Volkson Press

E-ISSN: 2976-2421
CODEN: JRAOCQ

Journal of Rock Art (JRA)

DOI:http://doi.org/10.65098/jra.01.2026.68.83

RESEARCH ARTICLE

A Study on the Construction of a Knowledge Graph of Helan Mountain Rock Art Based on Database Development

Yang Wang, Xihong Shu*

Institute for Advanced Study in History of Science, Northwest University, Xi'an 710069, China
**Corresponding Author E-mail: shuxihong@163.com*

ARTICLE DETAILS

Article History:

Received 15 Apr 2026
Accepted 21 May 2026
Available online 30 May 2026

Online Article Code

ABSTRACT

Helan Mountain rock art, as a representative example of rock art in northern China, embodies abundant prehistoric cultural information. Its digital preservation and intelligent analysis are of great significance for tracing the origins of Chinese civilization. Addressing current issues in rock art research in China, such as data fragmentation, insufficient semantic linkage, and the lack of spatiotemporal evolutionary relationships, this study constructs a database of Helan Mountain rock art based on the international standard CIDOC Conceptual Reference Model (CRM). On this basis, a knowledge graph of rock art is further developed. By establishing a standardized metadata framework for rock art, this study designs a data model comprising 17 core metadata elements across three categories: descriptive, geospatial, and administrative. Building upon the database, a semantic network is constructed that integrates multiple dimensions, including symbolic entities, cultural meanings, geographic locations, and production techniques. The knowledge graph is visualized using Neo4j, revealing the intrinsic relationships of Helan Mountain rock art in terms of spatial distribution, cultural characteristics, and thematic evolution. This research aims to provide a new digital analytical approach for rock art studies.

KEYWORDS

Human Face Rock Art, Image Recognition, Digital Humanities

1. INTRODUCTION

Rock art, as a significant component of China's cultural heritage, is widely distributed across remote environments such as canyon cliffs, forested regions, and grasslands. This geographical inaccessibility poses substantial challenges to its effective preservation, transmission, and sustainable utilization. Consequently, the digital preservation, development, and utilization of rock art are of critical importance for realizing both its economic and social value, as well as for advancing cultural revitalization and continuity. The digital safeguarding and activation of rock art heritage not only contribute to economic benefits and social capital but also foster cultural confidence and a sense of national identity. Therefore, proactive and systematic measures are required to ensure the preservation, development, and sustainable use of rock art heritage, thereby promoting the long-term transmission and flourishing of Chinese culture.

With the advent of the digital era, the digital preservation and development of rock art heritage have emerged as a key research direction. At present, regions such as Europe, Africa, Australia, and the Americas have made notable progress in the digital preservation of rock art, establishing information platforms that support the study of prehistoric art and culture while facilitating cultural dissemination and academic exchange. In contrast, the digital preservation of rock art heritage in China remains in a developmental stage. It is therefore necessary to systematically review international research on digital preservation frameworks for rock art, and to explore new paradigms, models, and methodologies for the digital humanities-based preservation of rock art heritage.

This study seeks to establish a foundational framework for a Chinese rock art heritage database, to investigate sustainable approaches for the construction and dissemination of a knowledge graph of Helan Mountain rock art, and to develop an integrated heritage communication chain encompassing database construction, knowledge graph development, and dissemination strategies. Through scientific and accessible methods of documentation and communication, this approach aims to enable the valuable rock art heritage to achieve more diversified and sustainable forms of transmission under digital preservation.

2. RELATED WORK

Rock art was discovered relatively early in regions outside China, where substantial achievements have been made in its survey, conservation, and research, as well as in the development of foundational theories and methodologies within rock art studies. Several influential international academic organizations have been established, including the International Federation of Rock Art Organizations and other related institutions dedicated to rock art conservation and research, which have played a significant role in advancing the global study and protection of rock art.

In terms of the digital preservation and application of rock art cultural heritage, the international scholarly community has also conducted extensive explorations. For instance, the Origins Centre in South

Africa, the country's first rock art museum, has gained international recognition. The South African Rock Art Digital Archive is among the most comprehensive digital repositories worldwide, containing a wide range of materials, including historical documents, photographs, rubbings, tracings, and slides. Similarly, the Swedish Rock Art Research Archives, as a national-level repository with substantial financial and technical support, encompasses extensive datasets and has laid a solid foundation for Scandinavia to become a major center of rock art research in Europe.

Furthermore, several countries in Europe, the Americas, and Africa have developed specialized rock art websites based on relatively well-established datasets. These include platforms dedicated to sites such as Lascaux Cave and Chauvet Cave in France, as well as other initiatives like the Bradshaw Foundation and the Rock Art of England project. These platforms, characterized by rich and diverse content, present rock art resources and research developments through high-quality images, videos, dynamic visualizations, and scholarly publications. They have greatly facilitated access to rock art information for both researchers and the general public, thereby providing strong support for research and conservation efforts.

Chinese rock art is globally renowned for its long history, wide geographical distribution, diverse thematic content, and vast quantity. It vividly records the production practices, daily life, spiritual beliefs, and artistic expressions of different prehistoric communities, and occupies an important position within the global corpus of rock art. Thousands of rock art sites are distributed across China, offering rich material for understanding the origins of Chinese civilization and the formation of early cultural spheres. They are of great significance for interpreting the "pluralistic unity" pattern of Chinese civilization and constitute an essential component of its origin, formation, and development.

However, due to the fact that most rock art sites are located in remote areas such as mountainous regions, deserts, and grasslands, they are highly vulnerable to both natural and anthropogenic damage. Their preservation has therefore remained a persistent challenge. Under such circumstances, it is necessary to comprehensively reassess the emerging difficulties and challenges faced in rock art conservation research in China. In the absence of major breakthroughs in physical conservation technologies, the rapidly developing field of digital humanities may offer a promising alternative pathway for achieving transformative progress in rock art preservation and research.

In recent years, digital humanities approaches have been widely applied across the humanities and social sciences, opening up new research pathways. The emergence of various algorithms and technologies has provided new perspectives for rock art studies, gradually steering the field toward digitalization and intelligent analysis. For example, Shu and Xia (2022), in Rock Art Cultural Heritage and Digital Humanities Preservation, systematically discussed new trends, models, and methods in the digital humanities-based preservation of rock art heritage. Shu et al. (2022) further explored the application of digital fuzzy recognition techniques to analyze similarities between rock art symbols and oracle bone script, suggesting potential correlations. Zhang et al. (2022) examined the opportunities and challenges facing Chinese rock art within the broader context of digital humanities by analyzing its structural system, investigation methods, and management practices.

In addition, a number of studies have applied advanced technologies to rock art conservation and research. These include methods for detecting subsurface deterioration using thermal infrared imaging, image restoration based on Deep Residual Image Fusion and Multi-scale Mapping (Wei et al., 2025), object detection of Helan Mountain rock art using Faster Region-based Convolutional Neural Network (R-CNN) (Li et al., 2025), and classification (Wang, 2025) and identification (Jia et al., 2022) based on deep learning techniques. Such studies have significantly expanded the scope of digital humanities research in rock art.

Internationally, recent years have also witnessed notable advances. In 2020, a research team from the University of Ioannina in Greece developed two automated methods for detecting rock art features and, through experiments at three sites, found that background information in images could be more informative than the rock art motifs themselves (Tsigkas et al., 2020). Kowlessar et al. (2021) employed deep learning models such as Alex Krizhevsky Network, Visual Geometry Group Network, and Residual Network (ResNet) to classify artistic styles of rock art in Arnhem Land, Australia, and attempted to construct a stylistic chronology. In the same year, a team led by Andrea Jalandoni in Australia applied deep learning techniques to detect rock art in rock imagery, demonstrating the feasibility of such approaches (Jalandoni et al., 2022). Furthermore, Horn et al. (2021) combined R-CNN, data augmentation, and transfer learning based on 3D scan-generated images to develop models for the localization and classification of Swedish rock art.

These studies collectively demonstrate the effectiveness of deep learning in rock art detection and classification, providing strong support for the future development of rock art research and offering valuable references for image recognition studies of rock art in China.

3. SYSTEM DESIGN OF THE NORTHERN CHINA ROCK ART DATABASE

The preservation of rock art is a global challenge. Due to its location in open and often remote environments, rock art is subject to various natural and anthropogenic threats, making comprehensive physical conservation difficult. In most cases, preservation efforts can only aim to slow down deterioration and extend the lifespan of rock art. At present, some conservation and management institutions in China have adopted experimental physical and chemical interventions, such as cleaning surface deposits, reinforcing rock fissures, and stabilizing cliff structures. However, these approaches remain limited in scope and have yet to be widely implemented, as their long-term effectiveness still requires validation.

Against this backdrop, the application of digital humanities technologies for rock art preservation becomes particularly necessary. A fundamental prerequisite for such efforts is the establishment of a comprehensive and systematic database of rock art in northern China.

The design of a rock art database must first ensure the standardization of data acquisition. This requires that field investigations strictly adhere to established recording standards, whereby photographic documentation is accompanied by the systematic collection of associated metadata. Such data include the name and identification number of the rock art, geographic location, production technique, longitude and latitude, elevation, state of preservation, and content description. Where necessary, line drawings should be produced to complement photographic records. This approach provides a comprehensive and detailed dataset, forming a solid foundation for database construction.

As a distinctive form of cultural heritage, the database design for northern China rock art should incorporate the following characteristics:

(1) High domain specificity: Metadata standards must be comprehensive and aligned with both domestic and international practices in rock art research, while avoiding direct replication of metadata schemas from other heritage domains.

(2) Diverse digital resources with strong interconnectivity: Different types of data—such as rubbings, photographs, and related scholarly publications of the same rock art object—should be semantically linked through digital image annotation to enable efficient retrieval of associated resources.

(3) Geospatial and environmental information: Metadata should include detailed spatial attributes, such as site descriptions, relative height from the ground, longitude, latitude, and elevation.

(4) High-resolution and large-volume image data: Digital image resources require high precision and substantial storage capacity.

(5) Copyright and intellectual property management: The system must address issues related to data ownership and usage rights.

In response to these requirements, this study proposes a database system for northern China rock art based on the CIDOC CRM, an international standard (ISO 21127:2023) designed for the integration and exchange of cultural heritage information (Doerr et al., 2003). The module design

Table 1 Rock Art Information Description Framework Based on CIDOC CRM

CIDOC CRM Class	Corresponding Entity in Rock Art Database	Description
E1 CRM Entity	Rock Art, Rock Art Sites, Rock Art Motifs	The Superclass of All Entities
E2 Temporal Entity	Creation Period, Discovery Period	Describes Temporal Information Related to Rock Art
E3 Condition State	Preservation Status, Integrity	Describes the Physical Condition of Rock Art
E4 Event	Discovery of Rock Art, Conservation Actions	Describes Significant Events Related to Rock Art
E5 Event (Destruction)	Damage to Rock Art, Disappearance	Describes Destruction or Loss Events
E6 Activity	Field Survey, Digital Acquisition	Describes Modern Data Collection Activities
E7 Modification	Restoration, Conservation Treatment	Describes Modification Activities Applied to Rock Art
E8 Attribute Assignment	Classification, Attribute Tagging	Describes Categorization Activities
E9 Condition Assessment	Preservation Assessment, Value Assessment	Describes Evaluation Activities
E10 Identifier Assignment	Rock Art Numbering, Identifier Allocation	Describes Identifier Assignment Processes
E11 Measurement	Dimension Measurement, Spatial Measurement	Describes Measurement Activities
E12 Type Assignment	Stylistic Classification	Describes Classification of Artistic Styles
E13 Physical Object	Rock Art Carrier, Rock Surface	Describes Physical Objects
E14 Biological Object	Human and Animal Figures in Rock Art	Describes Biological Entities
E15 Person	Creators, Discoverers, Researchers	Describes Human Actors
E16 Man-Made Object	Rubbings, Photographs, Digital Copies	Describes Man-made Objects
E17 Physical Man-Made Thing	Replicas, Conservation Materials	Describes Artificial Physical Objects
E18 Physical Feature	Size, Color, Texture	Describes Physical Attributes

CIDOC CRM Class	Corresponding Entity in Rock Art Database	Description
E19 Place	Location, Geographic Coordinates, Spatial Region	Describes Spatial Information
E20 Conceptual Object	Rock Art Symbols, Cultural Concepts	Describes Conceptual Entities
E21 Right	Intellectual Property Rights, Usage Rights	Describes Rights-related Information
E22 Document	Survey Records, Research Reports	Describes Documentary Resources
E23 Rights Statement	Access Permissions, Terms of Use	Describes Permission-Related Information
E24 Linguistic Object	Descriptions, Textual Records	Describes Linguistic Entities
E25 Inscription	Texts or Markings Associated with Rock Art	Describes Inscriptional Information
E26 Title	Rock Art Name	Describes Title Information
E27 Legal Body	Research Institutions, Administrative Agencies	Describes Legal Entities
E28 Appellation Pointer	Database Pointers, Web Links	Describes Referencing Information
E29 Identifier	Rock Art Identification Number	Describes Identifiers
E30 Right (Partial Definition)	Components of Rock Art, Spatial Divisions	Describes Part-Whole Relationships
E31 Spatial Coordinates	GPS Coordinates, Spatial Location	Describes Coordinate Information
E32 Conceptual Object	Rock Art Symbols, Cultural Concepts	Describes Conceptual Entities
E33 Contact Point	Contact Information, Institutional Details	Describes Contact Information
E34 Material	Rock Material, Pigment Composition	Describes Material Information
E35 Type	Rock Art Types, Stylistic Categories	Describes Typological Information
E36 Production	Creation, Replication	Describes Production Processes
E37 String	Textual Descriptions, Names	Describes Textual Data

follows the principle of user role-function permission alignment, with the data management module supporting data maintenance while ensuring data security and privacy protection (Table 1).

Furthermore, a data annotation model based on the semantic description of digital images is developed to enable associative retrieval and efficient utilization of digital assets. The system also incorporates user role differentiation and corresponding access control mechanisms tailored to different user groups. On this basis, an integrated online platform is established, including modules for digital museum exhibitions, thematic displays, special exhibitions, public engagement activities, and cultural and creative interactions. Ultimately, this approach aims to construct a comprehensive, systematic, and functionally robust database for northern China rock art.

3.1 Requirements Analysis of the Database System

The design of the northern China rock art database proposed in this study must take into account the characteristics, classification systems, and research demands associated with rock art in this region, in order to enable effective management, identification, and classification of rock art information.

First, the database system should possess the capacity to efficiently store and manage large-scale rock art image data. These data should comprehensively cover diverse rock art sites and stylistic variations across northern China, thereby ensuring both representativeness and completeness.

Second, the database must support multi-dimensional classification of rock art, including but not limited to geographic location, thematic content, and chronological period, so as to facilitate systematic data retrieval and analytical research.

Furthermore, considering the cultural context and historical significance of rock art, the database system should integrate auxiliary information from related domains such as the humanities and geography. This integration will enable researchers to achieve a more holistic understanding and interpretation of rock art. In addition, the construction of the database must emphasize data standardization and normalization, ensuring data accuracy and consistency, and thereby providing a reliable foundation for subsequent applications such as deep learning-based modeling and image recognition.

Finally, the database system should feature a user-friendly interface and strong usability, offering convenient functions for data querying, browsing, and downloading for both researchers and the general public. Such functionality will contribute to the dissemination and sharing of research outcomes in the field of rock art studies.

3.2 Database Architecture

The architectural design of the northern China rock art database system constitutes a core component of the overall system design. It must comprehensively address aspects such as data storage, processing, security, and system performance in order to support the functional requirements of the platform.

The data model design should clearly define entity relationships and attribute structures to ensure data integrity and accuracy. An appropriate database management system must be selected to accommodate the specific characteristics of rock art data. In terms of data storage, strategies for partitioning, backup, and recovery should be implemented to ensure data reliability. Data processing and analytical workflows must guarantee data quality and consistency, while also supporting advanced applications such as data mining and deep learning. Furthermore, system security and access control mechanisms should incorporate user authentication, authorization management, and data encryption to ensure stable and reliable system operation.

The overall framework is illustrated in Table 2. Based on the storage requirements of the core data model and the functional objectives of the system, this framework establishes a technical configuration for the rock art database. Centered on the integrated management of structured and unstructured data, the system supports unified storage of structured data and geospatial information. MongoDB is employed to complement the storage of semi-structured textual data, while MinIO is utilized for large-scale object storage. In addition, a search engine is incorporated to enhance system response performance. Together, these components form a technical infrastructure tailored to cultural heritage data management, ensuring both efficient data storage and convenient access.

3.3 Core Data Model Design

Based on the event-centric methodology of CIDOC CRM, this study constructs a core conceptual data model for the rock art database. The

Table 2 Architectural Design of the Rock Art Database System

Architecture Layer	Core Components	Technical Implementation	Functional Description
Presentation Layer	User Interface, Api Interfaces	React.js, RESTful API	Provides User Interaction and Data Service Interfaces
Business Logic Layer	Data Processing, Business Rules	Node.js, Python	Implements Business Logic and Data Processing Functions
Data Access Layer	Orm Framework, Data Query	Sequelize	Provides a Unified Data Access Interface
Data Storage Layer	Relational Database, File Storage	PostgreSQL, MongoDB, MinIO	Stores Structured Data and Unstructured Files
Infrastructure Layer	Servers, Network, Security	Docker, SSL/TLS	Provides Runtime Environment and Security Support

model systematically organizes the intrinsic logical relationships among rock art heritage elements through six primary entity classes—namely artwork, symbol, place, person, event, and document.

Within this framework, events function as the central linking mechanism, while attribute fields are used to standardize the essential characteristics of each entity. This conceptual model provides a foundational structure for subsequent data structuring, metadata standardization, and functional module design. It ensures both semantic consistency in data organization and the integrity of cultural heritage narratives. The core structure of the model is presented in Table 3.

3.4 Metadata Standard Design

Building upon the database system architecture and the core data model, the metadata standard serves as a critical bridge linking data entities and system applications. The quality of metadata design directly determines the standardization, reusability, and scholarly value of rock art data.

Rock art data exhibit multiple characteristics: they include structured identification information (e.g., artwork identifiers and creation periods), spatially referenced geographic information (e.g., longitude, latitude, and elevation), as well as semi-structured descriptive data and relational administrative information. In the absence of a unified metadata standard, issues such as data heterogeneity and semantic ambiguity are likely to arise, thereby negatively affecting retrieval efficiency, analytical depth, and interoperability across institutions. The proposed metadata schema is presented in Table 4.

3.5 Database Implementation

In addition to the design of the technical architecture, the implementation of the database requires the specification of data tables and system functional modules. As shown in Table 5, the core conceptual data model presented in Table 3 is mapped into a relational database schema, enabling structured data storage.

The table schema design follows the entity-relationship mapping principle. Relationships among entities are maintained through foreign keys (e.g., work_id and location_id), corresponding directly to the associations defined in the core data model. Field design not only covers the attribute definitions specified in Table 3 but also extends to include administrative information.

The indexing strategy is optimized for the query characteristics of rock art data. Spatial indexes support geospatial retrieval, full-text indexes improve the efficiency of textual queries, and standard indexes accelerate relational queries. This schema provides a robust underlying data organization for implementing Create, Read, Update, Delete (CRUD) operations, data quality control, and functional modules such as retrieval and analysis, thereby ensuring both efficiency and integrity in data access.

The functional design of the northern China rock art database system encompasses several core aspects, including data management, information retrieval, user management, and interactive services. The primary function of the system is to enable the input, updating, and storage of rock art information while ensuring standardized data processing.

In addition, the system provides capabilities for data retrieval, filtering, comparison, and analysis, and supports data visualization to present users with intuitive overviews of information. In terms of user management, strict access control mechanisms are implemented. The module design follows the principle of user role-function permission alignment, with the data management module supporting data maintenance while ensuring data security and privacy protection.

From a technical perspective, the front-end interface is developed using

Table 3 Core Data Model Design

Model Category	Core Entity	Relationships	Attribute Fields
Rock Art Entity	Rock Art Artwork (E1)	Produced by Creation Event (E36); Located at Place (E19)	Artwork Id (Unique Identifier), Title, Description, Creation Period, Material Carrier
Symbol Entity	Rock Art Symbol (E32)	Belongs to Artwork (E1); Classified Under Symbol Type (E35)	Symbol Id (Unique Identifier), Symbol Type, Meaning Description, Spatial Coordinates (Relative to Artwork)
Place Entity	Rock Art Site (E19)	Contains Artwork (E1); Associated with Spatial Coordinates (E31)	Place Id (Unique Identifier), Geographic Coordinates (Longitude and Latitude), Elevation, Environmental Description
Event Entity	Creation Event (E12)	Produces Artwork (E1); Involves Person (E15); Occurs at Place (E19)	Event Id (Unique Identifier), Event Type, Time, Location, Event Description
Document Entity	Research Document (E22)	Describes Artwork (E1); References Symbols (E20); Created by Researcher (E15)	Document Id (Unique Identifier), Title, Author, Publication Information, Abstract, Related Artworks

Table 4 Rock Art Metadata Standard

Metadata Category	Metadata Element	Description
Descriptive Metadata	Rock Art ID	Unique Identifier Associated with the Rock Art Entity, Following the Rule of "Site Abbreviation + Serial Number"
	Rock Art Name	Original or Scholarly Name of the Rock Art
	Rock Art Type	Comprehensive Classification Based on Symbol Entities (e.g., Human Figures, Animals, Anthropomorphic Faces, Hunting Scenes, Abstract Symbols)
	Rock Art Color	The Visible Color Characteristics of the Rock Art
	Rock Art Dimensions	Original Size of the Rock Art, Including Width and Height
	Content Description	Textual Description of the Rock Art Content
	Rock Art Attributes	Related Media Types, Including Photographs, Rubbings, and Line Drawings
	Production Technique	Technical Characteristics such as Carving, Engraving, or Painting
	Recorder	Individual Responsible for Recording the Data
	Preservation Status	Quantitative Assessment Using a Four-Level Scale: Intact (>90%), Minor Damage (70–90%), Moderate Damage (30–70%), Severe Weathering (<30%)
Geospatial Metadata	Discovery Location	Specific Location Associated with the Place Entity, Including Site or Panel Identification and Relative Height Above Ground
	Geographic Coordinates	Longitude and Latitude Based on the WGS84 Coordinate System (Precision up to 0.01°), Corresponding to the Spatial Coordinates Field
	Elevation	Absolute Elevation in Meters, Obtained via GPS Measurement or GIS Extraction
Administrative Metadata	Data Source	Records the Method of Data Acquisition (Field Survey, Literature Extraction, or Institutional Contribution) and Original Source
	Date of Data Entry	Records The Initial Database Entry Date in "YYYY-MM-DD" Format, Linked to System Logs
	Date of Data Update	Records Modification Time, Associated with Version Control Mechanisms
	Data Copyright	Specifies Usage Rights and Copyright Ownership

Table 5 Core Data Table Structure

Name	Main Fields	Index Design	Description
Rock_Art_Works	Work_Id (Pk), Title, Description, Creation_Period, Location_Id (Fk), Carrier_Type	Primary Key (Work_Id), Full Text (Title, Description), Index (Location_Id), Index (Creation_Period)	Stores Core Information of Rock Art Artworks; Linked to the Locations Table via Location_Id
Symbols	Symbol_Id (Pk), Work_Id (Fk), Symbol_Type, Meaning, Position_X, Position_Y	Primary Key (Symbol_Id), Index (Work_Id), Index (Symbol_Type), Index (Position_X, Position_Y)	Records Detailed Information of Rock Art Symbols; Position_X/Y Represent Relative Coordinates within the Artwork
Locations	Location_Id (Pk), Name, Coordinates (PostGIS Geometry), Altitude, Terrain_Type, Admin_ Division	Primary Key (Location_Id), Spatial Index (Coordinates), Index (Name), Index (Admin_Division)	Stores Geographic Information; Coordinates Use Point Type for Longitude and Latitude
Persons	Person_Id (Pk), Name, Role, Affiliation, Research_Field, Contact_Info	Primary Key (Person_Id), Index (Name), Index (Role), Index (Affiliation)	Records Information About Relevant Individuals; Role Distinguishes Creators, Researchers, etc.
Events	Event_Id (Pk), Event_Type, Work_ Id (Fk), Person_Id (Fk), Event_Date, Location_Id (Fk), Description	Primary Key (Event_Id), Index (Work_Id), Index (Event_Type), Index (Event_Date), Index (Person_Id)	Links Artworks, Persons, and Locations; Event_Date Supports Fuzzy Temporal Expressions (e.g., Neolithic)
Document	Doc_Id (Pk), Title, Author, Publication_Info, Abstract, Work_Id (Fk)	Primary Key (Doc_Id), Index (Work_Id), Full Text (Title, Author, Abstract), Index (Publication_Info)	Stores Research Documents; Linked to Related Rock Art Artworks
Digital_Files	File_Id (Pk), Work_Id (Fk), File_Type, File_Path, Resolution, Format, Size	Primary Key (File_Id), Index (Work_Id), Index (File_Type), Index (Format)	Stores Metadata of Digital Resources (Images/Scanned Documents); File_ Path Points to MinIO Storage
Metadata_Records	Record_Id (Pk), Entity_Type, Entity_Id, Metadata_Json (JSONB), Update_Time	Primary Key (Record_Id), Index (Entity_Type, Entity_Id), Index (Update_Time)	Stores Extended Metadata for Entities; Entity_Type Distinguishes Associated Entity Categories

Table 6 System Functional Module Design

Functional Module	Sub-Functions	Technical Implementation	User Roles
Data Management	Data Entry (Single/Batch), Editing, Deletion, Version Comparison, Review, and Publication	React.Js Form Components, Excel Import Parsing (Node.Js), Restful Apis, Workflow Engine	Administrators, Data Entry Personnel, and Review Experts
Retrieval and Query	Basic Search (Keywords), Advanced Search (Multi-Criteria), Spatial Query (Geographic Range), Full-Text Search (Semantic Matching)	Elasticsearch Query DSL, Postgis Spatial Functions, Front-End Search Components (React)	All Users
Data Analysis	Basic Statistics (Quantity/Type Distribution), Spatiotemporal Analysis (Creation Period-Location Relationships), Symbol Association Analysis	Python Libraries (Pandas, Numpy), Geospatial Analysis Tools (Geopandas), Visualization Components (Echarts)	Researchers, Administrators
Map Services	Rock Art Site Visualization, Spatial Distribution Heatmaps, Coordinate Positioning	Mapping Library (Leaflet), Geospatial Server (Geoserver), Postgis Spatial Computation	All Users
System Management	User Management (CRUD), Permission Allocation (RBAC Model), System Configuration, Operation Log Auditing	Node.Js-Based Access Control, Log Storage (Postgresql), Configuration Management Modules	System Administrators

React.js, while the back-end interacts with the PostgreSQL database through Node.js, forming a coordinated front-end-back-end-data layer architecture, as is shown in Table 6.

3.6 Data Case Demonstration

With the continuous advancement of digital technologies, approaches to the preservation and transmission of cultural heritage have undergone ongoing innovation. As an important component of China's cultural heritage, rock art in northern China documents the lifeways and belief systems of ancient human societies. In order to better preserve and present these valuable cultural resources, the rock art of northern China has been systematically organized and classified, and its detailed information has been incorporated into the database.

Figure 1 presents the original image and line drawing of the Sun God rock art motif at Helankou in the Helan Mountains. The use of line drawings enables a clearer visualization of the lines and compositional details of the rock art, providing researchers with more intuitive visual materials and facilitating a deeper appreciation of the distinctive aesthetic qualities of ancient art.

Figure 2 shows a standardized field survey registration form for Helan Mountain rock art, in which detailed information, such as images and location data, is systematically recorded for each individual rock art instance. Figure 3 illustrates the login interface of the rock art database system.

Subsequently, through system architecture design, the development of a core data model based on the event-centric methodology of CIDOC CRM, the establishment of a rock art metadata standard framework, and the configuration of database technologies alongside the design of core data table structures, a comprehensive and standardized workflow for rock art data, to encompass data acquisition, storage, and management which has been established. This framework effectively addresses the heterogeneity of rock art data, including image, geographic, historical, and cultural information, and provides both technical and institutional support for standardized data entry, efficient retrieval, and quality control.

However, the exploration of the value of rock art heritage requires not only structured databases for data management, but also mechanisms for uncovering the underlying semantic relationships embedded within the data. These include, for example, the correspondence between rock art symbols and their periods of creation, the pathways of cultural transmission across different regions, and the relational networks linking researchers and their scholarly outputs.

As a knowledge organization and representation tool built upon database systems, knowledge graphs are well-suited to address this limitation. By integrating entities, attributes, and relationships of rock art data, knowledge graphs enable the construction of semantically enriched networks, thereby facilitating deeper analysis and interpretation of rock art cultural heritage.

4. SYSTEM DESIGN OF THE NORTHERN CHINA ROCK ART DATABASE

Helan Mountain rock art embodies abundant information on prehistoric civilizations. However, current research remains insufficient in terms of data integration, semantic association, and the construction of

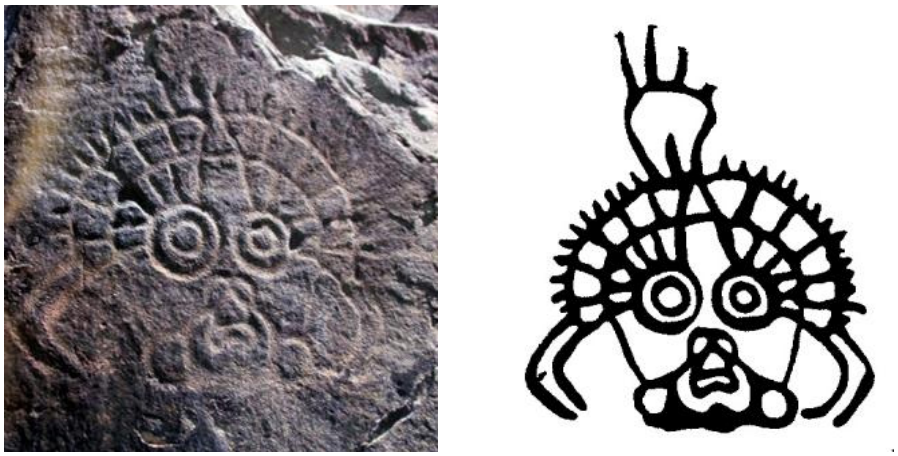
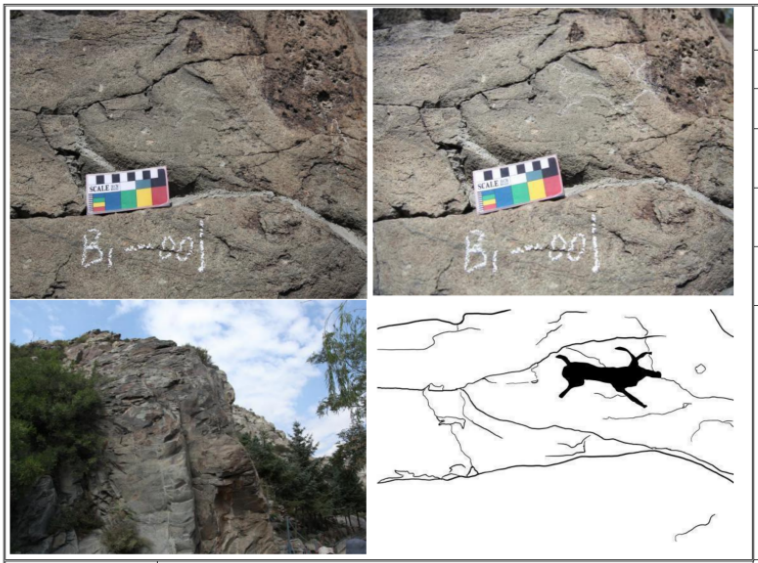


Figure 1 Human Face Rock Art in Helan Mountain



No.	HLK-B1--001						
Name	Animal (Sheep)						
Location	Site Area						
Preservation Status	Intact						
Number	One group (one sheep)						
Production Method	Chiseling						
Physical Preservation Location	On the stone wall east of the Donkey-Sheep Painting						
GPS	Latitude (N): 38°44'38.24" Longitude (E): 106°01'18.15" Altitude: 1468m					**Material**	Quartz Sandstone
Orientation	Facing East	**Height above Ground (m)**	3m	**Age**	Unknown	**Color**	Carrier: Blue-gray
Cultural Relic Category	■Rock art □Others	**Preservation Method**	■Physical Object ■Photo □Line Drawing □Rubbing □Mold Reproduction □Others（ ）				Rock art：light white
						Size（cm）	Length: 17CM Height: 10CM
Content Description	This group of rock paintings is a newly discovered mountain animal pattern of "one sheep" in this census. The carving grooves are shallow and clear. It is located on the upper left stone surface of the original Donkey-Sheep Painting, facing east.						
Census Date	2022/9/2	**On-site Census Personnel**	Zhang Jianguo, Li Jianping, Zhang Xu, Xu Xiaolong, Chen Fang, Yang Danni, Hou Kai, Zhu Rui, Ma Xiao				
Photographer	Hou Kai	**Image Resolution**	3.55MB				
Computer Input Time	2022/9/2	**Form Filler**	Chen Fang	**Line Drawing Artist**	Yang Danni	**GPS Importer**	Zhang Xu

Electronic File Storage Location	Photo	**Line Drawing**	Rubbing	Others	Note:
Computer					
Hard Disk					
CD Location					

Remarks	New Discovery	**Reviewer**	Nie Jun

Figure 2 Survey and Registration Form for Rock Paintings in Helan Mountain

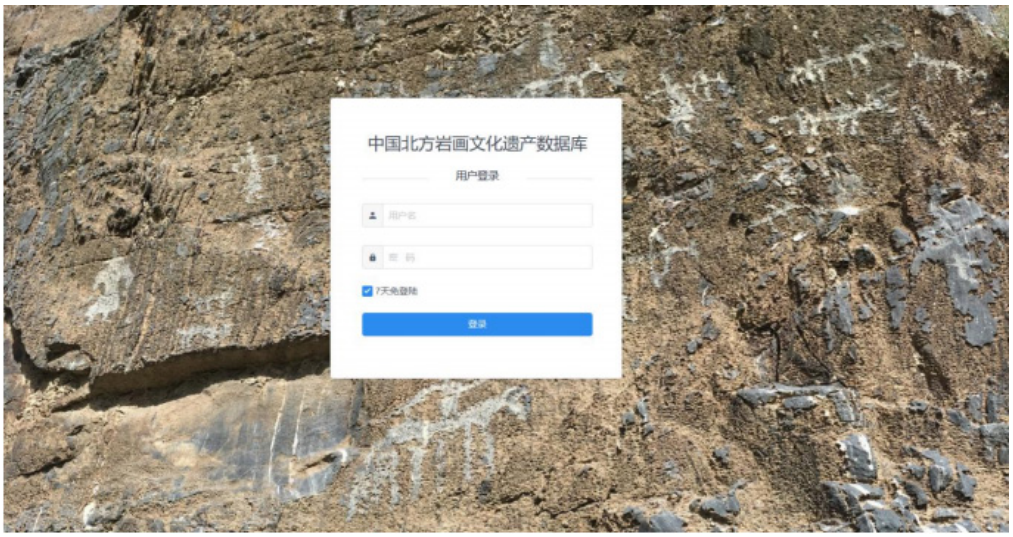


Figure 3 Database Login Interface

spatiotemporal evolutionary relationships. Traditional conservation approaches exhibit certain limitations in systematically uncovering the underlying cultural knowledge networks and dynamic evolutionary patterns of rock art. Although the database constructed in this study enables standardized data storage, it is not well-suited to intuitively represent multidimensional and cross-entity knowledge relationships.

As a knowledge organization and representation tool built upon database systems, a knowledge graph can effectively address these limitations. Integrating entities, attributes, and relationships of rock art data, it enables the construction of a semantically interconnected knowledge network. Therefore, taking Helan Mountain rock art as a case study, this research develops a dedicated knowledge graph to achieve semantic integration of multi-source data, entity relationship extraction, and graph-based visualization.

A unified knowledge framework is established to interlink visual features, spatiotemporal attributes, and cultural information, thereby supporting cross-modal querying and reasoning. This approach provides more in-depth knowledge services for academic research and cultural dissemination of rock art heritage. It also enables the intuitive representation of spatial distribution patterns and relational structures among rock art instances, offering structured evidence for studies on the origins of civilization.

4.1 Knowledge Graph Construction Workflow

Ontology design forms the foundation of the rock art knowledge graph, aiming to define the core entities and their interrelationships within the domain. Based on domain knowledge in cultural heritage studies, a series of key entities are identified and defined, including rock art categories, cultural meanings, and geographic locations. The relationships among these entities are explicitly specified—such as "belongs to," "is associated with," and "is distributed in"—to represent connections across different cultural, spatial, and temporal contexts.

The construction of a comprehensive rock art knowledge graph requires the integration of data from multiple sources, including images, scholarly literature, and field survey reports. This study adopts a multi-source data extraction and alignment strategy to ensure that heterogeneous data can be effectively integrated into the knowledge graph.

As illustrated in Figure 4, the construction of the Helan Mountain rock art knowledge graph follows a systematic implementation workflow, grounded in the comprehensive integration and semantic processing of multi-source heterogeneous data. Four major categories of data sources are incorporated: (1) structured data from the northern China rock art cultural heritage database, (2) semi-structured archival data in XML/JSON formats, (3) unstructured data such as research literature and survey reports, and (4) multimedia resources, including rock art images and line drawings.

At the knowledge processing layer, a ResNet50 model is first employed to perform symbol recognition and classification of rock art images, transforming visual information into knowledge entities. The core of this process lies in the extraction of image features and classification decisions through a convolutional neural network. The final output layer uses the Softmax function to compute the probability that a rock art instance belongs to a specific symbol category c:

$$P(y=c|I)=\frac{\exp\left(W_c^T \delta(I)+b_c\right)}{\sum_{j=1}^{C}\exp\left(W_j^T \delta(I)+b_j\right)} \quad (1)$$

In Formula (1), I denotes the input rock art image, while ϕI represents the feature vector extracted by the ResNet50 backbone network. Let c denote the total number of predefined rock art symbol categories (e.g., anthropomorphic faces, animals, geometric symbols). The parameters w_c and b_c correspond to the weights and biases associated with each category, respectively.

To extract entities and relationships—such as rock art symbols, cultural attributes, and geographic information—from textual data, a hybrid BERT-BiLSTM-CRF model is employed. For a given input text sequence $x=(x_1, x_2, ..., x_n)$, the model utilizes a Conditional Random Field layer to model the joint $y=(y_1, y_2, ..., y_n)$ conditional probability distribution over the label sequence in Formula (2):

$$P(y|x)=\frac{1}{Z(x)}\exp\left(\Sigma_{i=1}^{n}\Sigma_{k=1}^{K}\ddot{e}_k f_k\left(y_{i-1}, y_i, x, i\right)\right) \quad (2)$$

where $Z(x)$ is the normalization factor, f_k denotes the feature functions defined over adjacent labels and the observation sequence, λ_k represents the corresponding learnable weights, and k is the total number of feature functions. The model is trained by maximizing the log-likelihood of annotated text data, thereby enabling accurate extraction of structured entities and relational triples.

To address issues of entity ambiguity and relational inconsistency arising from multi-source data integration, a combination of rule-based reasoning and graph embedding techniques is adopted. Expert-defined rule sets are utilized to identify and resolve inconsistencies and conflicts within the data. For instance, when different data sources assign divergent cultural meanings to the same rock art symbol, the reasoning engine determines the most reliable interpretation based on predefined rules. Finally, the normalized triple data are persistently stored in the Neo4j graph database, forming a well-structured semantic network that

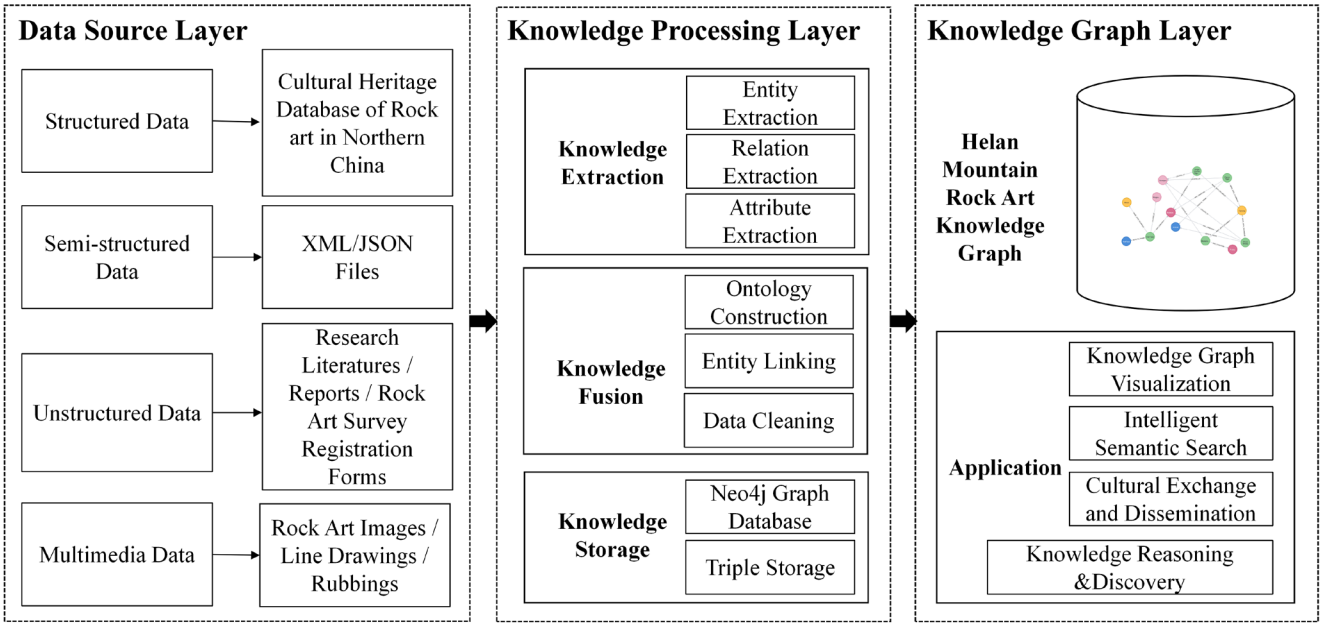


Figure 4 Construction Process of the Knowledge Graph of Helan Mountain Rock Art

supports subsequent querying, analysis, and knowledge inference.

At the knowledge graph layer, the aforementioned processing workflow generates a Helan Mountain rock art knowledge graph with rich semantic connections. This system not only supports visual interactive exploration but also empowers various intelligent applications, including intelligent semantic retrieval with natural language query support, knowledge discovery based on rules and path reasoning, and analysis of rock art cultural dissemination pathways. The framework effectively transforms raw data into structured knowledge, providing a technical foundation for in-depth cultural heritage research and digital dissemination.

4.2 Visualization of the Rock Art Knowledge Graph Based on Neo4j

To facilitate the systematic organization, analysis, and presentation of this valuable cultural heritage, this study constructs a knowledge graph of Helan Mountain rock art based on detailed field survey data and performs visualization using Neo4j.

The processed data are first transformed into a triple-based representation, enabling the structured modeling of multidimensional attributes of rock art, including spatial distribution, thematic content, production techniques, and preservation status, as is shown in Tables 7–9. This approach achieves the digital integration and intelligent association of rock art information. The core architecture is organized around three hierarchical levels: entity layer, relational layer, and conceptual layer.

At the entity level, ten representative rock art artworks are selected, covering five major thematic categories, including animals, human figures, symbols, composite motifs, and special patterns. At the relational level, a multidimensional network is constructed using relationships such as “located in,” “belongs to,” and “adopts.” At the conceptual level, standardized classification systems are defined, including geographic distribution, thematic categories, and production techniques. In addition, specific motifs, such as the Owl Face pattern, are explicitly annotated within the graph.

This structured representation enables intuitive observation of spatial distribution patterns of rock art in the Helan Mountains, clustering trends of thematic content, and geographic preferences associated with different production techniques.

The processed data are imported into Neo4j, and Cypher queries are executed to enable visualization of the knowledge graph, displaying all nodes and their relationships, as shown in Figure 5. This study presents a simplified knowledge graph example to achieve ontology-based representation and visualization of the multidimensional information associated with Helan Mountain rock art.

In this graph, geographic location serves as the central node, which is connected to rock art instance nodes through the LOCATED_AT relationship, forming a location-centered network structure. The graph also incorporates attribute nodes such as preservation status, production techniques, and thematic content. These nodes are linked to rock art instances through relationships such as DEPICTS_THEME, USES_TECHNIQUE, and HAS_CONDITION, and are visually distinguished using different colors. Through this multidimensional visualization—particularly when large volumes of rock art data are incorporated—researchers can more intuitively understand spatial distribution patterns, thematic preferences, technical characteristics, and preservation conditions of rock art.

Within the knowledge graph query module, Cypher query language further enables interactive visualization and graph-based querying, allowing results to focus on the association between spatial attributes and preservation conditions. As illustrated in Figure 6, a subgraph centered on the Owl Face motif is presented. The nodes in this subgraph include the rock art entity Owl Face, the geographic unit Xingouwai, thematic categories OwlFace and HumanFace, the production technique Mixed, and the preservation status RelativelyClear.

From the topological structure of the graph, it can be inferred that the Owl Face rock art is linked to Xingouwai through the LOCATED_AT relationship. It is also associated with the OwlFace thematic category via the DEPICTS_THEME relationship. Notably, an additional connection to the HumanFace category is observed, indicating a dual thematic attribution that was not explicitly defined in the original dataset, where the script only established a relationship between XGW19 (Owl Face) and the OwlFace category.

In terms of production techniques, the Mixed relationship is consistent with the original record, indicating that the motif was created using a combination of carving and grinding techniques. The preservation status is identified as RelativelyClear. Overall, Figure 6 reveals the relatively isolated occurrence of the Owl Face motif in Xingouwai, along with its technical characteristics. From an archaeological perspective, the Owl Face motif—being rare and symbolically significant within Helan Mountain rock art—may reflect the integration of multiple supernatural

Table 7 Sample of Entity-Level Triples for Helan Mountain Rock Art

Subject	Predicate	Object	Description
JCG1	Name	Three Sheep	Rock art No. 1 at Jiucaigou
JCG1	Theme	Animal	Depicts Animal Subjects
JCG1	Location	Jiucaigou	Located in the Jiucaigou Area
JCG1	Preservation Status	Relatively clear	Good Preservation Condition
JCG1	Technique	Carving	Produced using Carving Technique
JCG1	Color	Light Brown	Color Characteristics
JCG1	Orientation	Southeast	Facing Southeast
JCG1	Dimensions	29 × 22 cm	Size of the Rock Art
JCG3	Name	Tiger and Sheep	Rock Art No. 3 at Jiucaigou
JCG3	Theme	Hunting Scene	Depicts Animal Interaction
JCG3	Location	Jiucaigou	Located in the Jiucaigou Area
JCG3	Preservation Status	Clear	Well Preserved
JCG3	Technique	Carving	Produced Using Carving Technique
JCG3	Color	Light Brown	Color Characteristics
JCG3	Orientation	South	Facing South
JCG3	Dimensions	72 × 47 cm	Size of the Rock Art
XGW19	Name	Owl Face	Rock Art No. 19 at Xingouwai
XGW19	Theme	Special Pattern	Represents a Unique Motif
XGW19	Location	Xingouwai	Located in the Xingouwai Area
XGW19	Preservation Status	Good	Well Preserved
XGW19	Technique	Carving and grinding	Produced Using Combined Techniques
XGW19	Color	Grayish brown	Color Characteristics
XGW19	Orientation	North	Facing North
XGW19	Dimensions	85 × 76 cm	Size of the Rock Art

Table 8 Sample of Thematic Classification for Helan Mountain Rock Art

Subject	Predicate	Object	Description
Animal	Description	Sheep, Tigers, Cattle, And Other Animal Motifs	Content Description
Human	Description	Human Figures, Anthropomorphic Faces, etc.	Content Description
Symbol	Description	Geometric Symbols and Abstract Signs	Content Description
Composite	Description	Combination of Animals and Symbols	Content Description
Special Pattern	Description	Rare and Distinctive Motifs	Content Description

Table 9 Sample of Production Techniques for Helan Mountain Rock Art

Subject	Predicate	Object	Description
Carving	Description	Producing Patterns by Chiseling the Rock Surface with Tools	Technique Description
Grinding	Description	Forming Patterns by Abrading the Rock Surface	Technique Description
Carving and Grinding	Description	Combination Of Chiseling and Grinding Techniques	Composite Technique Description

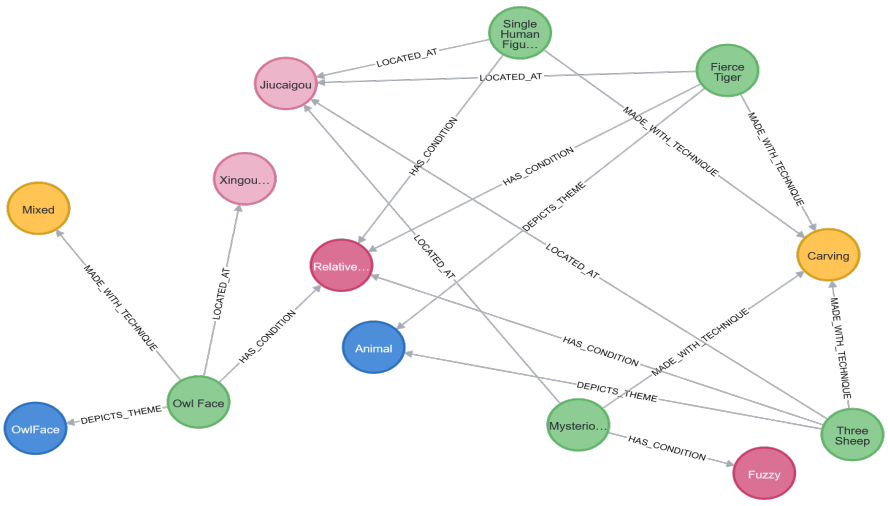


Figure 5 Survey and Registration Form for Rock Paintings in Helan Mountain

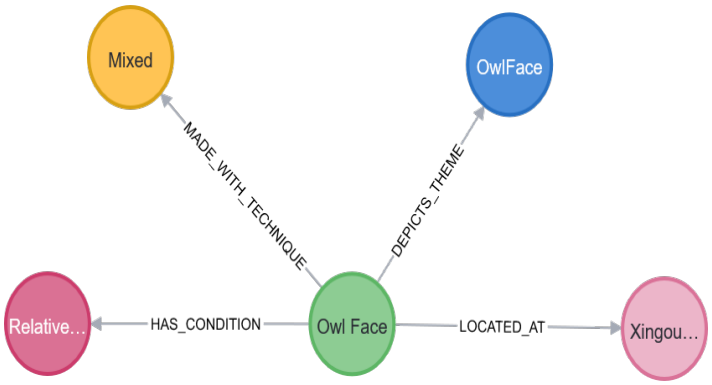


Figure 6 Survey and Registration Form for Rock Paintings in Helan Mountain

representations in prehistoric belief systems. The use of composite techniques further suggests that the creators possessed advanced and diversified production skills.

5. CONCLUSION

This study addresses the digital preservation and knowledge representation of Helan Mountain rock art by developing an integrated technical framework that combines a database system with a knowledge graph.

At the database level, a standardized data model based on the CIDOC CRM international standard is established, incorporating three categories of metadata: descriptive, geospatial, and administrative. This model enables the structured organization and unified management of multi-source data, including rock art images, spatial information, and research documentation. The database ensures data consistency and scalability while providing a reliable, structured foundation for subsequent semantic modeling.

At the knowledge graph level, the study builds upon the database to systematically model entities, attributes, and relationships of rock art. By integrating image recognition and text information extraction techniques, key elements such as symbol categories, cultural attributes, and spatial information are automatically extracted. Rule-based reasoning is further applied to resolve ambiguities and inconsistencies across multi-source data. The resulting knowledge graph, implemented in Neo4j, links geographic location, thematic content, production techniques, and preservation status into a unified semantic network, transforming fragmented data into structured and interconnected knowledge that supports querying and visualization.

Overall, this study establishes a technical workflow from data acquisition and structured storage to semantic modeling and graph-based visualization. It mitigates, to some extent, the issues of data fragmentation and weak interconnectivity in traditional rock art research. The proposed approach provides a practical framework for organizing and utilizing rock art data, and lays the groundwork for future developments in semantic reasoning and cross-modal analysis.

Future work may focus on expanding the scale and diversity of the knowledge graph, refining ontology design, and incorporating more advanced automated annotation methods. In addition, exploring cross-regional data integration and sharing mechanisms could further enhance the systematic and scalable study of rock art.

Author Contributions

Yang Wang contributed to methodology, resources, supervision, writing the original draft, review, and editing; Xihong Shu contributed to data curation, review, and editing of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was financially supported by the Interim Achievement of the Youth Fund Project on Humanities and Social Sciences Research by the Ministry of Education (Project Number: 24YJCZH047).

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