Heritage Science

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A study on the spatial distribution and historical evolution of grotto heritage: a case study of Gansu Province, China

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Abstract

Grottoes are a comprehensive art treasure trove that integrate architecture, sculpture, and murals. They showcase the historical spiritual civilization of humanity and provide a solid foundation for studying the dissemination and development of Buddhist culture. Gansu Province is an important node on the transmission route of Buddhist culture, constituting a relatively complete and rich history of Buddhist art and cultural history. This article uses GIS technology to systematically analyse the spatial distribution characteristics and spatiotemporal evolution patterns of grottoes in Gansu Province from the Wei Jin to the Ming and Qing dynasties and explores the main factors affecting their distribution. The results indicate the following: (1) the grottoes in Gansu Province exhibit clustering and uneven distribution characteristics, which form the core aggregation area of Qingyang Tianshui City and the secondary aggregation area of Wuwei and Zhangye City. (2) Spatiotemporal characteristics show significant changes in the number and focus of excavation and repair of grottoes in Gansu Province over the years. The Northern and Southern Dynasties, Sui and Tang Dynasties, and Ming and Qing Dynasties had more grottoes than the Wei, Jin, and Yuan Dynasties. The overall centre of gravity shifted from northwest to southeast. Natural factors such as topography, stratigraphy, and hydrology and cultural factors such as politics and transportation significantly impacted the spatial pattern of grotto heritage in Gansu Province. Exploring and studying the spatial layout of grotto heritage from the perspective of historical geography is beneficial for understanding the cultural development and historical changes in Buddhism and is of great significance for the development of landscape environmental protection and utilization of grotto heritage.

Keywords Gansu province, Grotto, Spatial distribution, Time and space evolution, GIS analysis

Introduction

Material cultural heritage contains rich historical, cultural, and artistic value and is a witness to human history and a cornerstone for exploring future development [1]. An important component of material cultural heritage, grottoes are a product of the exchange and dissemination of Buddhist culture [2]. The grotto heritage integrates various forms of artistic expression such as sculpture, murals, and architecture; grottoes witnessed cultural and intellectual exchanges among civilizations such as ancient India, ancient Greece, Rome, and Persia [3, 4] and were the depositories of important information regarding the integration of Chinese and Western ideas, culture, art, and other aspects of society. The grotto heritage has strong inclusiveness and significant global value [5]. In depth studies of this heritage are important for promoting global cultural exchange and achieving sustainable development [6].

As an important node in the dissemination of Buddhist culture, Gansu Province in China has preserved

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much cave heritage from different eras [7], forming a relatively complete and rich history of Buddhist cave art; this collection is important for studying the evolution of Buddhist art. Since the early 1900s, scholars from various countries have conducted archaeological investigations and studies on the heritage of Gansu grottoes. For example, the British scholar Stein [8], the French scholar Pelliot [9], the German scholar Grünwedel [10] and others have investigated the Mogao Grottoes of Dunhuang and recorded many grotto heritage materials via photography and drawings. Since the 1930s, Chinese scholars have made significant achievements in the study of grotto heritage, which can be divided into four aspects: periodization and dating [11], types and forms [12], art and style [13, 14], and protection and restoration [15, 16]. For example, Wei [17] divided the age of the existing cave in Maiji Mountain based on its shape and statue characteristics. Yang and Wang [18] performed statistics, calculation and analysis on the roof slope, building scale, structural stress and distribution of grottoes in different shapes of the Mogao Grottoes of Dunhuang and expounded the structural characteristics of grottoes. Russell and Smith [19] analysed the colour and decoration techniques of Dunhuang Buddhist scripture cave paintings and believed that historical rulers strongly influenced the formation of Dunhuang art in the tenth century. In the past, most scholars approached the history, culture and art of the grotto heritage in Gansu Province from a humanities perspective; little research included the geographical and spatial distribution characteristics of the grotto heritage.

In recent years, with the growth of cultural heritage protection work, geographic information technology (GIS) has been widely applied in the fields of material cultural heritage and historical geography [20]. Its use mainly includes building protection and restoration [21], archaeological information management [20, 22], landscape environment monitoring [5, 23], and other content, thus greatly improving the research efficiency of heritage protection. For example, the 3D Murale project jointly developed by Brunel University of London and multiple European colleges can mostly complete the acquisition and storage of 3D models of archaeological sites, thereby achieving on-site restoration of archaeological sites [24, 25]. Chiara used GIS to draw an archaeological risk map and archaeological potential map of Macherata Province and create a spatial analysis model [26]. Yan et al. [27] used GIS to explore the spatiotemporal evolution characteristics and factors influencing the distribution of traditional village heritage in Henan Province. In general, international scholars rarely study the spatial distribution and historical evolution of grotto heritage from a geographical perspective, but doing so not only reveals the ancient human understanding of the laws of physical geography during grotto construction; it also is conducive to the scientific and effective management and protection of grotto heritage in modern society [28].

Therefore, this study takes 246 grottoes and cliff carvings in Gansu Province as the research object, comprehensively uses the methods of quantitative geographical analysis and GIS spatial analysis to analyse natural factors such as elevation, lithology, rivers and politics, transportation and other human factors of the grotto cultural heritage in the study area and explores the relationship between ancient human activities and the natural environment. Taking the cultural heritage of grottoes in Gansu Province as an example, this study provides new thinking for the overall research of countries with grotto cultural heritage, with the aim of building a global database of grotto cultural heritage.

Methods

Study area

Gansu Province is in the hinterland of Northwest China (92° 13′–108° 46′ E, 32° 11′–42° 57′ N), bordering Shaanxi in the east, Xinjiang in the west, Sichuan and Qinghai in the south, Ningxia and Inner Mongolia in the north, and Mongolia in the northwest [29]. The region has complex terrain and diverse landforms, which can be divided into six major terrain areas, namely, Longnan Mountain, Longdong and Longxi Loess Plateau, Gannan Plateau, Hexi Corridor, Qilian Mountain, and the northern zone of Hexi Corridor. The overall landform features are high in the southwest and low in the northeast [30]. The surface water resources in Gansu Province mainly include the Yellow River, Yangtze River and inland river basins, which include nine river systems, namely, the Tao River, Huang River, Wei River, Jing River, Jialing River, Shule River, Heihe River, and Shiyang River [31]. Within the existing administrative divisions, the province has jurisdiction over the prefecture-level cities of Lanzhou, Baiyin, Qingyang, Pingliang, Tianshui, Wudu, Dingxi, Lintao, Wuwei, Zhangye, and Jiuquan as well as Linxia and Gannan Autonomous Prefecture.

The data on the remains of grotto temples presented in this paper mainly come from the third national cultural relics census [32]. The world cultural heritage in Gansu Province, the key cultural relics protection units of grotto temples at the national, provincial and municipal levels, and the unclassified grotto temples, cliffs and stone carvings are selected as the research objects (Fig. 1 and Table 1) and include 239 grotto temples and 7 cliff statues.

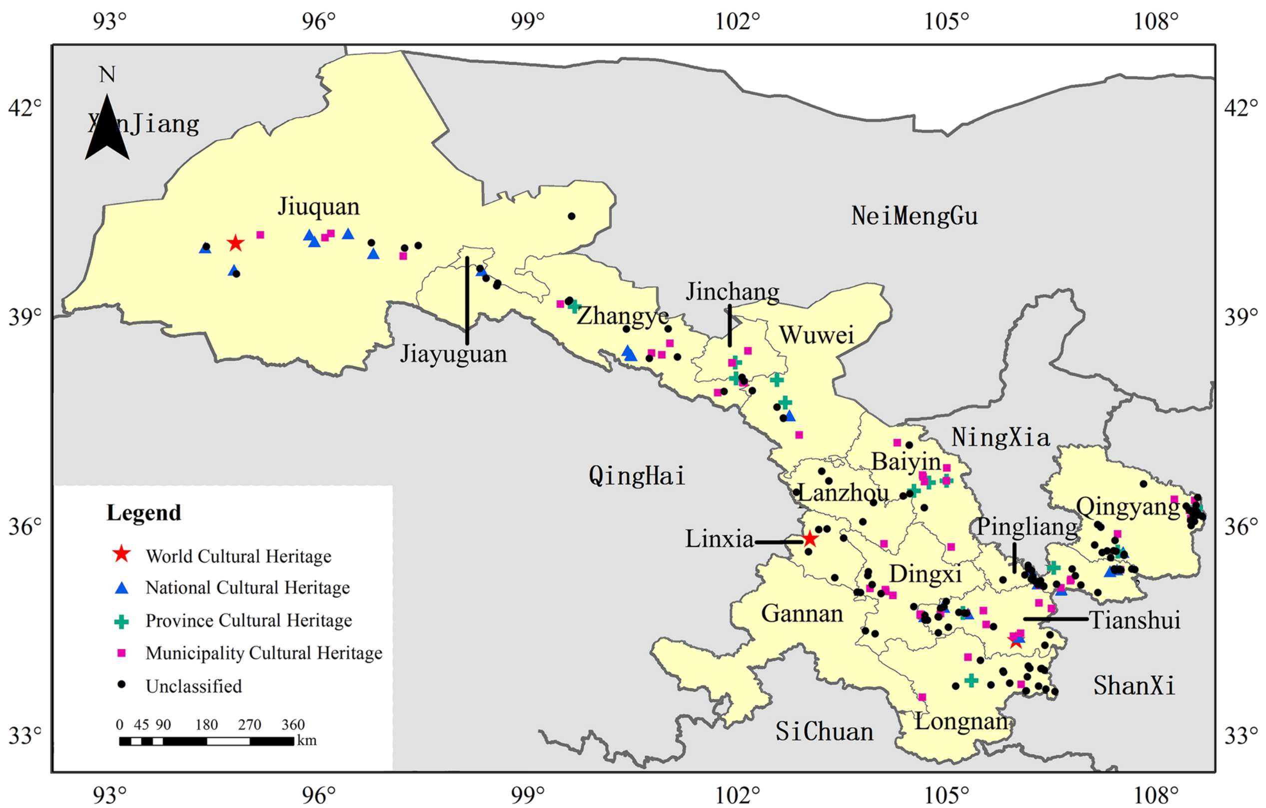

Fig. 1 Distribution of grottoes in Gansu Province

Table 1 Gansu Grotto census registration form

Municipality	World cultural heritage	National cultural heritage	Province cultural heritage	Municipality cultural heritage	Unclassified	Number
Pingliang	–	5	1	7	36	49
Qingyang	–	2	4	6	30	42
Tianshui	1	8	1	10	18	38
Longnan	–	–	1	3	18	22
Jiuquan	1	9	1	4	6	21
Zhangye	–	4	1	5	9	19
Baiyin	–	–	3	6	4	13
Dingxi	–	–	–	4	8	11
Jinchang	–	–	2	5	2	9
Wuwei	–	1	2	2	3	8
Linxia	1	–	–	–	6	7
Lanzhou	–	–	–	1	5	6
Jiayuguan	–	–	–	–	1	1

Research methods

The research methods involved the following steps. (1) The spatial distribution pattern and layout of the grotto temples were analysed by using the nearest neighbour indicator. (2) The Gini coefficient was used to calculate the disequilibrium degree of the number and density of grotto temples within prefecture-level units and determine whether there was spatial differentiation among grotto temples. (3) The kernel density estimation tool was used to identify the central area from the spatial distribution of the grotto temples. (4) The standard deviation ellipse was used to analyse the centrality, distribution, directionality and spatial range of the spatial distribution of the grotto temples [33].

Nearest neighbour indicator

Grotto temples can be abstracted as point-like elements with three spatial distribution types: random, uniform and cohesive. In research, the nearest point index is usually used for identification [34]. The formula is:

$$R = \frac{r}{r_1} = \frac{r}{\frac{1}{2\sqrt{n/s}}}$$

where R is the nearest point index and r is the actual nearest distance. Generally, the actual nearest linear distance between each point and its nearest point is measured by ArcGIS, and the average value is calculated; r_1 is the theoretical nearest distance, n is the number of points, and s is the area of the region. Point-like elements within a certain area mainly present three spatial distribution types: uniform, random and aggregated. When $R > 1$, the point elements are evenly distributed; when $R = 1$, the point elements are randomly distributed; and when $R < 1$, the point elements are clustered [35].

Imbalance index

The imbalance index can reflect the distribution balance of the grotto temples between the city-level units, and the Gini coefficient model is used for the calculation [36]. The formula is:

$$G = \frac{1}{2n^2u}\sum_{i=1}^{n}\sum_{j=1}^{n}\left|y_i - y_j\right|$$

where G is the imbalance index of the grotto temples; n = 246; u is the average number or density of grotto temples in the prefecture-level units yi; and yj represents the number or density of grotto temples in the ith and jth prefecture-level units, respectively.

Density analysis

Kernel density estimation can calculate the density of point elements around each output grid and can directly reflect the distribution characteristics of the core area of the grotto temple [37]. The formula is:

$$F(x) = \frac{1}{Nd}\sum_{i=1}^{n}K\left(\frac{x - x_i}{d}\right)$$

where F(x) is the estimated value of the kernel density, K is the Gaussian kernel function, x is the estimated point, x_i is the ith grotto temple point, d is the search radius, and N is the number of grotto temple points within the bandwidth [38].

Standard deviation ellipse and centre of gravity migration trajectory

The standard deviation ellipse can accurately reveal the overall characteristics of the spatial distribution of geographical elements [39]. The barycentre migration trajectory model can express the spatiotemporal evolution based on geographical elements [40]. The combination of the two methods has been widely used to study the spatiotemporal patterns within long time series data and over large areas. The calculation method is as follows:

$$\begin{cases} X = \sum_{i=1}^{n} x_i w_i / \sum_{i=1}^{n} w_i \\ Y = \sum_{i=1}^{n} y_i w_i / \sum_{i=1}^{n} w_i \end{cases}$$

where X and Y represent the coordinates of the centre of the standard deviation ellipse, X_i and Y_i represent the coordinates of pixel i, W_i is the weight, and N is the total number of pixels.

$$\tan\theta = \frac{\sum_{i=1}^{n}\overline{X}_i^2W_i^2 - \sum_{i=1}^{n}\overline{Y}_i^2W_i^2 + \sqrt{(\sum_{i=1}^{n}\overline{X}_i^2W_i^2 - \sum_{i=1}^{n}\overline{Y}_i^2W_i^2)^2 + 4(\sum_{i=1}^{n}\overline{XY}W_i)^2}}{2\sum_{i=1}^{n}\overline{XY}W_i}$$

where θ is the bearing angle and (Xi, Yi) is the coordinate difference between the spatial coordinates of the grotto temple in the study area and the central point $(\overline{X}_w, \overline{Y}_w)$.

$$\begin{cases} \sigma_x = \frac{\sqrt{2\sum_{i=1}^{n}(\overline{X}_i W_i \cos\theta - \overline{X}_i W_i \sin\theta)^2}}{n} \\ \sigma_y = \frac{\sqrt{2\sum_{i=1}^{n}(\overline{Y}_i W_i \sin\theta + \overline{Y}_i W_i \cos\theta)^2}}{n} \end{cases}$$

where σ_x and σ_y represent the standard deviation of the X-axis and Y-axis, namely, the length of the X axis and Y axis, respectively, and n is the total number of pixels.

Results

Spatial distribution characteristics

Spatial distribution type

At the provincial level, the geographical location of the remains of a grotto temple can be regarded as a point-like element, which can be expressed by coordinate points. According to the nearest neighbour index of the grotto temples in Gansu Province, the actual nearest neighbour distance is 11.09 km, the theoretical nearest neighbour distance is 20.8 km, and the nearest neighbour index is 0.53 < 1, indicating that the spatial distribution of the grotto temples in Gansu Province follows a typical agglomeration pattern, and the degree of aggregation is relatively high.

Degree of spatial distribution balance

The disequilibrium index can be used to study the equilibrium degree of the distribution of point elements within different regions. According to the Gini coefficient model, the imbalance index S = 0.448 (as calculated by Excel), and S < 0.5 indicates that the distribution of grotto temples in the province is slightly unbalanced. The total number of grotto temples in Pingliang, Qingyang and Tianshui is 52.2%; Jia Yuguan, Lanzhou city and Linxia Autonomous Prefecture have a relatively small number of grotto temples, accounting for 5.7% of the total number in the province. No grotto excavation has been found in Gannan Tibetan Autonomous Prefecture.

Spatial distribution density

The core density analysis tool of ArcGIS 10.7 software was used to generate the core density map from the spatial distribution of the caves in Gansu Province (Fig. 2). The spatial distribution density of the caves in Gansu Province is highly varied, presenting multipoint clustering that reveals three primary clustering centres and three secondary clustering centres, and the cluster edge is significant. Among them, Pingliang, Qingyang and

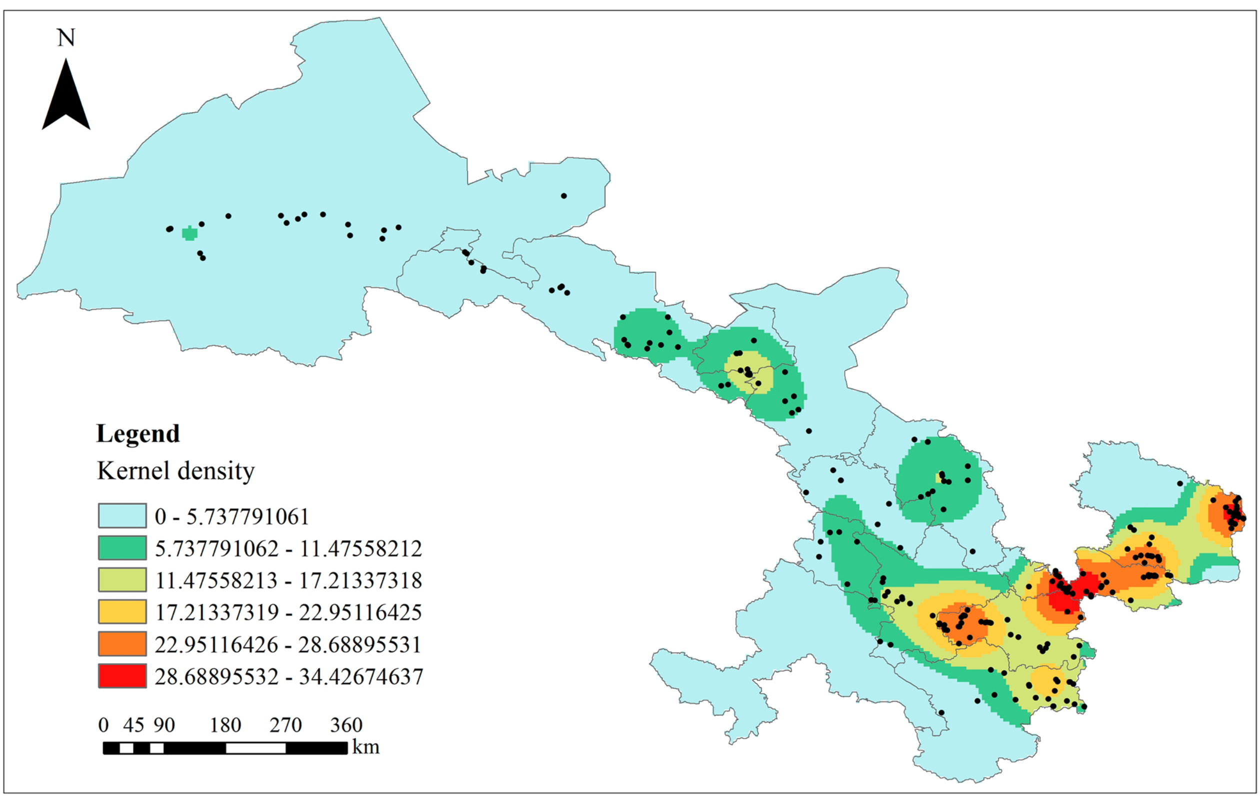

Fig. 2 Kernel density of the spatial distribution of grottoes in Gansu Province

Tianshui are high-density areas that are concentrated in the eastern and southern regions of Gansu Province and have a certain continuity. The distribution density decreases in a band or ring around the centre of the three clusters; Wuwei city, Zhangye city and Baiyin city are less dense areas, concentrated in the Hexi Corridor area, and the other areas have a low degree of aggregation and are sparsely distributed. The overall density of the grottoes in Gansu Province shows a gradually decreasing spatial distribution from the eastern and southern regions of Gansu Province to the Hexi region, which is closely related to the natural environment in Gansu Province.

Characteristics of spatiotemporal evolution

Time series evolution characteristics

The grottoes in Gansu Province have undergone development over dozens of dynasties since the Wei and Jin dynasties. To observe the excavation and evolution of grottoes in different periods more clearly, based on the number and scale of grotto heritage sites corresponding to previous historical and archaeological research results [7] and combined with relevant phased studies in the academic community [41], this study divides the excavation age of grotto temples into seven historical stages: the Wei Jin period (220–420 AD), Northern and Southern Dynasties period (421–581 AD), Sui Tang period (582–979 AD) Song Dynasty (960–1234 AD), Yuan Dynasty (1206–1368 AD), Ming Dynasty (1369–1644 AD), and Qing Dynasty (1616–1911 AD).

A statistical analysis of the number of excavations and renovations of grottoes in previous dynasties found that there were significant changes in the number of grottoes in Gansu Province at each stage (Table 2). During the Wei and Jin dynasties, Buddhism was introduced to China for a relatively short period, and relatively few people were engaged in cave excavation [42]. In the Northern and Southern Dynasties, as well as the Sui and Tang dynasties, emperors supported Buddhism, which led to its rapid development and growth in the construction and scale of grottoes. At this stage, people built many grotto temples, most of which were influential, such as the Mogao Grottoes, Bingling Temple Grottoes, Maijishan Grottoes, and Beishi Grottoes. In the Song Dynasty, the imperial court still adopted a protection policy for Buddhism and began to change to secularization. Therefore, ordinary people carried out Buddhist activities, and the number of grottoes increased. The reign of the Yuan Dynasty was short, and its rulers advocated Tibetan Buddhism; thus, the number of grottoes constructed was reduced. During the Ming and Qing dynasties,

Table 2 Statistical table of the ages of grotto excavations in Gansu Province

Periods	Wei and Jin Dynasties	Northern and Southern Dynasties	Sui and Tang Dynasties	Song Dynasty	Yuan Dynasty	Ming Dynasty	Qing Dynasty	Unknown
Number	11	56	32	20	10	56	37	24

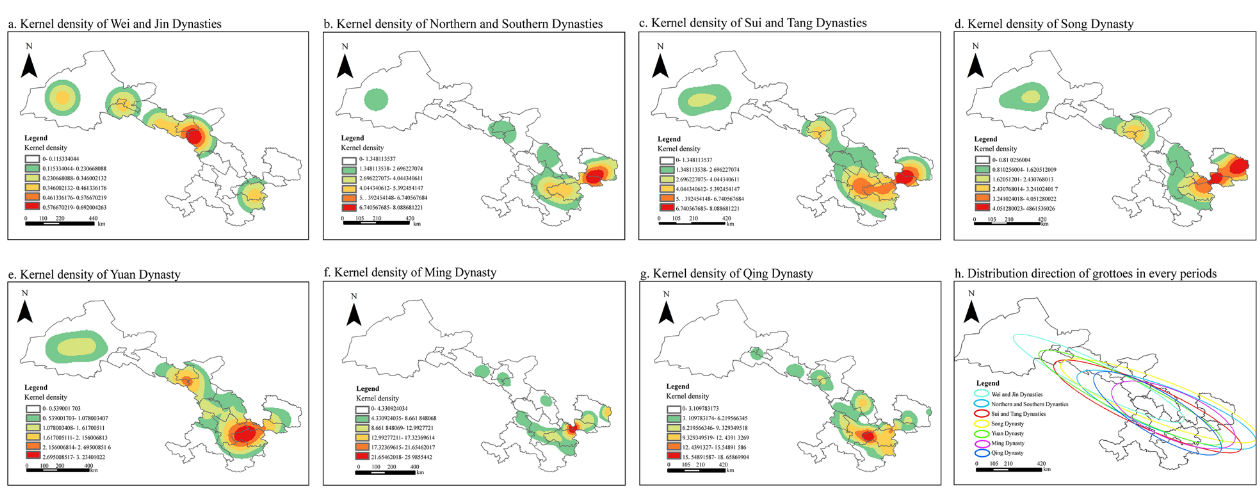

Fig. 3 Density and distribution direction of the caves in Gansu Province in every periods

most grottoes were renovated and patched by Buddhists, and temple buildings were built in front of some grottoes, resulting in an increase in grottoes.

Characteristics of directional evolution

The directional distribution ellipse tool in the spatial statistics module of ArcGIS 10.7 was used to process the data from seven grottoes in the study area, and seven different kernel density distribution maps and directional distribution ellipses were obtained (Fig. 3). The long-half axis of the ellipse represents the data distribution direction and the maximum diffusion direction; the short-half axis represents the data distribution range and the minimum diffusion direction; and the rotation angle represents the dominant direction of the distribution [43].

The analytical results of the standard deviation ellipse show that the distribution pattern of grottoes during different periods in Gansu Province generally presents a northwest to southeast trend. The number of grottoes in the Wei and Jin Dynasties was small, and the ellipse was elongated. The grottoes were randomly distributed, forming a relatively narrow distribution belt. During the Northern and Southern Dynasties, the construction of grottoes flourished, the long axis of the ellipse became shorter, and the level of the agglomeration area was clear, showing an overall pattern of higher density in the southeast and lower density in the northwest. During the Sui, Tang and Five Dynasties, the distribution of grottoes was relatively balanced, the length of the long axis of the ellipse significantly increased, and the overall pattern extended to the northwest. This pattern basically resulted in four groups of grottoes (i.e., in Hexi, Longzhong, Longdong, and Longnan) and laid the foundation for the pattern of millennium grotto development in Gansu. During the Song and Western Xia Dynasties, the elliptical rotation angle contracted inwards compared to that in the previous period, the scale of grotto distribution in the Longzhong region decreased, and the scale of grotto distribution in the Hexi region expanded. Although the Yuan Dynasty had only a small number of grottoes, they were widely distributed, forming two high-density clusters in eastern and central Gansu and the subcentral density area of Hexi. The distribution of grottoes during the Ming Dynasty significantly shortened the long axis of the ellipse but maintained a clear direction, with grottoes mainly concentrated in the central, eastern and southern regions of Gansu. During the Qing Dynasty, grottoes were distributed in all regions of Gansu Province, had a relatively balanced distribution and were more clearly dispersed compared to the previous stage. The core density of the grottoes has a certain continuity.

Evolutionary trend of the centres of grotto clusters

Centre migration analysis is a comprehensive statistical and representative method for studying the population distribution in a certain region [33, 44]. The centre of the scattered groups within the grotto temple site was the distribution centre of ancient Buddhism at that time. The change in the location of the points can indicate the overall trend of the spatial distribution of Buddhism at that time or indirectly reflect the migration process of the activity centre of Buddhist monks.

An examination of the evolutionary trend during seven historical stages shows that the grotto sites in Gansu Province progressed in a southeast–west–northeast–west–southeast–west pattern (Fig. 4). During the

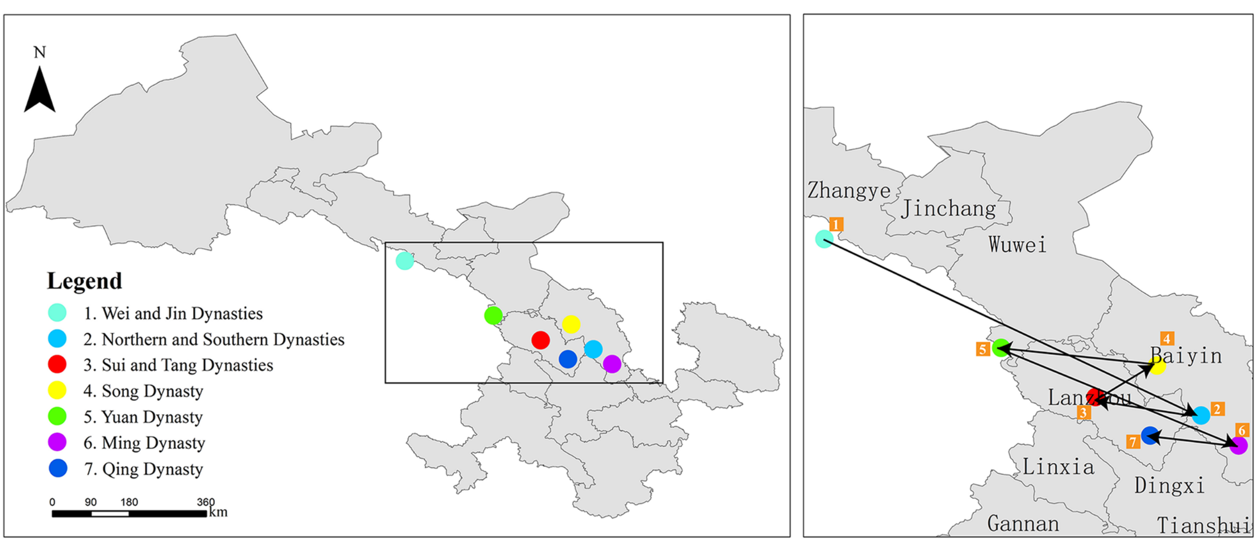

Fig. 4 Changes in the central locations of the grottoes in Gansu Province in every periods

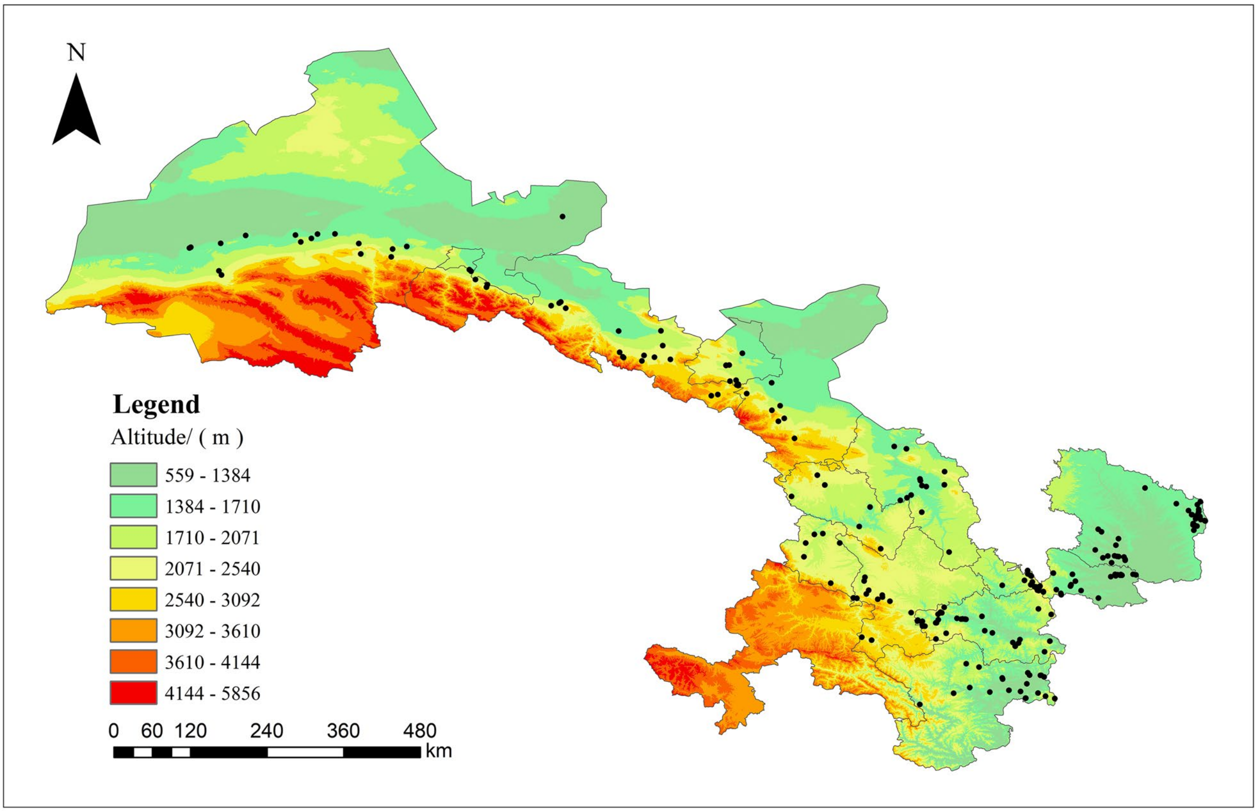

Fig. 5 Elevation distribution map of grottoes in Gansu Province

Table 3 Statistics of the elevation and quantity of grottoes in Gansu Province

Altitude (m)	500–1000	1000–1500	1500–2000	2000–2500	2500–3000
Number	6	101	69	59	11

Wei and Jin Dynasties, grotto temple repair mainly occurred within Minle County, Zhangye city (100.74° E, 38.01° N). During the Northern and Southern Dynasties, the central grotto temple location was in Jingyuan County, Baiyin city (104.71° E, 36.15° N), and it moved 512.57 km to the southeast relative to that during the Wei and Jin Dynasties. The central grotto temple locations during the Sui, Tang and Five Dynasties were in Gaolan County, Lanzhou city (103.60° E, 36.34° N), and they moved 126.58 km southwards relative to the location during the period of the Southern and Northern Dynasties. The central grotto temple location during the Song and Western Xia Dynasties was in Pingchuan District, Baiyin city (104.25° E, 36.68° N), and it moved 85.7 km to the north relative to that during the Sui, Tang and Five Dynasties. The central grotto temple location during the Yuan Dynasty was in Tianzhu County, Wuwei city (102.61° E, 36.87° N), and it moved 185 km to the northwest relative to that during the Song and Western Xia Dynasties. The central grotto temple location during the Ming Dynasty was in Huining County, Baiyin city (105.11° E, 35.84° N), and it moved 312.94 km to the southeast relative to that during the Yuan Dynasty. The central location during the Qing Dynasty was in Yuzhong County, Lanzhou city (104.18° E, 35.94° N), and it moved 104.61 km to the northwest relative to that during the Ming Dynasty.

Discussion

Natural factors

Landform factors

By superposing the distribution map of grotto temples in Gansu over the regional topographic elevation map (Fig. 5), the data show that the grotto temples are mainly concentrated in the four terrain areas of Longnan Mountain, Longdong and Longxi Loess Plateau, Qilian Mountain and Hexi Corridor.

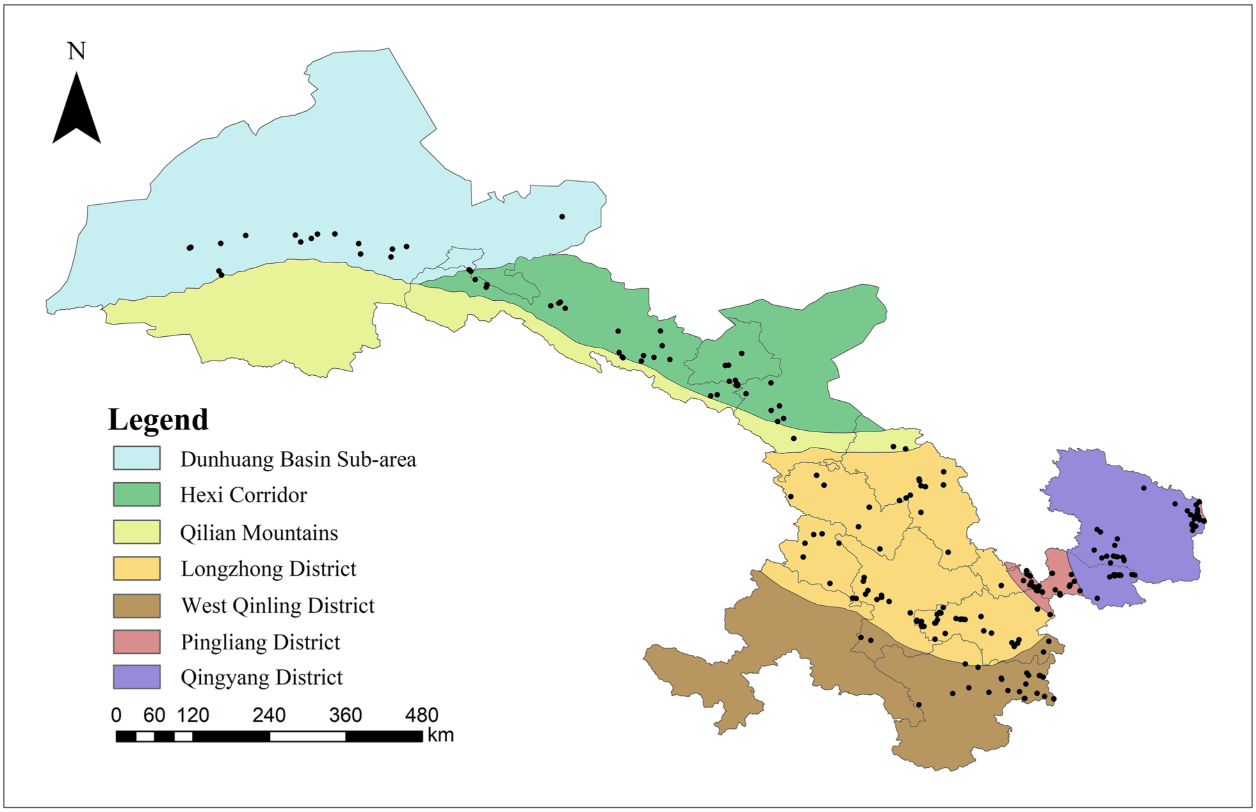

Fig. 6 Regional stratigraphy and distribution of grottoes in Gansu Province

Table 4 Number of grottoes in the stratigraphic regions of Gansu Province

Stratigraphic area	Dunhuang–Hexi Corridor	Qilian Mountains	Longzhong District	Longdong District	West Qinling District
Number	41	16	71	70	38

Table 3 shows that after the elevation exceeds 1500 m, the number of grottoes decreases with increasing elevation. The vast majority of grottoes are between 1000 and 2000 m in elevation, accounting for 69.1% of the total number in the province. Few grottoes are found at an elevation of 500–1000 m, as the distribution of rocks in plain areas is relatively small and relatively low, thus making it impossible to build a group of tall and concentrated cave statues. Landforms such as Zhongshan, high mountains, and extremely high mountains have limited areas for human production and living, making it difficult for ancient people to dig caves. Therefore, no cave resources are distributed in these areas. This factor indicates that the distribution of grottoes in Gansu Province is closely related to the terrain and landforms, and the differences in terrain and landforms impact the intensity of human development and utilization activities [45]. In addition, naturally formed cliffs do not require large-scale mountain cutting engineering during excavation, which helps craftsmen carry out construction and reduces the amount of work. Therefore, cliff surfaces with a slope of 70–80° are generally selected for excavation.

Lithologic factors

The stratigraphic sequence of Gansu Province is relatively complete, and the grottoes are generally distributed among five stratigraphic areas: Dunhuang–Hexi Corridor (including Dunhuang Basin and Hexi Corridor), Qilian Mountains, Longzhong District, Longdong District (including Pingliang District and Qingyang District) and West Qinling District (Fig. 6). The grottoes are mostly distributed within the Cretaceous sandstone areas of Longzhong and Longdong, which account for

The west wall of Cave 231th of Mogao Grottoes **The 13th Cave of Bingling Temple Grottoes** **The east wall of Cave 165th of Beishi Grottoes Temple**

Fig. 7 Grotto art represented by different lithology in Gansu Province

more than 57.3% of the total number of grottoes in Gansu Province. Furthermore, the lowest number of grottoes (accounting for less than 10%) is found in the Qilian Mountains (Table 4). This is because there are differences in the physical and mechanical properties of rock masses, as well as differences in rock chiselability and weathering resistance [46]. The lithology of the strata significant impacts the difficulty level of grotto excavation [20].

The lithology of different regions can also affect the expression style of cave art [47]. In the Dunhuang Basin community, the rock mass is poorly cemented, and the debris particles are poorly sorted and rounded [48], making it difficult to directly create art on the rock mass. Therefore, murals and wooden bone-coloured sculptures are mainly painted on the ground, such as in the Dunhuang Grottoes with the Mogao Grottoes as the core and the Liangzhou Grottoes with Tiantai Mountain and Mati Temple as the core. The Longzhong area is mostly composed of Tertiary sandstone formations with good cementation [49], which can be directly created on the rock mass. Therefore, these murals and stone sculptures have been preserved. They are mainly represented by the Bingling Temple and Maijishan Grottoes. Longdong District is mostly composed of sandstone and gravel rocks from the Cretaceous Liupanshan Group, with uniform and dense sandstone particles that are suitable for fine carving and are characterized by stone carving techniques [50]. However, the sandstone is prone to detachment, resulting in severe weathering of statues, such as the Beishi Grottoes Temple, Lianhua Temple, and other grotto groups (Fig. 7). The sandy conglomerate in the West Qinling Mountains is well cemented and has a rough and hard texture, which is not conducive to fine processing. It is often carved using the technique of "stone body clay sculpture", such as the Eight Peaks Cliff Grottoes. The sculpture is exquisite and delicate, with natural movements and vivid and rich expressions.

Table 5 Number of river buffer zones near grottoes in Gansu Province

River buffer zone (km)	1	2	3	4	5
Number	120	58	45	16	7

Water system factors

Arc GIS 10.7 was used to conduct a multiring buffer analysis on water systems above level 5 in Gansu Province, with ring values set at 1, 2, 3, 4, and 5 km. The buffer zone area of the river was calculated and overlaid with the distribution of grottoes for analysis. Table 5 shows that 90.7% of the grottoes are located within 3 km of the river, with 48.8% of the total grottoes located within 1 km of the river. As the distance increases, the number of grottoes shows a decreasing trend. This phenomenon indicates that water sources, as a necessary natural resource for human social production and life, are an important reference for selecting the geographical location for building grottoes [51]. This is because in ancient times, early monks usually practised meditation in caves after digging them. Therefore, being close to rivers can support living and production and provide conditions for the long-term development and prosperity of cave groups. Furthermore, river erosion means that the cliff terraces on both sides of the river provide excellent conditions for grotto excavations. Therefore, the vast majority of the remaining grottoes are near the river.

Figure 8 and Table 6 show that the locations of the grottoes are mostly distributed along the river system, with dense distribution in the outflow area and sparse distribution in the inflow area. In the Yellow River Basin, the Jinghe and Weihe River systems account for 52.4% of the total grottoes in Gansu Province. However, most of the grottoes in this region are relatively small in scale. Within the Jialing River water system of the Yangtze River basin, there are no nationally protected grottoes and only two

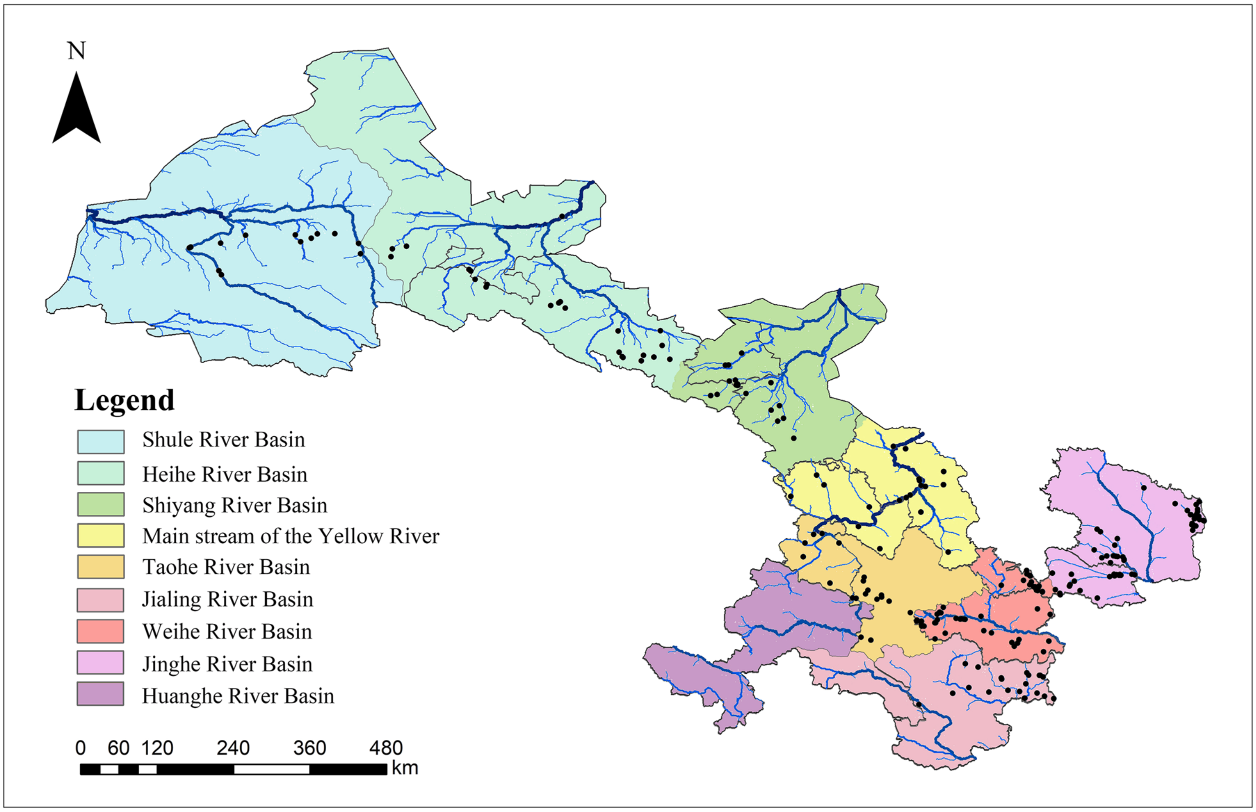

Fig. 8 River distribution map superimposed on grottoes in Gansu Province

Table 6 Statistics of the number of grottoes located in river basins in Gansu Province

Basin	Yellow River Basin					Yangtze River Basin	Continental River Basin		
	Taohe	Huanghe	Jinghe	Weihe	Trunk stream	Jialing	Shule	Heihe	Shiyang
Number	11	7	63	66	19	22	21	20	17

provincially protected grottoes, Bafeng Cliff and Foye Cliff, but the total number of grottoes is large. In the inland river basin, grotto distribution is relatively rare, the overall protection level is relatively high, and all of the grottoes are consolidated in large groups.

Human factors

Political factors

In Gansu Province during the Wei, Jin and Southern and Northern Dynasties, successively established regimes included the Qianliang, Houliang, Nanliang, Xiliang, Beiliang and Xiqin regimes. Wuwei has long been the political and cultural centre of the Hexi region, and Buddhism in the area has a long local history. During the late Jin Dynasty, Zen was most common in Liangzhou, and Buddhist monks were widespread throughout the region. The statues in the cave openings were similar to those of fire and tea in the Hexi region. The rulers of this period showed more or less support for Buddhism for the political purpose of stabilizing society, educating the people and strengthening their rule [52]. Buddhism, as a foreign religious culture, is particularly important in the context of its local rise. The monks catered to the political needs of the rulers and established a supernatural image for the people who occupied lower positions in society. This process promoted the acceptance and recognition of Buddhism by the upper and lower classes of the people and laid the foundation for the prosperity of Buddhism.

During the Sui, Tang and Song Dynasties, most of the grottoes were concentrated in southern Tianshui, middle

Pingliang and eastern Qingyang. Due to the influence of the political and economic factors within the geographical centre of Chang'an, the grottoes were closer to the Central Plains. Prosperity, economic development and cultural exchange led Buddhism and grotto art in the Sui and Tang Dynasties to reach a new peak. Especially during the Tang Dynasty, the emperors of all dynasties showed their support for the development of Buddhism. The political influence led to the development of the grottoes. The excavation of the new grottoes and the expansion of the original grottoes were carried out simultaneously.

In the Song Dynasty, rulers used Buddhism as an auxiliary means of promoting border politics, making Buddhism consciously subordinate to the ruling regime. As in the Central Plains region, the government gradually supported the rise of Buddhism in surrounding areas, leading to large-scale but relatively slow development in the Gansu region. Although the number of grottoes excavated decreased compared to the Sui and Tang dynasties, more renovations and repairs were undertaken. The scale of the grottoes was relatively small, mostly concentrated in the southeastern part of Gansu.

During the Ming and Qing Dynasties, the era of global right-of-way declined, and the era of sea power began. As the maritime silk road prospered, Gansu gradually changed from an important northwest area that offered economic, cultural and transportation advantages to a border area far away from the capital. The strategic positioning of the military became the main geographical feature, and economic decline inevitably affected cultural development. On the other hand, during this period, Chinese Buddhism overall was in a state of decline, and Gansu was no exception. In addition, although the decline in Buddhism caused it to fade into the social background overall, the complete secular transformation caused Buddhism to form a very deep cultural connection among the population; the resulting cave statues are still common. Small cave niches are scattered around the region and satisfy people's needs for belief; they

Table 7 Number of grottos within set distances from the road buffer zones in Gansu Province

Road buffer (km)	1	3	5	7	9
Number	21	86	69	42	28

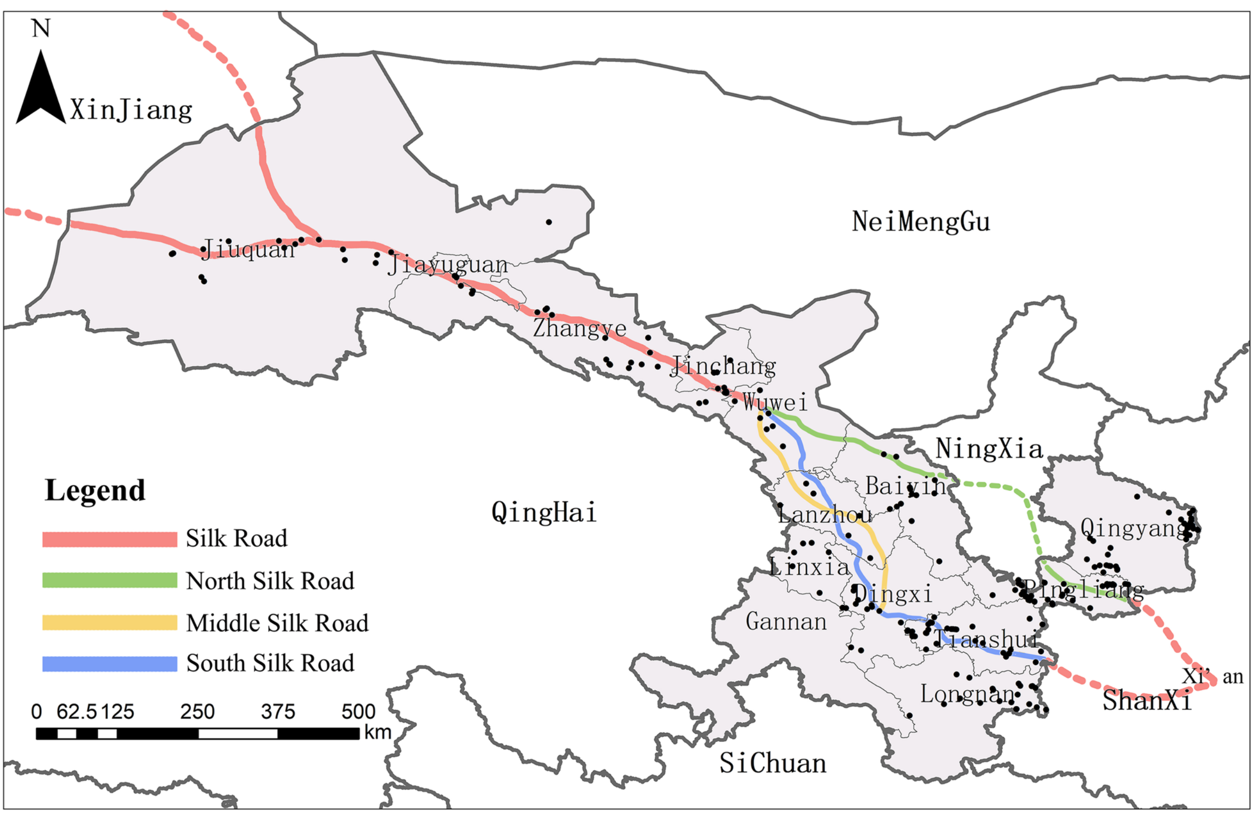

Fig. 9 Distribution of grottoes superimposed along the Gansu section of the Silk Road

remain an intrinsic part of daily life. Many small grottoes built during the Ming and Qing Dynasties are scattered throughout the country, thus widening the distribution of the four major grottoes in Gansu Province, namely, Hexi, Longzhong, Longnan and Longdong.

Traffic factors

Grottoes in Gansu Province are mainly distributed along the Silk Road, such as those in the Hexi Corridor, which are mainly distributed in the Qilian Mountains on the south side of the Silk Road. Longzhong Grottoes, Longnan Grottoes, and Longdong Grottoes are distributed along the southern, middle, and northern roads of the Qinlong section of the Silk Road, showing a gradual expansion trend from west to the east (Fig. 9). This growth occurred because, following the formation of the Silk Road from the second century BC to the first century AD, this section became an important channel for the trade of goods between China and the West [53]. In numerous cultural exchanges and disseminations, Buddhism became the main religion on the Silk Road after the third century, thus forming a large-scale and numerous cave heritage along transportation routes.

Based on the literature, the modern roads and railways in Gansu Province were filtered out, the main ancient roads were retained, and the buffer zone was analysed [54, 55]. The proportion of the number of grottoes within a buffer zone of 5 km was 71.54%, and then the number of grottoes began to decrease with increasing distance from the road, indicating that the roads have a certain agglomeration effect on human activities and have a close correlation with grotto excavation (Table 7).

Conclusions

This paper used GIS technology to analyse the relationship between the site selection of grotto cultural heritage and the geographical environment, as well as the space–time evolution law in different periods. The main conclusions are as follows:

(1) The distribution of grottoes in Gansu Province is condensed. The distribution of grottoes in the whole region is uneven and ranges from concentrated to highly concentrated, and the grottoes are centred in the main gathering area of Pingliang city–Tianshui city and the secondary gathering area of Zhangye city–Baiyin city. The overall density shows a spatial distribution pattern that gradually decreases from the eastern and southern regions of Gansu to the inland regions of Hexi.

(2) There is an imbalance in the timing of grottoes in Gansu Province, and the number of grottoes preserved since the Ming and Qing Dynasties has changed significantly. The Northern and Southern Dynasties, the Sui and Tang Dynasties, and the Ming and Qing Dynasties had the largest number, accounting for 73% of the total number, while the Wei, Jin, Song and Yuan Dynasties had a small number. During these eight periods, the overall central location of the grottoes showed a shift from the northwest to the southeast, moving a total of 1327 km.

(3) The natural geographical environment, topography, lithology and hydrology play important roles in the distribution of grottoes in Gansu Province. The vast majority of grottoes are distributed within an elevation range of approximately 1000–1500 m. Once the elevation exceeds 1500 m, the number of grottoes decreases with increasing height; 90.7% of the grottoes are within 3 km of the river. With increasing distance, the number of grottoes decreases.

(4) In terms of human geography, the political environment and traffic route factors greatly impact the distribution of grottoes in Gansu Province. As the political power centre changed, the distribution centre of the grottoes moved. Grottoes are basically distributed along the Silk Road and show a trend of linear expansion from west to east.

Grotto heritage contains rich philosophical wisdom in the interaction between humans and nature and plays an indispensable role in the study of past social culture. Modern scientific informatization offers a new perspective for recognizing and exploring grotto heritage. A comprehensive understanding of grotto heritage in China and other countries and regions is the key to correctly utilizing this vast historical and cultural resource. Scientific technologies such as geographic information systems and water quality, soil, and meteorological data can be used to collect, organize, analyse, and display environmental data related to grotto heritage. These techniques can lead to a better understanding of the natural environmental conditions and changing trends and provide a scientific basis and decision-making support for the environmental protection of grotto heritage. Furthermore, GIS integration with data related to various natural disaster risks (earthquake, rainstorm, thunder and lightning) can provide disaster risk assessments, early warning releases and emergency responses, as well as technical support for protection.

Abbreviations

GIS	Geographic information system
DEM	Digital elevation model
SRTM	Radar Topography Mission

Acknowledgements
The authors would like to thank the anonymous reviewers and the editor for their very instructive suggestions that helped improve the quality of this paper.

Author contributions
YRZ: Methodology, software, validation, formal analysis, survey, data management, manuscript writing, submission, revision. All authors have read and agreed to the published version of the manuscript.

Funding
This work was supported by the National Social Science Foundation of China "Research on the value of cultural heritage of grottoes and temples in Gansu section of the Silk Road" (Grant No. 16XKG006).

Availability of data and materials
The data presented in this study are available from the corresponding author upon request.

Declarations

Competing interests
The authors declare that they have no competing interests.

Received: 14 March 2023 Accepted: 29 July 2023
Published online: 02 August 2023

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