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Evidence from Liao dynasty tombs: an empirical analysis of song greenish-white porcelain trade

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This study analyzes 16 pieces of greenish-white porcelain unearthed from the Hongjiajie cemetery, the family burial site of Han Derang of the Liao Dynasty in Beizhen, Liaoning. Using energy-dispersive X-ray fluorescence (EDXRF) and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), the chemical compositions of the bodies and glazes were examined. The results show a high-silica, low-alumina profile typical of southern Chinese kilns and strong compositional similarity with the Hutian Kiln in Jingdezhen. The glazes are calcium-based, and their MnO and P_2O_5 features correspond to Northern Song Hutian greenish-white ware. Trace and rare earth element patterns further confirm the Hutian provenance. Synthesizing analytical, historical, and archaeological evidence, the study suggests these ceramics reached the Liao realm via maritime trade, reflecting the close economic and cultural exchanges between northern and southern China during the mid-to-late Liao period.

The Beizhen region in Liaoning Province, situated on the eastern foothills of the Yiwulü Mountain (see [Fig. 1]), was a significant burial ground for high-ranking nobles of the Liao Dynasty (916–1125AD). Recent archaeological excavations in this area have provided substantial material evidence and a research foundation for deepening our understanding of Liao political structures, burial customs, and material culture. The Hongjiajie cemetery is located on a hillside northwest of Hongjiajie village in Futun Subdistrict, Beizhen City, Jinzhou City, Liaoning Province. From 2015 to 2017, with approval from the National Cultural Heritage Administration, the Liaoning Provincial Institute of Cultural Relics and Archaeology, in collaboration with the Jinzhou Municipal Institute of Cultural Relics and Archaeology and the Beizhen Cultural Relics Office, conducted rescue excavations and peripheral surveys of the Hongjiajie cemetery. Four tombs (M1–M4) were excavated[1], Based on the epitaphs unearthed for Yelü Longyun (Han Derang[2], Yelü Hongren[3], and Yelü Hongli[4], combined with the spatial arrangement of the tombs, the site was conclusively identified as the family cemetery of the eminent Liao minister Han Derang. The four tombs span the period from 1011 CE (mid-Liao) to 1096 CE (late-Liao)[5]. Archaeological findings confirm that the Hongjiajie cemetery belonged to the most important subsidiary burial complex associated with the Liao imperial mausoleums at Yiwulü Mountain. Although repeatedly looted, the cemetery yielded abundant burial goods, predominantly ceramics, including various types such as greenish-white porcelain (qingbai ware). These finds provide crucial primary materials for researching Liao Dynasty ceramics and their circulation through trade networks.

During the Song-Liao period, ceramics as significant handicraft products of economic exchange, entered Liao territory from Song territory through tributary missions, customs-regulated market trade, and private trade. Following the prevalence of the "Hua–Yi Tongfeng" concept, literally, harmony between Hua (Han) and Yi(non-Han) cultures, from the mid-Liao period onward, the Khitan nobility exhibited a notable trend towards cultural assimilation and adoption of Han Chinese lifestyles. Archaeological evidence indicates a marked increase in the quantity of greenish-white porcelain within Liao territories after the mid-11th century. Tea wares, such as cup stands, conical bowls, and incense utensils, gradually replaced traditional vessels like the jars with cockscomb-shaped lugs, reflecting a shift in the lifestyle and preferences of the Khitan aristocracy[6]. Regarding the import routes of porcelains from Song territory, scholarly consensus points to the existence of both overland and maritime pathways[7]. Prior to the mid-Liao period, overland trade via official border markets was dominant; by the late Liao period, maritime transport likely became the primary route, with southern merchant ships reaching Liao territories via the Grand Canal, Huai River, and Bohai Bay[8]. The study of greenish-white porcelain excavated from Liao sites provides crucial empirical data for understanding trade interactions between the Song and Liao. Previous research on excavated ceramics has largely relied on archaeological typology and lacks support

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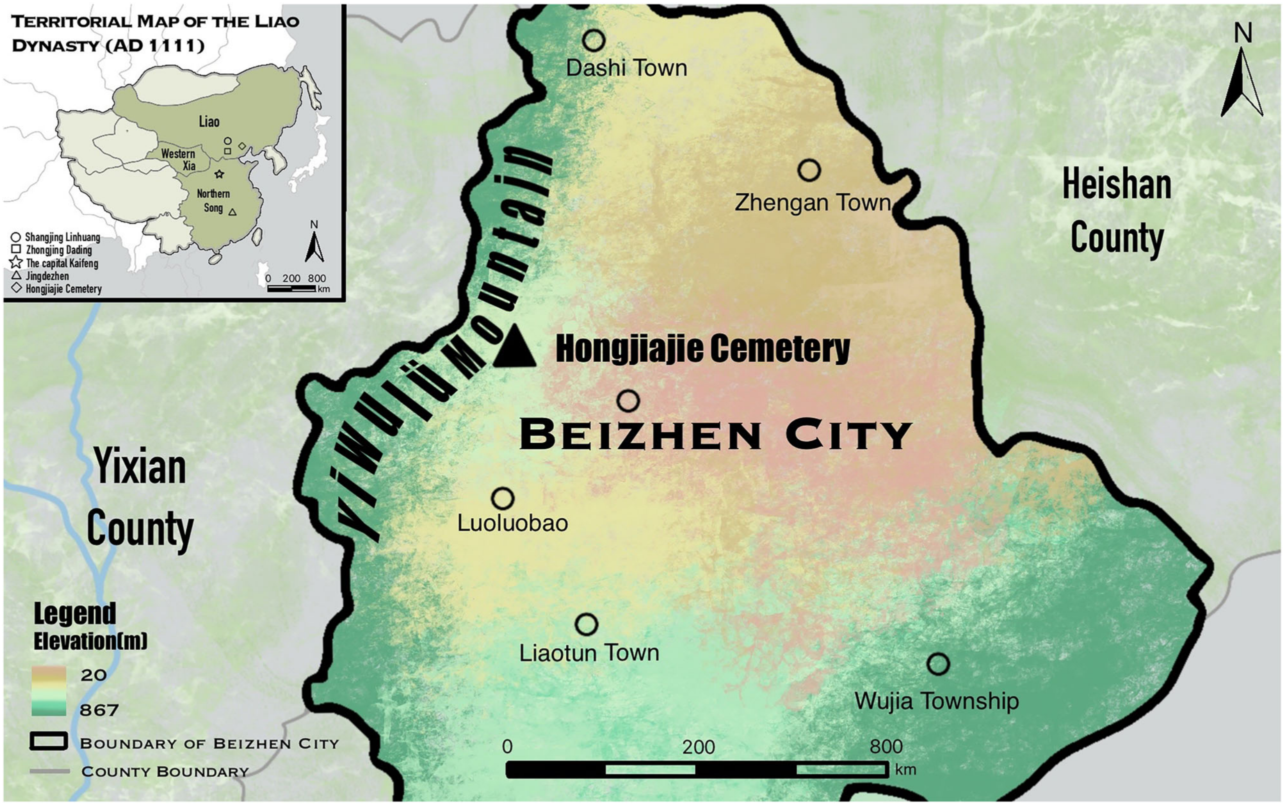

Fig. 1 | Map showing the location of the Hongjiajie cemetery in Beizhen, Liaoning.

from systematic scientific data. In recent years, a growing number of technical means have been applied to the analysis and study of greenish-white porcelain[9–11]. Furthermore, the introduction of elemental analysis techniques into archaeological research has opened the way for provenance studies of burial ceramics[12–15], by integrating the distinct geochemical composition of artifacts with factor analysis of their chemical components to determine their possible provenance[16–18]. Utilizing scientific techniques to determine the provenance of excavated ceramics is a vital direction in archaeological science, as the major and trace element compositional signatures of porcelains from different kilns provide a "chemical fingerprint" for identifying their origin[19,20].

Against this backdrop, the greenish-white porcelain excavated from the Hongjiajie cemetery serves as direct evidence of the consumption of southern ceramics by the upper echelons of the Liao aristocracy. Determining its precise origin and circulation routes is therefore crucial for understanding the dynamics of north-south trade and ceramic consumption patterns during the Song-Liao period. To address these questions, this study selected 16 greenish-white porcelain samples from the Hongjiajie cemetery, photographs of representative samples are shown in [Fig. 2]. We conducted a non-destructive, systematic analysis of the major and trace element composition of their bodies and glazes using a combination of energy-dispersive X-ray fluorescence (EDXRF) and laser ablation-inductively coupled plasma mass spectrometry (LA-ICP-MS). The resulting data were compared with reference materials from known kilns through multivariate statistical methods to scientifically determine their production origin. By synthesizing analytical results with historical and archaeological evidence, this study reconstructs the trade networks that distributed greenish-white porcelain between Song and Liao territories, providing new scientific evidence for understanding Liao-period ceramic trade and multi-ethnic exchange.

Methods

Sixteen samples of greenish-white porcelain were analyzed using energy-dispersive X-ray fluorescence (ED-XRF) spectroscopy and Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) in this study. While ED-XRF was employed to determine the major elements[21,22], LA-ICP-MS was used to measure the trace elements for provenance identification[23–25]. Sample details are presented in Table S1. All samples were excavated from the Hongjiajie cemetery M1–M4 (during the mid-to-late Liao Dynasty) in Beizhen, Liaoning, and were provided by the Liaoning Provincial Institute of Cultural Relics and Archaeology.

Energy-dispersive X-ray fluorescence

Prior to analysis, all specimens were cleaned in a CQ-250 ultrasonic cleaner for 20 min and dried in a 101–1 electric forced-air drying oven. Subsequently, the major and minor elemental composition of the ceramic bodies and glazes from the Hongjiajie unearthed greenish-white porcelain samples was analyzed using an Eagle-III energy-dispersive X-ray fluorescence (ED-XRF) spectrometer (EDAX Inc., USA) at the Institute of Ancient Ceramic, Jingdezhen Ceramic University. The measurements were performed with a beam spot size of 300 μm, an tube voltage of 50 kV, and a tube current of 200 μA. The analytical results are presented in Table S2 and Table S3.

Laser ablation inductively coupled plasma mass spectrometry

Analysis was conducted at Createch Testing Tianjin Technology Co., LTD. using an Analytik Jena PQMS ICP-MS system coupled with a RESOLution 193 nm excimer laser ablation unit. Laser ablation was performed with a beam diameter of 40 μm, a repetition rate of 5 Hz, and an energy density of approximately 5.5 J/cm^2, using high-purity helium as the carrier gas. Prior to formal analysis, the instrument was tuned and optimized using the NIST 610 reference material to ensure optimal performance.

The LA-ICP-MS analysis employed a single-spot ablation mode. Each analysis consisted of a 15-second background acquisition (laser off), followed by a 45-second sample data acquisition period during which the laser was fired, and concluded with a 25-second washout period to purge the system. The total analysis time per spot was 85 s. To ensure data quality and enable quantitative calibration, a set of reference materials (NIST 610, NIST

Fig. 2 | Representative specimens of Greenish-white porcelain from the Hongjiajie cemetery.

612, BHVO-2G, BCR-2G, BIR-1G) was analyzed after every 10 unknown sample ablations[26]. Offline data processing, including signal selection for both sample and background, correction for instrumental sensitivity drift, and quantitative element concentration calculation, was performed using the software ICPMSDataCal[27,28]. The results are presented in Table S4 and Table S5.

Results

Major and minor elements of the bodies and glazes of greenish-white porcelain from the Hongjiajie cemetery

The EDXRF results showing major and minor oxide composition of the ceramic bodies of the greenish-white porcelain excavated from the Hongjiajie cemetery are presented in Table S2. The chemical analysis reveals SiO_2 contents ranging from 75.12% to 78.25% (mean: 76.99%) and Al_2O_3 contents between 16.15% and 18.81% (mean: 17.15%). This high-silica, low-alumina composition is typical of porcelain stone clays found in southern China. The mean concentrations of other major oxides are as follows: Na_2O at 0.69%, K_2O at 2.72%, CaO at 0.54%, MgO at 0.57%, Fe_2O_3 at 0.78%, and TiO_2 at 0.03%.

Major and minor oxide composition and the calculated b* values of the ceramic glazes of 16 samples are presented in Table S3. The glazes of the greenish-white porcelain from the Hongjiajie cemetery exhibit SiO_2 contents ranging from 67.59% to 76.14% (mean: 71.37%), Al_2O_3 from 11.25% to 14.72% (mean: 12.53%), and notably high CaO between 8.57% and 13.58% (mean: 11.01%). The combined mean content of Na_2O and K_2O is relatively low, at 2.66%. According to the classification standard for calcium-based glazes[29], the calculated b* values of the samples' glazes are all greater than 0.76, identifying them as typical "calcium glazes"[30,31]. Additionally, the glazes contain certain levels of MnO (mean: 0.06%) and P_2O_5 (mean: 0.22%), suggesting the possible use of plant ash as a raw material in the glaze formulation[32]. Further study is required to determine in what form the plant ash was introduced[33–35].

Trace elements of the greenish-white Porcelain from the Hongjiajie cemetery

To precisely trace the provenance of the greenish-white porcelain excavated from the Hongjiajie cemetery, this study employed laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) to analyze and compare the trace element compositions of these sherds with reference specimens from the Northern Song Hutian Kiln. Table S4 presents the LA-ICP-MS results for 41 trace elements in the bodies of the greenish-white porcelain from the Hongjiajie cemetery. For comparison, Table S5 provides the corresponding analytical data for the Northern Song Hutian Kiln reference specimens, which were obtained from the collection of the Ancient Ceramics Research Institute at the Jingdezhen Ceramic University.

Discussion

Greenish-white porcelain as a representative product of the Song Dynasty (960-1279AD), was primarily manufactured at the Jingdezhen kiln complex, with additional production centers including the Kejiachong kiln in Fanchang, Anhui, and the Qingshan kiln in Wuchang, Hubei[36]. Prior scientific research on ancient Chinese greenish-white porcelain has produced a substantial body of research focused on chemical composition analysis. For example, Wu et al.[37], Yang et al.[38], Chen et al.[39] studied the chemical composition of the greenish-white porcelain in different areas of China by using various advanced techniques. Based on these data, principal component analysis (PCA) was conducted using Origin software to compare the body compositions of the Hongjiajie greenish-white porcelain with reference data from several kiln sites in the Song dynasty: the Hutian Kiln in Jingdezhen[37], the Fanchang Kiln in Anhui[38], and the Qingshan Kiln in Wuchang, Hubei[39].

The results, presented in [Fig. 3], show that the first two principal components (PC1 and PC2) explain 62.4% of the total variance (PC1: 39.7%, PC2: 22.7%), adequately representing the major compositional features. The sample plots demonstrate clear separation trends with good intra-group clustering, indicating satisfactory analytical reproducibility. Specifically, the data points for the Hongjiajie and Hutian Kiln samples cluster closely within the negative region of PC1, revealing their proximity in principal component space and suggesting similar compositional characteristics. In contrast, samples from the Fanchang and Qingshan Kilns are distributed within the positive region of PC1, showing significant separation from both the Hongjiajie group and from each other. These results indicate that the bodies of the Hongjiajie greenish-white porcelain share a high degree of compositional similarity with those from the Northern Song Hutian Kiln in Jingdezhen. The close clustering observed in the PCA plot suggests that the greenish-white porcelain unearthed from the Hongjiajie cemetery likely originated from the Hutian Kiln in Jingdezhen.

Previous research on Northern Song (960–1127AD) Hutian greenish-white glazes indicates that the scatter plot of MnO versus P_2O_5 for this period is relatively dispersed compared to Southern Song (1127–1279AD) glazes, implying that the glaze recipe might still have been in an experimental phase[37]. [Fig. 4] presents a bivariate plot of MnO and P_2O_5 contents for the Hongjiajie glazes alongside those from Northern and Southern Song

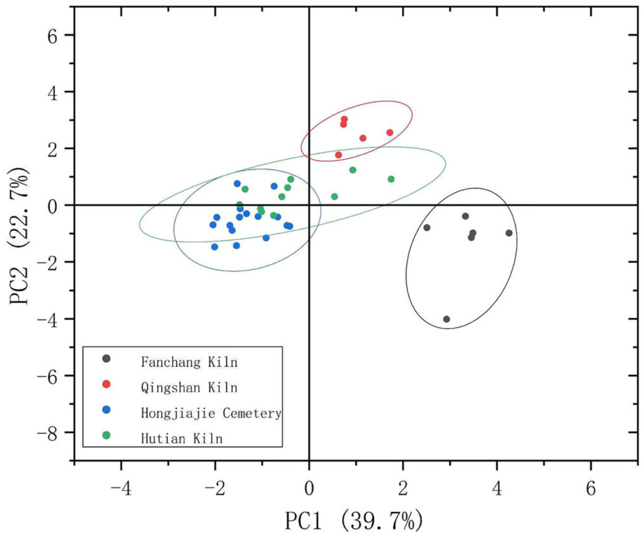

Fig. 3 | Principal Component Analysis (PCA) of Greenish-White Porcelain Body from the Hongjiajie Cemetery and Selected Southern Chinese Kilns. Black solid circles represent Fanchang Kiln, red solid circles represent Qingshan Kiln, blue solid circles represent Qingbai porcelain unearthed from Hongjiajie, and green solid circles represent Hutian Kiln.

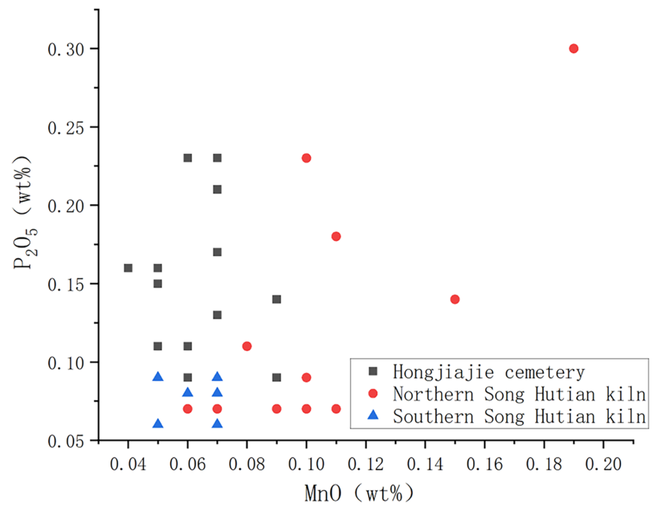

Fig. 4 | Bivariate plot of MnO and P2O5 contents in glazes from the Hongjiajie cemetery and the Northern vs. Southern Song Hutian kiln. Black squares represent Qingbai porcelain unearthed from Hongjiajie, red circles represent Hutian Kiln Qingbai porcelain from the Northern Song Dynasty, and blue triangles represent Hutian Kiln Qingbai porcelain from the Southern Song Dynasty.

Hutian glazes. The Hongjiajie data also show a dispersed distribution, sharing a similar pattern with the Northern Song Hutian glazes.

Trace elements occur at very low concentrations in ceramic bodies and are generally less affected by processing techniques such as deliberate levigation or conscious recipe modification. Consequently, they more reliably preserve the original geochemical signature of the raw clay material. Porcelain stone deposits from different regions form under specific geological settings, resulting in distinct trace element assemblages—often referred to as "chemical fingerprints"—that exhibit significant regional specificity. By systematically analyzing the trace element composition of ceramic samples and comparing them with reference data from potential production areas, it is possible to effectively differentiate products from various kilns and achieve precise provenance determination[40].

Although processes such as levigation in ceramic production can alter the content and distribution of certain elements (e.g., reducing concentrations of Ti and REEs during raw material preparation), elements that are primarily enriched in clay minerals, such as Li and Cs, as well as ratios of certain stable elements such as Nb/Ta and Zr/Hf, remain nearly unchanged during physical processing[41]. These stable indicators can thus directly reflect the geological background of the raw materials[42,43]. As shown in [Fig. 5], which presents scatter plots comparing selected trace elements and elemental ratios between the Hongjiajie greenish-white porcelain and Hutian Kiln greenish-white porcelain, the distributions of key pairs—such as Li versus Cs and the ratios of Nb/Ta and Zr/Hf— show that data points from both sources largely overlap.

Owing to their stable geochemical properties, rare earth elements (REES) are typically presented in sequence of increasing atomic number (which corresponds to increasing atomic mass and decreasing ionic radius). Cheng et al.[9] utilized instrumental neutron activate analysis (INAA) to indicate the differences of REEs pattern of greenish-white porcelain body from Hutian Kiln in different Dynasty. Li et al.[44] discriminated between Husi kiln and Jingdezhen greenish-white porcelains through LA-ICP-MS analysis of their trace element signatures. To mitigate analytical biases caused by the high isotopic abundance of other elements, the REE content data for the greenish-white porcelain from both the Hongjiajie cemetery and the Hutian Kiln were normalized using the composition of chondritic meteorites as a ref. 45. In the chondrite-normalized REE distribution pattern shown in [Fig. 6], the Hongjiajie greenish-white porcelain exhibits a pattern strikingly similar to that of the Hutian Kiln samples, characterized by relative enrichment of light rare earth elements (LREE), a relatively flat pattern for the heavy rare earth elements (HREE), and a pronounced negative Eu anomaly. This highly consistent REE distribution pattern strongly indicates that the raw materials used for these samples originated from the same geological unit or shared a common source. Combined with the concentrations and ratios of the majority of trace elements, this evidence confirms that the greenish-white porcelain unearthed from the Hongjiajie cemetery was produced at the Hutian Kiln in Jingdezhen.

During the Song-Liao period, ceramics as representative products of the Song economy and handicraft industry, entered Liao territory through tributary missions· customs-regulated market trade (Quechang), and private trade. Archaeological evidence indicates a marked increase in the quantity of greenish-white porcelain found at Liao sites after the mid-11th century, accounting for approximately one-quarter of the total porcelain excavated from tombs and pagoda foundations[6]. Types such as cup stands, conical tea bowls, incense burners, and powder boxes became increasingly prevalent, while traditional Khitan vessels like the cockscomb-shaped jar (Jiguanhu) gradually declined. This shift reflects a transformation in the lifestyle of the Khitan aristocracy, moving from a nomadic "relying on carts, horses, and dairy" existence towards more refined, Han-influenced practices such as tea drinking and incense use[7]. From the Northern Wei period onward, the Khitan nobility demonstrated a tendency to assimilate Han Chinese culture, with multicultural traditions gradually becoming a marker of their identity[46,47]. As recorded in the *Continued Comprehensive Mirror to Aid in Governance*, "as for institutions, rituals, food, drink, clothing, and pastimes, they have fully adopted Han customs"[48]. After the mid-Liao period, promoted by the concept of "Hua-yi Tongfeng" (Harmonious Culture between Han and Non-Han), the Khitan elite exhibited a significant trend of Sinicization in cultural identity and daily practice. Economically, official border markets and private trade between Song and Liao facilitated the exchange of technology, goods, and customs[49], notably reflected in the consumption of central and southern Chinese ceramics. The presence of greenish-white porcelain in all four tombs at the Hongjiajie cemetery further confirms the widespread use of southern ceramics among the Liao nobility.

Regarding the trade routes through which ceramics entered Liao territory, scholarly consensus holds that their inflow occurred primarily after the signing of the Chanyuan Treaty in 1004 through diplomatic missions and commercial exchanges between Song and Liao dynasties[6]. The first route was overland. Before the mid-Liao period, porcelain from the Central Plains, represented by Ding ware white porcelain, entered mainly through

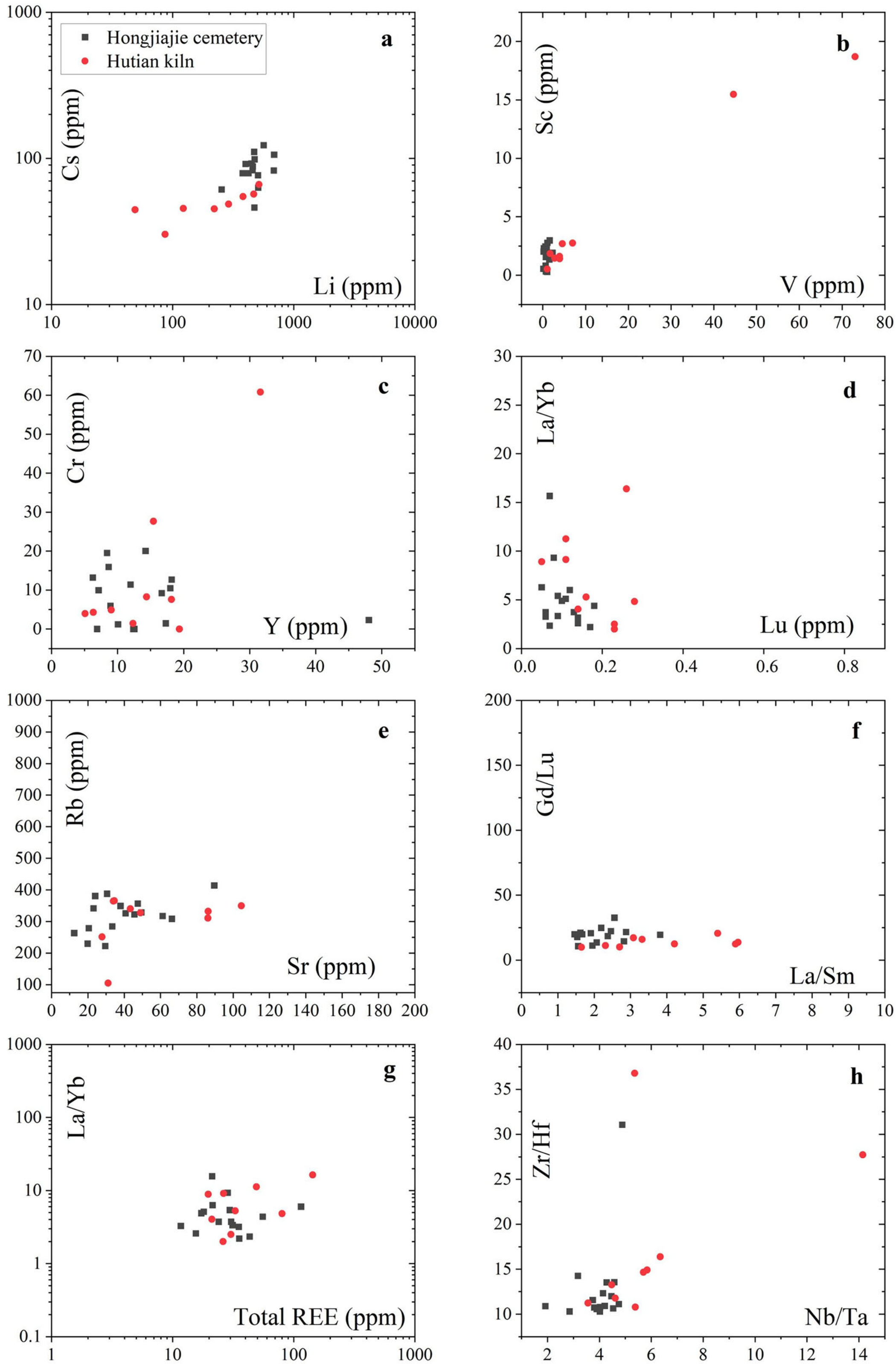

Fig. 5 | Comparison of ICP-MS trace elements contents or ratios among bodies of greenish-white porcelain from the Hongjiajie cemetery and Hutian Kiln of the Northern Song Dynasty (960–1127AD). (**a**) represents the distribution of Li and Cs; (**b**) represents the distribution of V and Sc; (**c**) represents the distribution of Y and Cr; (**d**) represents the distribution of the ratios Lu/La/Yb; (**e**) represents the distribution of Sr and Rb; (**f**) represents the distribution of the ratios La/Sm and Gd/Lu; (**g**) represents the distribution of Total REE and the ratios La/Yb; (**h**) represents the distribution of the ratios Nb/Ta and Zr/Hf.

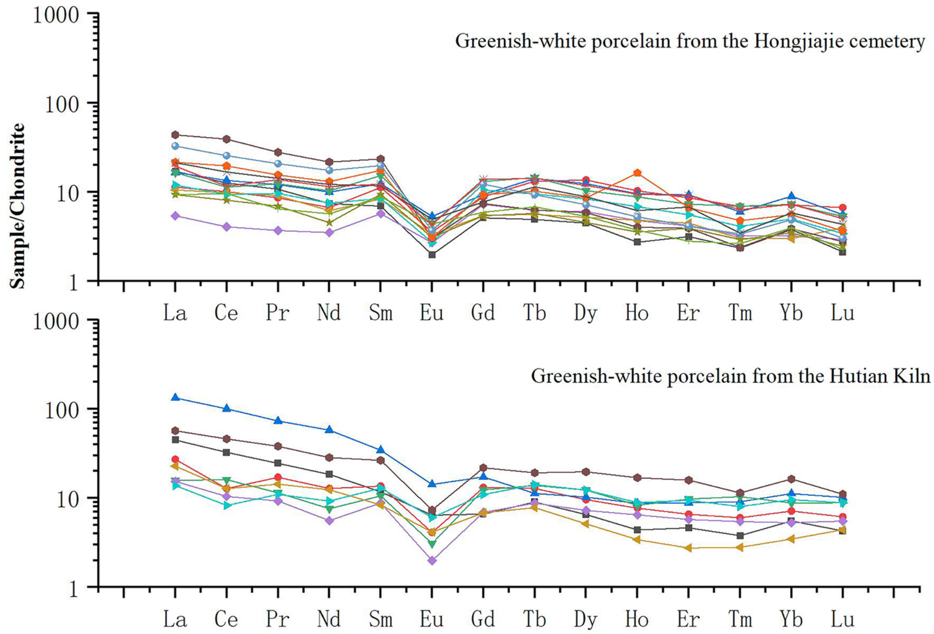

Fig. 6 | Chondrite-normalized rare earth element (REE) distribution patterns of greenish-white porcelain from the Hongjiajie cemetery and the Hutian Kiln.

official border markets or via unofficial smuggling along the Song-Liao frontier. During this phase, greenish-white porcelain had already begun to appear in the Liao territory[50]. The earliest tomb at the Hongjiajie cemetery dates to the mid-Liao period, around 1011 CE. Given its high-ranking aristocratic status, it is possible that some of the Qingbai ware from this tomb entered Liao territory through official border-market trade. The second route emerged as a maritime pathway during the late Liao period. Peng[6] argues that the sharp increase in greenish-white porcelain found in Liao tombs from the mid-11th to early 12th century—contrasted with its scarcity at contemporaneous Northern Song sites in the Central Plains—suggests maritime trade by Northern Song merchants as the primary mode of importation. This interpretation is supported by historical prohibitions against maritime smuggling. For instance, the *Song Huiyao · Xingfa II* (Penal Code of Nothern Song Dynasty) records: "In the fourth year of the Zhenghe era (1114 AD) under Emperor Huizong, merchants who engaged in maritime trade without obtaining official permits… shall receive double penalties if their destination is the Liao kingdom"[51]. There are also accounts of merchants "falsely obtaining permits for Goryeo but instead setting sail to conduct trade in the Liao"[7]. Based on discoveries of greenish-white porcelain at multiple sites on the Shandong Peninsula, Huang[8] proposed a possible maritime route for late Liao-period Jingdezhen wares: from Jingdezhen down the Changjiang River to Poyang Lake, down the Yangtze River to the lower Yangtze plain, entering the Grand Canal for north-south distribution; then from Yangzhou northward via the canal to Chu Prefecture, exiting to the sea via the Huai River, proceeding north to Haizhou and Dengzhou, and finally sailing along the Bohai Bay to Liao territory. Xue[52] systematically examined the maritime trade of Song and Yuan greenish-white porcelain, revealing the flourishing scale and significant impact of its export trade. Scientific analyses, including the trace element and REE distribution data from the greenish-white porcelain excavated at the Hongjiajie cemetery, confirm its origin as the Hutian Kiln in Jingdezhen. In the context of the prosperous maritime ceramic trade in the Northern Song period[53]. Given the considerable distance between Beizhen in Liaoning and Jingdezhen in Jiangxi, maritime transport utilizing the Yangtze River and eastern coastal waterways—compared to overland transit through multiple regions—would have offered significant advantages in efficiency and cost-effectiveness, aligning more closely with the economic logic of bulk ceramic trade.

In summary, this study confirms—through archaeometric analysis—that the greenish-white porcelain excavated from the Han Derang family cemetery of the Liao Dynasty originated from the Hutian Kiln in Jingdezhen. As a high-status Liao aristocratic burial, the presence of these ceramics not only demonstrates ceramic trade between Song and Liao dynasties, but also reflects the adoption and integration of Han Chinese cultural practices by the Khitan elite. While some greenish-white porcelain may have entered Liao territory through official border markets, historical documents and academic research suggest that maritime trade routes likely became the predominant source, especially from the mid-Liao period onward, thereby providing key scientific evidence for understanding the economic connections and cultural interactions between Song and Liao.

Data availability

The data generated and analyzed during this study are presented in the supplementary tables. Further inquiries can be directed to the corresponding author.

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X.Z. conducted experiments and manuscript writing; M.Z. supervised research design and conceptualization; Y.B. provided archaeological specimens and preliminary analysis; Y.J. performed language editing and revision; Y.Y. guided analytical methodology and research direction. The corresponding authors are Yongbin Yu (yu_yb1987@163.com) and Yimeng Bai (15040760@qq.com). All authors reviewed the manuscript.

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