientific archiving of rock art materials. If successfully implemented, this plan will exert a positive influence on the systematic conservation, development and utilisation of rock art in China.

Overall, digital projects for cultural heritage and rock art heritage are important practices of digital humanities, empowering heritage conservation and communication. The overall pattern shows that international projects started early, feature high standardisation, and have strong resource integration capabilities, while Chinese projects have distinctive characteristics but remain relatively underdeveloped in the rock art sector. International general digital heritage projects, such as *UNESCO's Memory of the World Programme* and *Google Arts & Culture*, as well as specialised rock art digital projects including the *Swedish Rock Art Research Archive* and the *Bradshaw Foundation Archive*, owe their success to clear standards and norms, support from professional institutions, and technologies tailored to conservation and research needs. They balance public accessibility and academic value, achieving effective documentation and wide dissemination of resources, yet also share common limitations such as superficial technical application and insufficient universal applicability. In China, general cultural heritage digitisation projects such as *Digital Dunhuang* and the *Palace Museum's Digital Cultural Relics Repository* have achieved remarkable results through localised innovation industry-university-research collaboration, forming distinctive models integrating conservation, communication, and industrial value. By contrast, although China has carried out regional digital attempts at Huashan and Helan Mountain, rock art digitisation nationwide remains at an early stage due to the lack of a leading authoritative body, unified standards, sufficient funding, technology and professional support.

The experience of both international and domestic projects demonstrates that the key to digital construction lies in balancing standards and professional adaptation, resource integration and multi-dimensional value, conservation priority and communication empowerment. To achieve systematic development, China's rock art digitisation must learn from international experience and domestic best practices in general heritage digitisation, and address weaknesses in national resource integration, unified standards and interdisciplinary professional collaboration.

Roles and functions of the rock art heritage archive database

The role of the rock art heritage archive database

A universal pattern observed worldwide regarding rock art heritage is that regions with higher population density tend to preserve fewer rock art remains; conversely, areas with lower population

Rock art heritage archive database	Traditional physical museum
Digital archives	Physical collections
Virtual display of digital museums	Physical exhibition
Digital remote learning and value-added applications	On-site education and promotion
Advantages: non-destructive to the heritage itself, accessible anywhere and anytime, diversified application scenarios	Disadvantages: vulnerable to damage, limited by time and space, monotonous educational scenarios

Table 1. Comparison of functions and advantages between rock art heritage archive database and offline physical museums.

density yield a greater number and higher likelihood of rock art discoveries. Consequently, large-scale rock art concentrations are typically distributed in sparsely populated areas such as grasslands, deserts, mountains and lakes (Zhang 2006). These remote locations greatly limit public access, presentation and dissemination of the heritage itself. Furthermore, international opinions diverge on conservation approaches for rock art. For instance, Scandinavian countries favour in-painting faint petroglyph forms, while a more universal standard advocates leaving cultural markings untouched. Thus, the traditional museum model of collection and physical display is not only unfeasible for rock art but would also cause severe damage. Removing rock art from its original context and Indigenous interpretations would result in a fundamental dislocation in time and space.

Rock art sites are scattered, with images carved on boulders, cliffs, pavements or cave walls. Their fragile materials make transportation and storage extremely difficult. In addition, physical museums are constrained by limited exhibition space, restricted opening hours, difficulties in archive retrieval, and limited value-added applications. As a result, the role and function of physical museums in rock art conservation are considerably limited.

In the current era of maturing digital humanities, new media based on digital media and network technologies, with its distinctive tools and communication modes different from traditional media, as well as its high speed and quality of information transmission, can effectively support the digital conservation and industrial development of rock art heritage (Deng 2015). Against this background, the rock art heritage archive database provides a relatively complete solution for the protection of rock art and the efficient utilisation of heritage resources. Against this background, the rock art heritage archive database provides a relatively complete solution for the protection of rock art and the efficient utilisation of heritage resources.

Constructing a rock art heritage archive database centred on digital resources fulfils the role of a rock art digital museum, establishing a virtual space for the collection and display of rock art knowledge in

cyberspace. Beyond recording and exhibiting rock art resources, its functions can extend to research, education, and even the cultural and creative industries. It directly responds to the digitalisation of cultural heritage and adapts to contemporary global conditions, including political volatility, economic slowdown, and rapid changes in the social and cultural environment. However, staffing, budget support, institutional investment, and project sustainability related to data organisation and maintenance remain important issues to be addressed.

The functions of the rock art heritage archive database

The rock art heritage archive database takes digital collection, virtual display, digital learning and value-added application as the core pillars for the digital development of rock art. By closely integrating advanced network technology with ancient and exquisite rock art, the database can support the decentralised physical rock art heritage sites on the ground in their functions of collection, exhibition, education, research, and industrial development through integrated and coordinated advancement. Compared with traditional physical museums, where collections are vulnerable to damage, access is time-limited, and educational scenarios are monotonous, the digital archiving and virtual display of the rock art heritage archive database offer the advantages of *damage-free preservation and anytime, anywhere access, free from the constraints of time and space*. Thanks to the convenience of remote learning and efficient resource retrieval, digital resources can better empower public education and industrial development by constructing diversified application scenarios.

In the current global field of rock art research and site management, a mature system has been formed for discussions on data organisation, interpretation, integration of Indigenous worldviews, and participation of cultural inheritors. *The IFRAO Code of Ethics* clearly defines data collection fields, prohibits the unauthorised release of coordinates to prevent damage, and emphasises the central position of Indigenous peoples in data definition and interpretation (*Protection: Members will not disclose the*

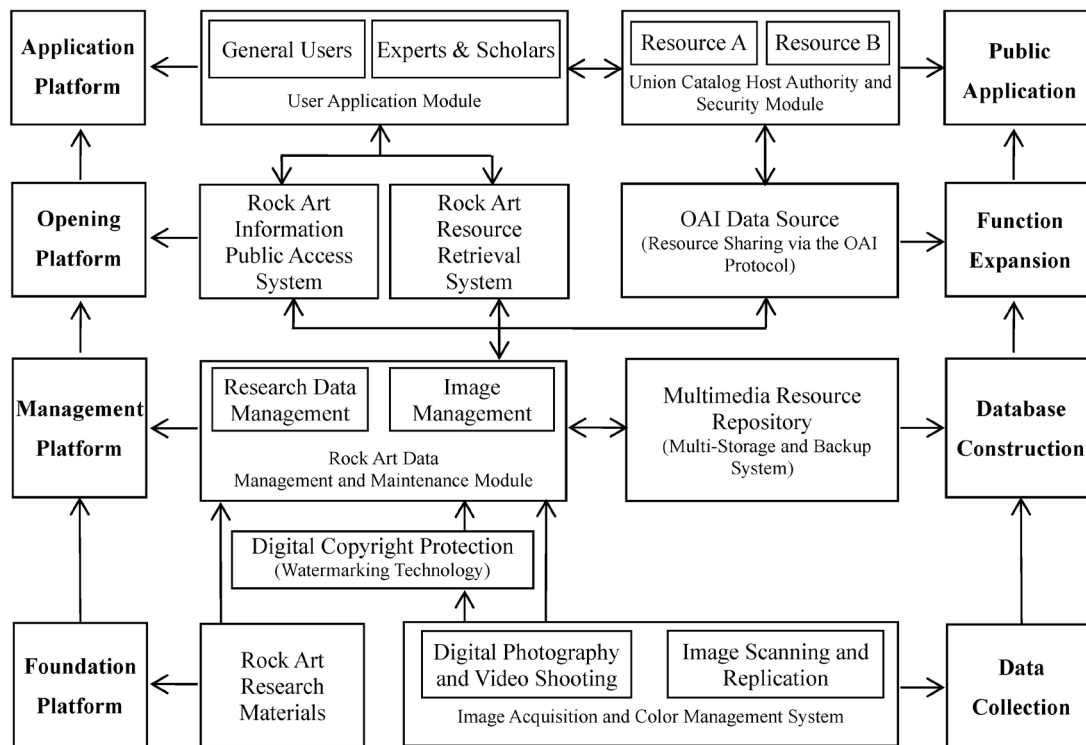


Figure 1. Systematic logical framework of the rock art archive database.

locations of non-public and unprotected rock art sites to the general public. Ultimately, the best protection will depend on the awareness of the general public of the value of rock art. Part of any conservation effort should include the education of the public towards respect for rock art wherever it occurs, serving as the cornerstone of global rock art data standards (IFRAO 2026). Such a standardised cultural documentation model is of important reference value for China's rock art resources.

Systematic logical framework of the rock art heritage archive database

As a form of pictorial art based on graphic language, rock art requires comprehensive consideration of the multimodal characteristics of databases that integrate resource collection and dissemination. It is essential to adopt new technologies and concepts to build a scientific and rational logical framework that covers core data while addressing practical usage needs, enabling the rock art heritage archive database to support core functions of efficient management, query, research and utilisation. Programming with scripting languages such as VB and JavaScript can enable not only effective database operations but also realise integration with web pages. Leveraging the retrieval advantages of ASP technology (Li 2014), multiple retrieval approaches, including rock art classification, chronology, social functions and production methods, are introduced to achieve secure management and efficient retrieval of data and information such as rock art themes, dimensions, geographic coordinates, colours, features, the contextual settings of rock art mountains and high-definition images. The logical

framework of the rock art heritage archive database must fully cover the spectrum from physical entities to digital formats and from surface phenomena to intrinsic connotations. It should include both the physical and image information of rock art itself, as well as associated cultural backgrounds and conservation research history. Meanwhile, digital technologies and management functions ensure data usability and security, ultimately supporting the conservation, research and dissemination of rock art. The systematic construction of a rock art archive database mainly comprises a four-tier platform: *foundation, management, opening and application*. These tiers correspond to a systematic framework of four steps: *data collection, database construction, function expansion, public application*, with digital technologies and information systems integrated into each tier.

Resource foundation platform

Scientific documentation of rock art is the foundation for the systematic construction of a rock art heritage archive database. Some scholars have pointed out the current issue of inconsistent digital documentation standards for rock art and proposed that the integration of social science practices and digital humanities is almost invariably associated with database construction (Shu and Pan 2022). Based on the importance level of rock art and the needs for research, publication or exhibition, data screening should be conducted to establish basic rock art archives, and a unified documentation standard should be formulated. It covers a wealth of content, including physical location, iconographic

Ontology information	Documentation content
Basic identification	Number, name, alias or local name
Spatial location	Site name, approximate coordinate location, rock type, support type
Physical characteristics	Panel size, preservation status, colour
Pictogram/Petroglyph content	Composition, technique, motif elements
Dating information	Chronometric and relative dating

Table 2. Basic information of rock art heritage.

characteristics, chronometric dating and material types, and serves as the core basic data module of the database.

Documentation norms for digital acquisition of rock art

Rock art is a part of tangible cultural heritage, and scholars usually formulate documentation standards for rock art heritage in accordance with the norms for cultural relics protection. Internationally, one of the most applicable normative models is the CIDOC CRM developed by the *International Committee for Documentation* (CIDOC 2026), a subsidiary body of the *International Council of Museums (ICOM)*. This model can be used to describe the historical, artistic and cultural information embodied in stone cultural relics. Its international standard has been updated to *ISO 21127:2023 (ISO 2026)*, which aims to provide a reference ontology for sharing cultural heritage information to enable effective communication, sharing and collaboration among different institutions.

In terms of data documentation standards, chronometric dating of rock art also emphasises the need for repeatable and verifiable scientific methods. Therefore, standardised data recording formats should be established, including sampling location, method, time and calibration data, to support subsequent cross-dating and database integration (Yang 2023).

In China, there are currently no specific norms for rock art, but work can be carried out with reference to national cultural relics protection industry standards: *Code for Investigation of the Protection Engineering of the Stone Monument (WW/T 0063—2015)* (NCHA 2016) and *Three-Dimensional Digital Acquisition and Processing of Cave Temples (WW/T 0117—2023)* (NCHA 2024), so as to construct an expandable motif library of rock art symbols.

Drawing on the documentation methods proposed by many rock art scholars and based on the cultural relic and iconic characteristics inherent in rock art field survey data, a relatively unified documentation standard has now been formulated. From the perspective of systematic construction, the digital documentation information of rock art can be divided into five main components: basic identification, spatial location, physical characteristics,

pictogram/petroglyph content and chronometric information.

Basic identification includes number, name, alias or local name. The number shall be a unique code containing hierarchical information such as region, site and individual serial number. The name should be typically representative, such as *Sun God Rock Art* or *Hunting Rock Art*.

Spatial location includes site name, location and support type. The site name should follow the standard names designated by archaeological authorities; multiple individual sites form a site complex, and a single site is often further subdivided into multiple panels. Location information should include latitude and longitude, altitude, and relative position (as clearly stipulated by the IFRAO, the specific coordinates of non-public and unprotected rock art sites shall not be disclosed to the public to prevent unauthorised access). Examples of relative position include *the middle section of the southern cliff of XX Mountain*. Rock type refers to the lithological composition of the support, such as sandstone, granite, basalt, limestone, etc., and support types include rockshelters, pavements, cliffs, boulders, cave walls, and other forms.

Physical characteristics include information such as panel size, preservation status and colour. Panel size shall record the length, width, height or thickness, as well as the groove depth; preservation status describes the integrity, weathering degree and anthropogenic damage, e.g. *partial spalling, with modern engravings*; colour describes the original hue and extant tone, and a reference image of the *IFRAO Standard Scale* shall be provided to facilitate subsequent colour calibration.

Pictogram/petroglyph content includes composition, motif types, production techniques and motif elements. Composition covers single panels or grouped panels as well as narrative sequences; motifs include hunting, ritual ceremony, zoomorphs, symbols, anthropomorphs and the like; production techniques comprise painting, stencil, drawing, percussion petroglyph, abrasion petroglyph, engraving, combined techniques and other methods; motif elements shall describe the quantity and characteristics of anthropomorphs, zoomorphs and

Category	Documentation content
Regional environment	Site overview, natural environment
Cultural system	Humanistic environment, archaeological cultural system, historical period, archaeological conclusions
Historical context	Historical documents, research history, conservation history
Folk interpretation	Indigenous interpretations, indigenous oral histories, ethnographic records, scientific research achievements

Table 3. Documentation content of rock art-associated contexts.

artefacts.

Dating information is determined by relative dating correlated with surrounding sites and cultural layers, or by chronometric dating methods derived from data including radiocarbon dating, microerosion analysis and radioisotope testing (Hurst et al. 2009). At present, the common dating methods for rock art mainly comprise traditional archaeological methods, radioactive isotope dating methods, physical and chemical analysis dating methods, weathering and erosion dating methods, digital and optical dating methods, etc. (Bednarik 2025). Some scholars also make analogies between dating evidence and archaeological stratigraphy, associated relics as well as artistic styles.

Documentation norms for rock art associated contexts

The associated contexts of rock art and the rock art itself form a contextual relationship. This category compiles background information related to rock art, including its affiliated cultural system, historical context, archaeological research conclusions, and Indigenous interpretations. It provides support for the research and value interpretation of rock art, serves to explain the cultural connotation, historical background and environmental correlation of rock art and enhances the research value of the database.

Converting visual symbols into structured data through digital technologies is a key step in rock art analysis. It supports the construction of a digital evidence chain for cultural interpretation, and embodies the modern research paradigm of *data-driven interpretation* in rock art studies (Shu et al. 2024).

The regional environment includes the site overview and the natural environment. The site overview covers information such as site area and cultural accumulation layers; the natural environment involves geological and geomorphic features like mountains and rivers, climatic characteristics including the comparison of ancient and modern climates, and vegetation types associated with rock art motifs.

Cultural System encompasses the human environment and archaeological cultural systems. For the cultural sphere to which the rock art belongs, it shall be specified whether it is the *Northern Grassland Culture*, *Southwest Ethnic Culture*, *Eastern Marine*

Culture, *Central Plains Agricultural Culture* of China, etc. The archaeological cultural system shall clearly indicate the affiliated archaeological cultures (e.g. *Yangshao Culture*, *Hongshan Culture*) and historical periods such as the *Neolithic Age* and *Bronze Age*, as well as relevant archaeological conclusions on the rock art. In addition, it shall include information such as the distribution of contemporary surrounding sites.

Historical Context contains relevant historical document records, such as descriptions of rock art locations in ancient books, with research and conservation history being an indispensable part. The research and conservation history involves the discovery process (including discovery time, discoverer, and the first record situation); research history (such as relevant academic papers, monographs, research viewpoints, and a bibliography of documents publishing research on the site); and conservation history (such as conservation measures including reinforcement, fencing and digitalisation, restoration records, and disaster events such as the impact of earthquakes, forest fires and floods on rock art).

Folk Interpretation includes Indigenous oral histories and ethnographic records such as legends and interpretations of rock art by local Indigenous peoples, as well as research projects, monographs and achievements of relevant scholars and institutions (a bibliography of documents on the research of the site). It should be noted that discussions related to the interpretation and dissemination of rock art shall place the Indigenous peoples' worldviews, right to expression and participation at the core.

Multimedia visualisation and digital documentation of rock art

Multimedia resources of rock art intuitively present rock art information through visual data such as images, videos and 3D models. As a *digital twin* (i.e. a virtual replica of physical rock art) (Qin and Zhang 2018) of physical rock art, it relies on high-quality digital documentation.

World cultural heritage data are generally based on international standards and norms, with internationally accepted format requirements also applicable to digital photographs and 3D models. Image acquisition technologies for rock art, such

Category	Documentation content
Image data	High-resolution photographs, rubbings, sketches, notes and other original documents
Video data	On-site videos, video recordings of the acquisition process
Digital models	2D planar vector models, 3D scene models

Table 4. Documentation content of rock art multimedia.

as high-resolution digital imaging and 3D laser scanning (Trinks et al. 2005), shall also comply with the metadata standards of international databases.

Rock art image data includes high-resolution photographs—such as panoramic shots showing the contextual environment of rock art, close-up details revealing texture and spalling traces, and multispectral photographs for identifying faded motifs—as well as scanned copies of early recorded original documents, rubbings and hand-drawn sketches, all of which are essential materials for digital archiving. Based on the application of international colour standards in the field of cultural heritage, the sRGB colour space is recommended for the ease of colour reconstitution and calibration, given its excellent compatibility and suitability for the online display of rock art images.

Internationally accepted formats for digital photographs may refer to the *Recommended Format Statement* proposed by the *Library of Congress* (LOC 2026), with TIFF, JPEG2000 and PNG as the preferred formats. Compatibility with multiple formats demonstrates strong adaptability in the current era of diversified acquisition hardware. Technically, shooting shall be conducted at the maximum resolution and bit depth, ideally reaching 16 bits per channel. A colour profile shall be embedded or a specified colour space adopted; *Discrete Wavelet Transform* (DWT) is recommended over *Discrete Cosine Transform* (DCT). Lossless compression or a low compression ratio shall be prioritised, and files shall be unlayered, uncompressed or only subject to lossless compression. In addition, metadata including title, creator and creation date must be included. Through digital image processing of these data, researchers can conduct high-precision digital tracing, which not only corrects errors in previous records, but also identifies the superimposition sequence of multi-layered rock art, thereby inferring the relative chronological order and discovering neglected early motifs (Wang and Shu 2024).

Video data comprise on-site recordings that dynamically demonstrate the spatial relationships of rock art and video footage of the digital acquisition process. Digital models serve as an important supplement to rock art multimedia materials, including 3D scene models of rock art supports and motifs generated via laser scanning and photogrammetry, which support zoom and rotation for viewing. Line drawings are vector tracings of rock art images, also

known as digital tracings, used to clearly present motif outlines.

Internationally accepted formats for 3D models shall adopt common universal standards such as OBJ, FBX and STL. The OBJ format is a widely used 3D model format that supports the storage of polygonal model, material and texture information; the FBX format is commonly used for data exchange between different 3D software and can well preserve geometric information, animation, materials and other elements of models; the STL format is mainly used for rapid prototyping and 3D printing, describing the surface shape of 3D objects in the form of triangular meshes. In addition, specific fields or projects may also use formats such as LASER for storing point cloud data.

The future development goal of rock art resource digitalisation is to gradually complete the digital construction of all surveyed rock art and actively explore the application of rock art 3D imaging and virtual reality technologies.

Resource management platform

After the basic content of digital archives is established through data acquisition, it will be uniformly sent to the Information Centre for post-processing to form a multimedia resource library and core database, which are then integrated into the resource management system to support subsequent functional expansion and diversified value applications. The main content of post-processing is a digital copyright protection system, including watermark embedding and backup storage. A variety of watermark patterns are designed according to different authorised subjects, which are used for identification in researcher borrowing and future commercial authorisation, respectively. The functions of the management platform mainly include image management and upload, background data management, data deposit and withdrawal, request response location conversion, data statistics, storage and backup, etc. The data management and maintenance module of the management platform, the user application module of the application platform, and the permission and security module are the technical application elements required for the construction and operation of the integrated database, including storage architecture, query and retrieval function design, security protection mechanisms, etc. They ensure the efficient and stable operation of the

database, the orderly management, efficient query and diversified application of data and meet the needs of different users. The data management and maintenance module includes data entry and editing that supports multi-user permission management for administrators, researchers, the public, etc., and records data modification logs (who made the modification, when, and what content was modified); it also includes data classification and indexing that categorises data by keywords such as region, age and motif, and supports multi-dimensional retrieval such as *Qin and Han dynasties + squatting human motif + southwest region*. In addition, it enables regular updates of information on newly discovered rock art, as well as multiple storage and automatic backup to avoid data loss.

Resource opening platform

Through the resource retrieval system and information disclosure system of the rock art archive database, digital achievements provide information retrieval, virtual exhibition hall browsing and book collection sharing for general users, experts and scholars with different levels of inquiry services, learning and research, thus realising the functional expansion of the rock art database. In addition, the rock art data open platforms in various regions achieve the goal of resource sharing with databases or museum resources in other regions through the international universality of the *OAI protocol mechanism* (Chang 2007). The rock art resource retrieval system provides professional rock art knowledge and image resources for research by experts and scholars; the rock art information disclosure system offers the general public an integrated interface for easy browsing and inquiry of rock art digital achievements, including brief background information, explanatory notes and JPG images of rock art, serving as the front-end display interface of the rock art resource management system. The functions of the open platform mainly include supporting the correspondence between actual storage directories and logical virtual thematic directories; providing multiple query functions such as image retrieval, full-text retrieval and field retrieval, as well as supporting member login, image access permission control and replacement of web page layout styles.

Resource application platform

Users' demands for cultural resources are endless. In the new internet era, there is a need for digital technologies and application platforms that adapt to contemporary cultural needs. The digital application of rock art resources is not restricted by space: it can be accessed via wired networks in libraries and homes, and also through various mobile terminal devices via wireless networks outdoors. This brings rock art to users' fingertips anytime and anywhere, realising the application transformation of rock art in diverse scenarios. The user application module features

advanced retrieval with multi-criteria combination, supporting complex search functions such as fuzzy retrieval with name and keyword association, and spatial retrieval based on map location query. It is equipped with analytical tools that provide statistical functions (e.g. the proportion of rock art motif distributions in a specific region) and spatiotemporal distribution analysis functions (e.g. generating rock art chronology-geographic distribution maps). In addition, it offers sharing and output functions including data export in PDF report and CSV table formats, as well as online sharing that opens basic information to the public and complete data to researchers. The permission and security module shall be configured with hierarchical permissions: the public are allowed to view basic information and images; professional researchers have access to raw data and research literatures; administrators are granted modification permissions. To prevent malicious tampering, security safeguards such as data encryption and access log recording shall be enabled.

User interface design of rock art database

The external display of rock art databases usually adopts a digital museum-style user interface, whose structure shall include basic frameworks such as multilingual rock art information, a digital virtual exhibition hall, a multimedia display and experience system, and a co-creation platform for cultural and creative products. Through interactive interfaces at all levels, it emphasises the application paths of high-precision technology application, multi-dimensional data integration, cross-platform function design and sustainable industrial development.

Multilingual global rock art information

With the rise of information globalisation, the development of multilingual websites has become an inevitable trend. As an online virtual museum open to the public, the rock art archive database inevitably adopts a platform architecture with a multilingual collaborative work system (Hu and Ying 2004). With the increasing maturity of real-time web page translation, multilingual global rock art information will become increasingly accessible. Special attention should be paid to the translation and calibration of some professional terms in the rock art field into multiple languages. Robert G. Bednarik, Convener of the IFRAO, organised international rock art experts to compile the *Glossary of rock art research: a multilingual dictionary* from 2000 to 2001. This work has established terminological norms for the standard semantic meaning of rock art, including Chinese rock art terms, which provides guiding significance for the translation of professional terms in the storage and open query of the rock art archive database. The core of the information content is to integrate, disseminate and share high-precision and multi-dimensional rock art data worldwide by establishing universal

documentation norms, thus building an information platform for collaborative research.

Themed digital virtual exhibition halls for rock art

With the advent of the intelligent media era, digital technology has exerted an all-round infiltration and reshaping effect on rock art archive databases. Coupled with the emergence of the contactless experience economy in the post-pandemic era, a series of emerging digital service forms such as cloud exhibition viewing, cloud roaming and cloud tourism have mushroomed, being frequently applied to various exhibition scenarios, cultural and museum venues as well as tourist destinations. The new symbolic discourse forms brought about by the new technological environment have fostered a brand-new connection between media, space and humans, and further reshaped the multi-dimensional interactive relationships between space and media, humans and media, as well as humans and humans. *Cloud exhibition viewing* is a comprehensive application based on the digital preservation and display of museum collections and online information technology services. From the perspective of users' interactive behaviours in exhibition viewing, there are currently two distinct types: *digital virtual exhibition viewing* and *live online exhibition viewing*. The former presents exhibits in the form of digital content in thematic exhibition halls of virtual museums, where visitors need to proactively navigate their viewing routes and enjoy a high degree of autonomy. The latter relies on professional hosts to provide fixed-route live commentary and interactions based on the exhibit displays of offline museums, enabling visitors to have a stronger sense of actual participation. What they have in common is that users watch exhibitions online via mobile terminals such as computers or mobile phones (Lu and Yao 2021). For each specific rock art-themed exhibition, it is necessary to create appeal through the specialisation, thematisation and popularisation of virtual or physical exhibition halls, so as to arouse more visitors' interest in cloud exhibition viewing.

Various types of multimedia display and experience systems

Physical visits to rock art usually take place in the wilderness, along coasts, or among mountain forests. The natural cycles of sunrise and sunset, tidal changes, shifting light and shadow, wind and rain, and the chirping of insects and singing of birds set off the static rock art images. Against the backdrop of a well-preserved natural ecosystem, the humanistic aura of rock art is heightened, creating a magical on-site experience for visitors—it is as if they are time-travelling passersby conversing with their ancestors. Such a wonderful on-site sensory experience is a spiritual pleasure that ordinary web browsing on a screen can hardly match. In physical rock art museums such as the *Yinchuan World Rock Art Museum*, mixed reality (MR) technology can be adopted to enhance

visitors' immersive experience. MR technology requires the integration and interaction of real and virtual reality, creating an environment where physical and virtual objects can coexist and interact with each other. The introduction of MR technology in physical museums can enrich and improve the transmission and experience of cultural relic information, enabling cultural relic collections to exert their social and cultural enlightenment educational functions to the fullest extent (Xu 2018). However, for the vast majority of rock art remains, the construction of physical museums is greatly limited by site conditions, making it difficult to truly reproduce the complete natural ecological scenes where the rock art remains are located. Thus, the advantages of rock art digital museums come to the fore. Free from the constraints of time span and spatial scale, digital museums can achieve a realistic simulation of the natural ecosystems of rock art heritage sites by creating high-quality multimedia visual and auditory systems. Coupled with new wearable devices such as virtual reality (VR) glasses, helmets and haptic feedback gloves, they can bring viewers a vivid, immersive feeling, effectively enhancing the immersive interactive experience of visitors to digital museums.

From a technical perspective, the web-based existence forms of rock art digital virtual museums include four types: *2D web page style*, *web-based 3D cultural relic display*, *full 3D interactive mode*, and *panoramic 3D mode* (Zhu et al. 2005). With the development of 5G technology, VR cloud exhibitions adopt a combination of *Web 3D technology*, *3D digital modelling technology* and *VR virtual panoramic technology* to truly simulate offline scenes. Users can experience an *immersive interactive exhibition viewing with a 3D perspective* in the virtual space, and obtain a strong sense of spatial proximity. As a new exhibition mode emerging alongside the development of Web 3.0, virtual roaming and other technologies in the post-pandemic era, the cloud display mode has formed a mutually supportive and interdependent development pattern with traditional offline exhibitions in the past three years, thanks to its unique spatial characteristics and display advantages. Efforts should be made to actively develop rock art-themed cloud exhibitions, cloud audio-visual experiences and cloud interactive experiences, so as to promote the connection between the supply and demand of rock art virtual museums and users at the *cloud end and fingertips*. Meanwhile, the emergence of the metaverse ecology has brought new impacts on the cloud display mode once again. The decentralised mode of the metaverse ecology, coupled with the application of NFT technology, realises the connection between the social identity, social environment and virtual artwork value of virtual visitors with the cloud display space. On the one hand, it endows virtual visitors with a more realistic exhibition viewing experience through social identity authentication and a tailored social environment; on

the other hand, it establishes a reality-interconnected value system for digital avatars and exhibits. These approaches effectively improve the exhibition quality of online virtual museums and further drive the future development of digital cloud exhibitions (Pan 2022). In museum multimedia experiences, situational factors are positively correlated with exhibition viewing effects and immersive experience, and video, audio, lighting and electronic effects are the most favoured multimedia forms by visitors. Featuring thematic content, rock art virtual museums should improve the immersion of multimedia exhibitions from the aspects of enhancing interaction, connecting with reality and optimising media through cross-platform function design, and strengthen the display effect of multimedia experiences (Gu et al. 2021), thus providing a practical basis for the construction of smart museums.

Co-creation platform for value-added creative products of rock art

As an important manifestation of the historical and cultural heritage of the Chinese nation, Chinese rock art is a common treasure of humanity worldwide. The carriers of rock art possess unique characteristics, making it difficult for traditional museology and cultural and artistic creation to exert their influence in the field of rock art. As a vital cultural heritage resource, rock art needs to align with modern lifestyles and current fashion trends, and its artistic value and social added value should be explored from the perspectives of conservation, utilisation and innovation. Strengthening the excavation and interpretation of rock art value, and conducting new artistic creation and redesign of rock art can help rock art gain new value in the new era and open up new channels for pre-Historic rock art to enter people's daily lives. Currently, major digital museums worldwide have set up cultural and creative sections. Rock art is usually presented in the form of visual symbols with strong expressive tension, boasting a symbolic advantage in the design and development of cultural and creative products. However, as most rock art represents the religious beliefs and ideological concepts of pre-Historic humans, its signifier and signified are not always directly expressive at first glance. Therefore, the design of rock art cultural and creative products should not simply appropriate symbols; instead, it needs to be combined with professional interpretation to convey more accurate information to viewers. This requires practitioners engaged in rock art cultural and creative industries to have an open and inclusive mindset while maintaining a rigorous and prudent academic attitude, so as to accurately convey the intrinsic true information contained beneath the surface of rock art to the public. Within this framework, a digital co-creation platform for rock art heritage integrating rock art experts and scholars, designers and public visitors should be built

by utilising digital resources, exploring the co-creation market for cultural and creative products of rock art heritage, and endowing the digital dissemination of rock art heritage with more sustainable value.

Rock art is the common mother tongue of humanity, and exchanges within the international rock art academic community have grown increasingly frequent. Rock art digital museums also shoulder the mission of opening up, sharing, communicating and integrating with the public worldwide. As an application module of rock art archive databases, digital rock art museums of all countries, in addition to developing their own basic databases, should take the initiative to contact the relevant departments of major domestic rock art heritage sites, integrate pertinent collection information, and establish a national-scale digital integration platform for rock art. This is not only a necessity for their own development but also aligns with the current context of museum digitalisation and smart museum construction, serving as a crucial starting point for digital integration, open sharing and resource activation in museums today (Zhao 2022).

Conclusion

The archive database of rock art heritage is not only a foundational digital infrastructure providing cultural information services to the public but also bears profound practical value and strategic significance. Its core lies in relying on cutting-edge network technologies to present non-renewable rock art resources in the form of high-fidelity digital images, supplemented by structured textual descriptive data, and further integrating them to construct a knowledge graph featuring mutual verification of images and texts and semantic correlation. This knowledge system not only supports convenient query and diversified utilisation for the public but also provides a solid foundation for the in-depth excavation and innovative application of cultural value. To ensure the accuracy of information dissemination, it is imperative to establish an advanced standard process and technical system for image colour calibration, striving to truly reproduce the visual effects and spatial context of rock art at its original sites in the digital environment. Meanwhile, a fully functional public information service platform should be developed to provide efficient and reliable image-text retrieval and query services, meeting the learning and research needs of researchers, educators and the general public. Where conditions permit, the construction of the database should also prospectively integrate the development demands of culture-tourism integration. By virtue of technologies such as 3D modelling, Virtual Reality (VR) and Augmented Reality (AR), an immersive and interactive cloud roaming experience can be created in the virtual space, expanding the display boundaries and participation dimensions of rock art heritage. Beyond serving the professional research community, the rock art

archive database can widely open high-quality rock art resources to the whole society through the carrier of the *Rock Art Digital Museum*. This effectively promotes the popularisation and dissemination of the cultural value of rock art, empowers the value-added development of the cultural and creative industry, and stimulates the original vitality of cultural and creative products. Especially for immovable rock art heritage, the in-depth involvement of cultural creativity holds extremely important, transformative and promotional value.

The construction of a national rock art database requires the integration of massive data sources, and ensuring the consistency, accuracy and timeliness of the data will pose enormous challenges. The integration of data sources and the guarantee of data quality for the national rock art database is a professional, systematic and long-term project. Its challenges stem not only from the distribution characteristics of rock art heritage itself and the diverse heterogeneity of data, but also from the lack of cross-entity coordination mechanisms, unified technical specifications and a full-life-cycle data quality management and control system. To address these challenges, it is necessary to formulate national unified norms for the documentation, collection and indexing of rock art data based on the *IFRAO International Rock Art Glossary*; establish a cross-departmental and cross-field mechanism for the sharing and collaborative management of rock art data to break down data silos; develop multi-form data integration and quality control technologies tailored to the characteristics of rock art, and build a full-life-cycle data quality assurance system; meanwhile, set up a professional rock art data management team to realise the collaboration of rock art research experts, digital technicians and archive managers. This will fundamentally ensure the consistency, accuracy and timeliness of the database data, laying a solid foundation for the construction and sustainable operation of the national rock art database.

From the perspective of digital humanities, professional managers of the database should proactively assume the roles of coordinators and promoters. On the one hand, they should actively introduce high-level R&D teams and collaborate with rock art research experts to deeply interpret its rich historical connotations and symbolic meanings; on the other hand, they should encourage technical practitioners to develop world-class digital products, continuously adopt the latest network and intelligent technologies, and fully unlock the unique opportunities and development potential contained in rock art heritage in the digital era. Currently, the digitalisation work in China's rock art academic community is still in the initial preparation stage. Coupled with the critical window period of the rapid development of global digital technologies, it is the optimal time to launch systematic construction. Moreover, the current rapid

advancement of *artificial intelligence (AI)* technology is in urgent need of high-quality cultural resources such as rock art heritage to provide data sources. We have reason to expect that, with the joint efforts of academic colleagues, cross-field collaboration and strong support from all sectors of society, the construction of the rock art heritage archive database will lay a solid foundation for Chinese rock art to enter public aesthetic horizons, integrate into contemporary cultural life, and conduct in-depth dialogues with the international academic community. The pulse of civilisation carried by pre-Historic art will surely inject a steady stream of innovative vitality into building a more influential new model of cultural communication and developing high-value-added creative industries.

Furthermore, the significance of the rock art heritage archive database far exceeds that of an ordinary public cultural service platform. In essence, it constitutes a digital universal language for all humanity. By virtue of the philosophy and technical means of open sharing, it fosters cultural exchange, mutual learning, and knowledge integration on a global scale. By proactively linking domestic rock art heritage sites and relevant institutions to build a nationwide digital integration platform for rock art, this project is not only highly aligned with the current trend of full museum digitalisation and smart museum construction, but also will serve as a key engine to activate cultural heritage resources, advance open sharing and realise sustainable inheritance.

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