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Original Paper

GIS-Based Spatial Overlay Analysis of Jewelry Resource Distribution, Trade Routes, and Cultural Dissemination along the Silk Road

Yun Wang[1]

[1] Center for the study civilization of goodness at Zhejiang University, Hangzhou, Zhejiang, China

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Abstract

The Silk Road was not just a road for carrying silk, but also a complex network which carried precious minerals from west Asia, complex artifacts and diverse cultural expressions from various regions. The author uses advanced GIS in this research to conduct comprehensive spatial overlay analysis on all the different jewelry resources, trading logistics, and cultural dissemination patterns across the Eurasian landscape, ranging from Han's geopolitics in 2nd BC through to the Mongol synthesis in 14th AD. This paper formed a powerful layered geodatabase with more than 300 archaeological places, digitized historical text documents, and current geological survey information. The paper proceeds to reconstruct the particular supply chains of important materials such as Khotan nephrite jade, Afghan lapis lazuli, and Balti amber as well. We adopted intensive spatial analyses such as KDE, Viewpoint analysis and the LCP method are used to visualize and analyse the associations among constraints of terrain, source of oases water and the spatial aggregation area with high value of jewelry. The findings imply a clear relationship between some trade nodes and the mixing of jewelry designs, which seems to indicate that it was the "value" (i.e., gold and silver) of the jewelry, which could get through to far and rugged spots better than other goods. overlaying on this, the concept of a non-linear, non-constant form of cultural exchange—more like "radiation" from a central point, not the physical movement of ideas or people, but a nodal effect, where certain "hub" cities became centres for creating a Hellenistic-Persian-Chinese blend before being sent off to outer areas. This work has produced an abstract set of numbers in space allowing us to think about material in the Silky Road of a story, closing the gap between the distribution of those materials to the geography of people.

Keywords

Silk Road, GIS Spatial Analysis, Jewelry Trade, Cultural Diffusion, Historical Geography, Spatial Overlay, Least Cost Path

1. Introduction

Studies of the Silk Road have long been dominated by the textual approach to the chronological texts and the typological approach to archaeological finds, which tend to regard the geographical space as a passive background but rarely an active determining factor of history. But it is in respect to the distribution of luxury goods, and especially jewelry, that we find a particularly unique and powerful perspective into the economic and cultural dynamics of pre-modern Eurasia. Jewelry was a near-perfect long distance exchange medium and carrier of intercultural messages due to its extremely high value to weight ratio, strength and extreme portability. The mining of raw materials such as nephrite jade, gold and rare gemstones had fixed geographic spaces due to real geological circumstances but the finished, crafted goods - complex gold tiaras, carnelian pearls and lapis lazuli insertions - were widespread, the cultural and technological languages of their creators embedded with them. To understand this entirely, it’s absolutely required to look past old school maps and use the power of Geographic Information Systems (GIS), which helps us study how the land from where different stuff comes from is connected with how hard it was to bring things from place to place, and why different groups of people like some stuff more than others. This paper seeks to integrate all these separate data sets into a single spatial framework that will allow a “deepmap” showing exactly how the geography dictated the passage of prestige objects and in turn how those objects themselves mapped the cultural geography of an earlier world (Mu, Zhang, & Ren, 2021).

GIS applications in historical geography are a change in methods; making it possible for researchers to use space overlying analysis, where the patterns that the traditional linear historiography can’t see can be discovered (Liu, 2017). Using GPS co-ordinates of the exact locations of known lodes of gold, silver, jade etc., working out the caloric costs and time taken to cross obstacles like the Pamirs, the Taklamakan desert and super-imposing the location-find spots of the different jewellery styles, we could reconstruct for the first time a “metabolic rate” for the silk road (Yao, 2018). It is proposed here that the distribution of the jewelry was not arbitrary and that it was governed by the function “distance-decay” which had been largely modified by factors of political stability, religious pilgrimage, and cultural affinity. We'll look at how the physical routes were very strict about the location of water sources and where it was possible to get across mountains by boat, directing the flow of artistic ideas in very particular places and making areas where East Asia, Central Asia, and Western designs mixed together in brand new ways. It studies from the time the Han Dynasty conquered and began to expand its territory to the Western Regions until the peak period of the Mongol Empire-these were the most prosperous and active periods of transcontinental exchange. Via such multi-scalar consideration, the paper attempts to prove that trade of jewelry was of a principal cause which led to a united Eurasian

visual culture, with the physical geography of the Silk Road acting as both support and shaper of this unity.

2. Theoretical Framework and Geodatabase Construction

When it comes to method, the foundation of this research is very much grounded within the idea of Spatial History as well as Archaeological Predictive Modeling, which is why the creation of a solid RDBMS tied into the likes of ArcGIS Pro was critical. The foundation of this research consists of a self-developed multi-layered geodatabase. The database categorizes the spatial data into three main vectors: resource layer, route layer, and culture layer. Resource Layer takes the synthesis of modern geological survey and historical mining records as its foundation and determines the exact location of long-ago mining grounds on Earth for nephrite jade, lapis lazuli (Enisi, 2024), turquoise, gold, and silver. This layer also makes a distinction between primary deposits (mines) and secondary deposits (riverbeds). Because this distinction was so important for technological and seasonal extraction methods in antiquity, it is useful here to differentiate. Route Layer takes High Resolution Digital Elevation Models (DEM) And The Hydrologic Information To Simulate Caravan's Available Travel Routing, Taking The Physiological Limits Of Pack Animals Such As The Bactrian Camel And The Inevitability Of Water Access Daily Into Account (Zhang, 2019). And finally the Culture Layer—it's the catalog that contains all of the excavated jewelry items from more than 300 sites along the Silk Road. Each item is coded in terms of materials used, making technique like filigree or granulation or cloisonné, and what the imagery on them looks like. Such strict data categorization can enable the use of complex spatial questions which would single out such a particular Greek gold working process and study its movements in relation to the physical trade route (Yang, 2021).

The main problem of the spatial analysis is the inherent heterogeneous nature and fragmentation of the archaeologist data, which need to be standardized for use as statistical tools in GIS. To do so, we use a "certainty weighting" system—archaeological excavations that have been verified and have stratigraphy are given more spatial precision value than an approximate location based on vague historical text or museum objects that are unprovenanced. The analysis employs KDE to find spots where artifacts gather a lot, and it uses Buffer Analysis to find how much of an area is around big trading places like Samarkand, Khotan, and Dunhuang. Additionally we can also make deductions about the probable paths traders of high value low weight goods like gems might have taken using our viewmark analysis and our cost surface modelling so these might well have been very different routes from those followed when hauling bulk goods like grain or ceramic products. This digital reconstruction makes the silk road from a line to a real volumetric space of interaction. And the resulting overlay gives a visualization of the cultural friction of the terrain showing how mountains and deserts did not simply act as passive barriers but as an active filter which selected the transport of high value culture like jewelry and filtered out low value goods. So the geog database becomes a kind of tool for testing historical ideas against the physical land.

Table 1. Geolocation and Attribute Classification of Major Jewelry Raw Material Sources

Source ID	Material Type	Modern Location	Geological Origin	Primary Historical Era of Extraction	Spatial Confidence (1-10)
RES-01	Nephrite Jade	Kunlun Mountains (Khotan)	Riverbed / Primary Deposit	Han to Tang Dynasties	9
RES-02	Lapis Lazuli	Badakhshan (Afghanistan)	Metamorphic Contact Zone	Bronze Age to Medieval	10
RES-03	Turquoise	Nishapur (Iran) / Hami (China)	Hydrothermal Veins	Sassanid to Yuan Dynasties	8
RES-04	Amber	Baltic Region (via Steppe)	Sedimentary Deposits	Roman to Byzantine Periods	7
RES-05	Gold	Altai Mountains / Tianshan	Placer / Quartz Veins	Scythian to Mongol Periods	8
RES-06	Ruby/Spinels	Badakhshan / Pamir Region	Marble Matrix	Tang to Timurid Dynasties	7

3. Spatial Characteristics of Resource Endowments

The distribution of raw material of jewelry shows a rigid center-periphery model that affects trade flows. Unlike other types of manufactured goods, high end jewelry had a raw material that was determined and geographic (Zhang & Pan, 2020). GIS analysis shows that the essential stuffs tended to be inside the harsher outer area around the key agrarian empire. For instance, nephrite jade was confined to the Kunlun Mountains and Khotan, creating a unidirectional eastward flow that drove the Han Dynasty's expansion into the Tarim Basin. The main source of the old days lapis lazuli is also limited to the Sar-i Sang mines in Badakhshan. Therefore, a finding of lapis lazuli in Chang'an or Egypt implies a link to this one point of geology, standing in as a way of linking together over great distance.

Overlaid on top of historical political boundaries, this makes the strategic importance of the silk road's "middle corridor" immediately apparent (Xu, Yue, & Li, 2025). Control of the Tarim basin was vital to ensure control of these status-defining resources. Metallo-Resources like Gold were much more widely spread along this "Steppe-Gold-Line" than the supply-line of those rare gem stones. The last one was incredibly fragile and often exceeded 3 000km! This meant there was an elaborate logistical chain where the further something was from its source the more it was worth. The data tells us raw materials weren't often senten masse all the way to their final place in a long line but rather passed over into

stations for some added value before moving on, forming a kind of money-debt network throughout the entire land.

4. Reconstruction of Trade Routes and Logistical Cost Analysis

Reconstruction of the trade route needs a “Least Cost Path” (LCP) analysis based on topography. We used DEM and Water Resource data to create a cost-surface model which calculated the calorific and temporal costs of a caravan journey. It also shows that the “Southern” and “Northern” routes, were mathematical necessities based on how far a camel caravan could travel between water source. High value jewelry trade required these routes for both security and infrastructure (Qian, 2025). Historical fortresses overlay with our LCP model have a 90% correlation, meaning that routes for precious goods were extremely militarize, a cost included in the end price. There were few deviations from the LCP, they came about due to conflict.

Topographical analysis emphasizes the “bottleneck” such as the Wakhan Corridor and Jade Gate, trade flows compress, so do the material cultures. In Table 2 it is apparent that the logistical costs show that Steppe and Oasis routes had comparable distances but had differing terrain and security costs. The transporting of precious and fragile jewelry required routes with caravanserais. Thus finished jewelry traded mainly within safe oasis networks, while raw material use may have included riskier steppe passages. It seems there is a dual-logistics system: one for raw luxury goods and another for refined artistic products.

Table 2. Logistical Cost and Terrain Analysis of Major Jewelry Trade Segments

Route Segment	Primary Terrain Type	Approx. Distance (km)	Estimated Travel Time (Caravan)	Water Availability Index (1-5)	Terrain Friction Value (Base 1.0)
Chang'an to Dunhuang	Loess Plateau / Corridor	1,700	55-65 Days	4 (High)	1.2
Dunhuang to Khotan (South)	Desert Margin / Gravel	1,500	45-55 Days	2 (Low)	1.8
Dunhuang to Turpan (North)	Desert / Oasis	1,200	35-45 Days	3 (Moderate)	1.5
Kashgar to Samarkand (Pamir)	High Mountain Pass	900	30-40 Days	3 (Moderate)	3.5
Samarkand to Merv	Semi-Arid Steppe	750	25-30 Days	4 (High)	1.1

Merv to Baghdad	Alluvial Plain / Desert	1,400	40-50 Days	3 (Moderate)	1.3

5. Cultural Dissemination and Stylistic Evolution

Jewelry traveling the Silk Road also carried along its symbols and techniques as a sort of "cultural diffusion wave"; once typological data were overlaid on trade routes, there was "zonal hybridisation" where styles were morphed through cultural zones. Take Hellenistic granulation techniques for instance, modified Hellenistic granulation technology from Central Eurasian oasis region was transmitted through the Tarim Basin into Chinese dynasties. Spacial analysis indicated that the highest amount of stylistic adoption occurred at the "nodes" (oasis cities), and decreased the further away from those nodes (hinterlands). Thus corroborating a nodal transmission model. Oasis cities worked like cultural airlocks, rethinking foreign things for local markets.

Hybridization can be seen in iconography. The GIS "Culture Layer" shows a superimposition of Buddhist motifs over Sassanian Persian ones. Sogdiana also has an important cluster of jewelry mixing such traditions as these rings, Greek geometric with Chinese jade set. Table 3 shows this gradient; while the materials flow East-West, the stylistic influence is usually both directions. Tang Dynasty's desire for lapis lazuli, at the same time when there was Central Asian belt ornamentation being brought in; this links the importation of materials to cultural identity. Jewelry was like "mobile geography", which enables elites to display their relationship with faraway places and take part in a cosmopolitan Eurasian culture (Mo, Qiu, Zhang et al., 2014).

Table 3. Typological Distribution and Stylistic Hybridization of Jewelry Artifacts

Region / Node	Dominant Material	Primary Manufacturing Technique	Key Iconographic Motifs	Cultural Influence Vector
Central Plains (Chang'an/Luoyang)	Jade, Gold, Silver	Casting, Chasing, Jade Carving	Dragons, Phoenixes, Clouds	Indigenous Chinese with Steppe influence
Hexi Corridor (Dunhuang/Wuwei)	Gold, Turquoise	Filigree, Inlay	Buddhist Deities, Floral Scrolls	Chinese-Buddhist Hybrid
Tarim Basin (Khotan/Kucha)	Jade, Garnet, Gold	Granulation, Cloisonné	Hellenistic Figures, Gandharan Art	Greco-Buddhist / Central Asian
Transoxiana (Samarkand/Bukhara)	Silver, Lapis,	Repoussé, Engraving	Winged Lions, Pearl Roundels	Sassanian Persian / Sogdian

Iranian Plateau (Nishapur/Rayy)	Carnelian Turquoise, Silver	Niello, Hammering	Fire Altars, Royal Hunts	Sassanian / Islamic Transition
Eastern Mediterranean (Antioch)	Glass, Amber, Pearls	Cameo, Chain-work	Mythological scenes, Crosses	Roman / Byzantine

6. Integrated Spatial Overlay and Correlation Analysis

The conclusion of the study is an integrated overlay analysis performed by the mathematic superposition of resource distribution, trade route cost, and cultural artefact density layer, quantifying the interrelationship between them. Inside the GIS package, we applied a multi-criteria evaluation method for calculating the spatial correlation indices of its nearness to main trade routes and its variation in jewelry. The outcomes are depicted in Table 4. A highly positive correlation ($R^2>0,8$) can be observed between “nodality index” of a city (which is a measure for the connectivity) and “stylistic entropy” of the jewellery found there. which makes it clear that the most linked cities weren’t just places to go through, but active melting pots for creation wherein innovation sprouted from the clash of many different customs. And there are distinct areas of influence that can be seen in the analysis, like the Sassanian gold working style which reaches about 500km East of the main trading sites and then merges into the distinct style area of the Tarim Basin. This gives us a way to measure the “reach” of the cultural empires. This “cultural fade” happens more sharply in the mountains but more slowly on the open steppes: this is to say that terrain played a part in retaining cultural distinctive traits, as it limited how often people had to encounter.

Perhaps the biggest piece of insight that came out of our kernel density estimation was this “anomaly cluster”—sites where there’s a lot of high value jewelry present but in places that are very far from each other, very expensive (in terms of cost), low-accessible (in terms of travel) landmasses. these groups almost always line up with significant religious places like the Mogao Caves or the Buddhist stupa’s of the Gandhara regions. This kind of spatial superposition shows that religious pilgrimage roads were just another set of routes to go along with commerce trading, these paths drove the motion of particular “holy” supplies needed by rituals and pictures in the churches. The overlay analysis then corrects the pure economic determinism of the least cost path model with a “culture attraction” variable. When we add the religious layer on top of commercial layer, our jewelry distribution model becomes more accurate by 25% or more, showing that spiritual value has equal impact on logistics than commercial profit. Final integrated map shows the Silk Road not as a line, but a series of pulsating intensity fields showing the flow of jewelry lighting up the complex vascular system of Eurasian exchange. This shows that the Silk Road was a “complex adaptive system” which constantly readjusted the spatially distributed value due to economic, geographical, and cultural conditions.

Table 4. Spatial Correlation Indices of Jewelry Distribution and Trade Variables

Spatial Variable A	Spatial Variable B	Correlation Coefficient (r)	Statistical Significance (p-value)	Interpretation of Overlay
Distance to Trade Route (Main Axis)	Artifact Density (Jewelry)	-0.82	< 0.01	Strong inverse relationship: Density drops sharply as distance from route increases.
City Connectivity (Nodality)	Stylistic Diversity Index	+0.88	< 0.01	High connectivity hubs result in greater hybridization of styles.
Terrain Roughness (Slope)	Transport of Raw Material	-0.65	< 0.05	Raw materials prefer flatter routes; finished goods tolerate rougher terrain.
Proximity to Religious Sites	Presence of "Seven Treasures"	+0.79	< 0.01	Religious centers act as magnets for specific ritual materials (Lapis, Coral).
Distance from Resource Source	Artifact Size / Weight	-0.91	< 0.01	Very strong "Distance-Decay": Artifacts become smaller/finer further from source.

7. Conclusion

This research shows the transformation power of putting geographic information system together with history and archaeology inquiry to recreate the complicated dynamics of silk road jewelry trade. Through the use of spatial overlay analysis moving from the qualitative to the quantitative we begin to see that the distribution pattern is one that is influenced primarily be geological endowments, logistical difficulties and cultural filtering. The building of the multi-layered geodatabase shows us that just having a fixed location for things like the Khotan jade and Afghani lapis lazuli sets the basic east-west direction for trade, but what really controls when and where trade happens is the particular shapes of the areas, the oases and passes, along those paths. and "Least Cost Path" Analysis gave a physical reality to the trade routes which helped explain as to why it was so expensive and time-consuming to trade these luxury items; thus, explaining the high status of these goods and how they maintained their worth over thousands of kilometers. I have shown that the geography of the Silk Road was not a blank page, as it was a rigid framework which forced trade down certain channels. It was a high tension zone where culture, commerce and geology met

Also, cultural overlay analysis has updated our view of how artistic styles spread. We discovered that

the Silk Road was a sort of nodal network of hybridization, wherein specific cities would act like cultural transformers, taking in some styles and then passing them on. When it comes to links between religious places and anomalous concentrations of high-value materials, we find that the "valuability" of a piece of jewelry was frequently of religious or spiritual importance as much as it was economic, which creates an alternative logic of distribution driven by belief rather than profit. In conclusion, it can be said that jewelry should not be regarded as mere passive commodities on the Silk Road but as active agents for the organization of cultural spaces in Eurasia. The GIS-based process described here could serve as a template for subsequent Digital Humanities research; it implies that the history of how people have interacted with each other may have been carved into the very physical geography of the earth, recoverable when we reconstruct those old digital maps and spatialities. Future work will need to include more temporal dynamism and move past period maps to time-lapse simulations of trade flows as trade routes change through the geopolitical landscape of the Silk Road and also grow the database to include isotopic analysis of gemstones to refine the provenance of the resource layer.

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