Social Network Analysis of Ancient Japanese Obsidian Artifacts Reflecting Sampling Bias Reduction

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Abstract
This study aims to investigate the dynamics of obsidian trade networks during the Jomon period (approximately 15,000 to 2,400 years ago), the hunting and gathering era in Japan. To improve regional representation and reduce the distortions caused by small sample sizes, we performed clustering based on a large-scale dataset and conducted social network analysis. The research results revealed that the trade networks during the Jomon period were not constant; they expanded throughout the southern Kanto region during the Middle Jomon period (5,500–4,500 years cal BP) and ceased to function during the Late Jomon period (4,500–3,200 years cal BP). Furthermore, to enhance the readability and interpretability of the dataset, we implemented clustering using the density-based spatial clustering of applications with noise (DBSCAN) method. The results showed that in every time division of the Jomon period, the average intra-cluster cosine similarity of each cluster was higher than the similarity between sites outside the clusters, confirming the reasonableness of an analysis considering regional representation. In addition, to verify the robustness of the network in the social network analysis after clustering, we also performed a bootstrap simulation analysis. The results showed high network' robustness and demonstrated that the sampling after clustering had a minimal impact on this study's findings.

Keywords: social network analysis, obsidian artifact, DBSCAN, clustering, ancient Japan, Jomon period

Introduction

This study aims to reveal the changes in obsidian trade networks during the Jomon period (15,000 to 2,400 years ago), the hunting and gathering era in Japan. We conducted clustering using a large-scale dataset to improve regional representation and reduce the distortion caused by small sample sizes, and then performed social network analysis. Obsidian is a type of volcanic glass that was used for making sharp stone tools and processing food and wood materials (Ono, 2011). In archaeology, the similarities and differences in artifacts are used as indicators of contact and relationships between groups (Freund, 2013). As obsidian provenances are limited, identifying them is essential for understanding trade networks and resource procurement (Freund, 2013). Shells and jade ornaments from the Jomon period have been found in regions of Japan far from their production sites, suggesting the existence of extensive trade (Hashiguchi, 1999). However, the Jomon period spans approximately 13,000 years, during which cultural transitions can be observed; therefore, it is hypothesized that the trade range was not constant and instead expanded and contracted over time. To investigate the expansion and contraction of the Jomon period trade networks, we conducted a social network analysis of obsidian artifacts. This approach allowed us to clarify how trade networks changed over time.

The Kanto region is located in the eastern part of the Japanese mainland, and its obsidian provenance analysis is considered to be of the highest quality and quantity in the world (Tsumura & Tateishi, 2013). In this study, we focus on obsidian from the Jomon period in the Kanto region. According to a survey conducted in 2011, approximately 21,000 obsidian artifacts had been found at over 270 sites (Nihon-kokogaku-kyokai 2011 nendo tochigi-taikai-jikkoiinkai, 2011). However, when dealing with large-scale data, social network analysis graphs can become overly complex, making it difficult to derive useful interpretations.

In archaeology, it is important to consider that archaeological sites, artifacts, and features represent only a portion of what originally existed. In particular, with chemical analysis methods such as obsidian provenance analysis, it is difficult to target all excavated items due to constraints associated with excavation periods and budgets. The dataset used in this study also includes sites where only a few artifacts or, in extreme cases, just one artifact per site have been analyzed (Tsumura & Tateishi, 2013). When the sample size of obsidian at each site is small, the regional composition ratio may be distorted, potentially affecting the results (Golitko & Feinman, 2015). To address this issue, this study conducts clustering by region to improve the readability and interpretability of the dataset and then applies social network analysis. This approach can help reduce the distortion caused by small sample sizes.

Related Work

Obsidian Analysis of Japan's Kanto Region

Regarding the analysis of obsidian provenances in the Kanto region, Suzuki (1973, 1974) investigated trends in provenances and timing, and Warashina and Higashimura (1988) collected and organized information on obsidian and sanukaito provenances. Since the late 1980s, the proliferation of X-ray fluorescence analysis equipment has led to an increase in obsidian provenance analyses, and various studies focusing on archaeological issues across the Kanto region have been conducted (Kanayama, 1994; Kojo, 1996; Daikuhara, 2008; Ikeya, 2009). Furthermore, Sugihara and Kobayashi (2008) and Tsutsumi (2018) investigated resource development and supply from specific provenances from the Paleolithic to the middle Yayoi period (–2,000 years cBP).

Subsequently, the Japanese Archaeological Association compiled a collection of obsidian provenance analyses in the Kanto region in 2011 (Nihon-kokogaku-kyokai 2011 nendo tochigi-taikai-jikkoiinkai, 2011). Tsumura and Tateishi (2013) used these materials and statistical analysis methods to verify the patterns of provenances and consumption sites in the Kanto region during the Jomon period. As a result, the authors suggested that the obsidian trade network changed with time. They also quantitatively analyzed the relationship between provenances and consumption sites; however, the dynamics of the trade network among consumption sites have not been sufficiently investigated, and there remain many unexplained details. It is difficult to visualize and interpret large amounts of data using conventional methods, and social network analysis has only recently been established as a tool in archaeology.

Social Network Analysis of Obsidian Artifacts

Regarding research using social network analysis to study obsidian trade networks, there have been several such studies of areas like Mesoamerica and New Zealand. For example, Golitko et al. (2012) assumed that the inland land trading network in Mesoamerica collapsed and the coastal maritime trading network developed at the end of the Classical period. In addition, Golitko and Feinman (2015) suggested that the hierarchy and scale of the network decreased over time, indicating that the economy of Mesoamerica was not centralized. Furthermore, through a social network analysis of obsidian provenances, Ladefoged et al. (2019) observed that the selection of provenances in Maori society in 15th-century New Zealand was influenced by the community to which they belonged.

These studies used the social network analysis of obsidian provenances to represent archaeological sites and provenances of obsidian as “nodes.” Nodes are supplemented with attribute information such as geographic location, estimated age, and the amount or percentage of obsidian at the provenance. Links established based on the similarity between nodes (i.e., similarity in the proportion of obsidian) reflect the relationship between them. Social network analysis focuses on these nodes and their relationships, adopting an approach that considers the system a combination of the two (Ladefoged et al., 2019).

Impact of Sampling

In the social network analysis of the obsidian trade, the data size typically ranges from several hundred to several thousand obsidian artifacts. For example, Ladefoged et al. (2019) analyzed 2,404 obsidian artifacts from 15 sites, Meissner (2017) analyzed 2,630 obsidian artifacts from 796 sites, and Mills et al. (2013) analyzed 4,805 obsidian artifacts. Golitko et al. (2012) and Golitko and Feinman (2015) used data from 121 and 242 sites, respectively, although they did not stipulate the exact number of obsidian artifacts used in their social network analyses. In contrast, the present study used a large dataset of approximately 21,000 obsidian artifacts from over 270 sites (Nihon-kokogaku-kyokai 2011 nendo tochigi-taikai-jikkoiinkai, 2011). However, a drawback of such a large dataset is that the resulting social network graph may be too complex to yield useful interpretations.

Archaeological data such as sites, artifacts, and structures are often only a partial representation of what actually existed. In particular, the chemical analysis techniques used in obsidian provenance studies do not typically analyze all excavated artifacts due to constraints related to excavation durations and budgets. The dataset used in the present study includes sites where only a few or even only one artifact was analyzed for obsidian (Tsumura & Tateishi, 2013). In such cases, there is a risk of bias in regional composition and therefore of biased results (Golitko & Feinman, 2015). Consequently, Golitko and Freiman (2015) excluded obsidian samples of less than 10 per site from their study. They also mentioned combining sets of sites from specific time periods to create a pooled set of frequencies for the entire region but did not provide suggestions for specific methods.

In social network analysis, studies that consider sampling effects have shown that node-level indicators such as degree centrality are susceptible to sampling effects, while network indicators such as distance, centrality, and diameter are robust to node removal (Wey et al., 2008). Mills et al. (2013) used bootstrap simulation analysis to verify a dataset from the American Southwest and found that while individual node scores may vary due to sampling, summary statistics at the network level, such as centrality, are relatively stable.

Problem Formulation

This study conducted a social network analysis of obsidian artifacts to investigate the expansion and contraction of the trade network in the Jomon period. To improve the readability and interpretability of the large dataset we used and reduce the distortion caused by small sample sizes, we clustered the obsidian samples at each site by region and performed a social network analysis. We then performed a bootstrap simulation analysis to test the robustness of the network in the clustered social network analysis.

Materials and Methods

Dataset of Obsidian Assemblages

This study focused on obsidian artifacts excavated from Jomon period sites in the Kanto region. The Kanto region is located in the eastern part of Honshu and is surrounded by Tokyo Bay, Sagami Bay, the Pacific Ocean, and mountainous areas to the north and northwest (Figure 1). The obsidian artifacts brought to southern Kanto have been found to have originated from islands further south in Tokyo Bay and the surrounding mountainous areas. These obsidian artifacts were transported by sea from the island areas and brought to the consuming areas via a route that diverted to the north from the mountainous area to the northwest (Sugihara & Kobayashi, 2008; Tateishi, 2010).

The dataset for this study was based on the results of previous obsidian provenance analyses conducted on Jomon period sites in the Kanto region and compiled by the Japan Archaeological Association at the Tochigi meeting in 2011 (Nihon-kokogaku-kyokai 2011 nendo tochigi-taikai-jikkoiinkai, 2011). Although this dataset was compiled in 2011, it is still valuable because of the vast amount of data it comprises and because it includes obsidian provenances that have been reported in the years since. The present study's analysis focused on eight main production areas: 1) Takahara-yama, 2) Wada-toge, 3) Omegura, 4) Suwa, 5) Tateshina, 6) Kozu-shima, 7) Hakone, and 8) Amagi. For convenience, Wada-toge, Omegura, Suwa, and Tateshina are collectively referred to as the "Shinshu group" and are considered to belong to the mountainous area known as the "Central Highlands." Several other production areas were excluded from the analysis due to the small number of obsidian artifacts that have been found there.

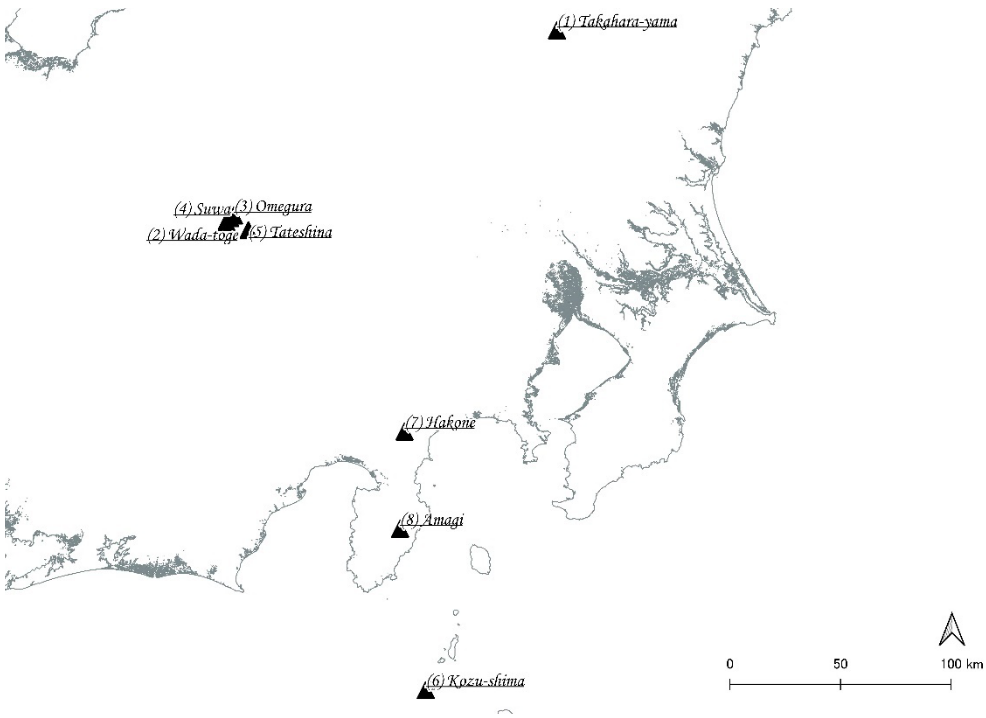

Figure 1 - Location of major obsidian provenance areas.

Clustering

As mentioned earlier, to improve the readability and interpretability of the data and reduce the distortion caused by a small sample size, we performed clustering by region and summarized the results as aggregate values for each region. Assuming that adjacent sites have interactions and share information, we applied the density-based spatial clustering of applications with noise (DBSCAN) algorithm (a density-based algorithm for discovering clusters in large spatial databases with noise) (Ester et al. 1996) to group the geographical locations of the sites. Many other clustering methods do not consider noise and assign all sites to clusters, which can result in sites being clustered even if they cannot access each other. However, the DBSCAN algorithm defines regions as clusters based on the number of points (density) within a radius (ε value) (minPts). If the density within the region exceeds a certain threshold, the cluster expands, but if there are no nearby points within the radius, it is considered noise (Figure 2). The ε value is determined based on the factor at issue (such as physical distance), and the minPts is the optimal size of the minimum cluster. In this study, we set the ε value to 10km, which is commonly accepted as the activity range of the ancient Jomon people (Akazawa, 1982; Koizumi, 2016). The minPts was set to a minimum of three. The DBSCAN algorithm was used for each of the five divisions of the Jomon period.

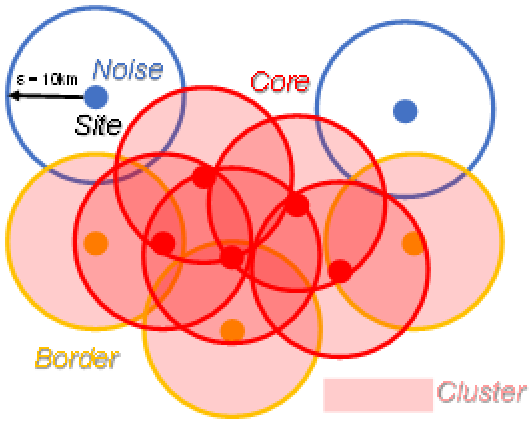

Figure 2 - Image of clustering using the DBSCAN method.

We treated these clusters as a single region, summed up the obsidian provenances in each region, and calculated the proportion of obsidian provenances in each cluster.

The composition ratio (R) was defined by the following equation:

$$R_{i,j} = N_{i,j} / T_i,$$

where $R_{i,j}$ indicates the composition ratio of provenance j in cluster (or single site) i, T_i indicates the total number of analyzed obsidian artifacts in i, and $N_{i,j}$ indicates the number of obsidian artifacts of provenance j in cluster i.

As mentionedabove, a small number of obsidian samples may distort the regional composition ratio and potentially affect the results (Golitko & Feinman, 2015). Therefore, we excluded clusters with fewer than 30 obsidian artifacts from the analysis. On the other hand, sites without geographical relationships forming clusters but with more than 30 obsidian artifacts were used as single sites for the analysis by calculating the obsidian provenance composition ratio in the same way as for the clusters.

Similarity

We calculated similarity and performed social network analysis for each period division. Following Ladefoged et al. (2019), we measured the similarity of the obsidian provenance compositions between clusters, between each cluster and individual sites, and within each cluster by calculating cosine similarity. We calculated the provenance composition ratio for each cluster and individual site from the total number of obsidian artifacts and treated them as vectors. Specifically, since this study included eight provenances, they were represented as eight-dimensional vectors.

The cosine similarity (Sim) was expressed by the following formula:

$$Sim_{A,B} = (\vec{a} \cdot \vec{b}) / (|\vec{a}| \cdot |\vec{b}|)$$

where $Sim_{A,B}$ represents the similarity between A and B (where A and B are clusters or individual sites, and $\vec{a}$ and $\vec{b}$ are vectors corresponding to A and B, and $|\ |$ indicates the magnitude of the vector). If the provenance compositions of A and B are similar, the direction of vectors $\vec{a}$ and $\vec{b}$ becomes close, and the value of $\cos\vartheta$ approaches 1. Conversely, if they are dissimilar, the value approaches 0.

Network Analysis

We created an undirected network based on the cosine similarity of obsidian provenance composition ratio between clusters and single sites. This network revealed the relationships between consumption sites for each period. Each cluster or single site was represented as a node, and a link was generated between nodes when the cosine similarity between them exceeded 0.9. We also calculated the network density for these networks for each period.

The network density (D) was defined as the ratio of the number of actual links in the network to the total number of possible links in the network. Density was expressed by the following equation:

$$D = m / (n * (n - 1) / 2)$$

where *n* represents the number of nodes in the network and *m* represents the number of links. The density value varies within the range of 0 to 1, such that the closer the value is to 1, the higher the network density, indicating a close relationship. Conversely, values close to 0 indicate that there are few relationships in the network.

When the threshold is not set, the network density is equivalent to the average cosine similarity between each node pair. In this case, the network density does not need to satisfy the condition that the cosine similarity is greater than 0.9.

Bootstrap Simulation

We conducted a simulation using the bootstrap method on the data clustered with the DBSCAN method and calculated the virtual cosine similarity and network density of the social network analysis. This simulation was executed 100 times. The mean and standard deviation of the cosine similarity and network density were calculated and compared with the actual data.

Results and Discussion

Clustering

Based on the results of clustering using DBSCAN, some clusters were excluded from the analysis, as they contained less than 30 obsidian artifacts. For details of the number of clusters and single sites for each period, as well as the total number and composition ratios of obsidian artifacts by provenance, please refer to Sakahira and Tsumura (2023).

Table 1 shows the cosine similarity between clusters and between single sites and clusters for each period, which verified whether the clustering by DBSCAN ensured regional representativeness. The results showed that for each division of the Jomon period, the average cosine similarity within each cluster was higher than the similarity between sites not belonging to the cluster. For example, in period 1, the average cosine similarity of sites not belonging to a cluster (no cluster) was 0.280, which was lower than the values for B1, B2, B4, and B5.

From these results, it can be inferred that nearby archaeological sites hold information on obsidian and the flow of obsidian between each site. It was thus reasonable to aggregate values between adjacent sites by region and analyze them from the perspective of regional representativeness.

Table 1 - Network density and cosine similarity within each cluster and between sites not belonging to a cluster in each period category.

Period 1 Beginning and Earlier Jomon		Period 2 Early Jomon		Period 3 Middle Jomon		Period 4 Late Jomon		Period 5 Last Jomon	
Network density	0.444		0.200		0.405		0.143		0.256
Average of actual cosine similarity between clusters	0.623		0.411		0.716		0.535		0.508
Average of cosine similarity between sites not belonging to a cluster (no Cluster)	0.280		0.402		0.538		0.447		0.644
Average of cosine similarity within a cluster	0.500		0.692		0.760		0.641		0.987
B1	0.760	E1	0.670	M1	0.421	L1	0.872	T1	0.983
B2	0.717	E2	0.752	M2	0.737	L2	0.800	T2	0.987
B4	0.552	E3	0.672	M3	0.892	L3	0.503	T3	0.984
B5	0.472	E5	0.576	M4	0.835	L4	0.495		
		E6	0.714	M5	0.644	L5	0.682		
		E7	0.767	M6	0.904	L6	0.483		
				M7	0.884	L7	0.650		

Social Network Analysis

The graph of the social network analysis showed that each cluster until the Early Jomon period had a high proportion of obsidian from nearby provenances. However, in the Middle Jomon period, obsidian from the island provenances crossed the sea and spread widely in the southern Kanto region. From the Late Jomon period onward, the distribution of obsidian from island provenances became limited, and obsidian from inland provenances began to appear instead (Figures 3, 4, and 5).

Additionally, we found that the network density between clusters and the cosine similarity between sites within clusters during the Middle Jomon period (Table 1) were higher than those before the Early Jomon period and after the Late Jomon period. These results suggest that the obsidian trading network developed throughout the southern Kanto region during the Middle Jomon period and ceased to function during the later period. For more details of these analyses, please refer to Sakahira and Tsumura (2023).

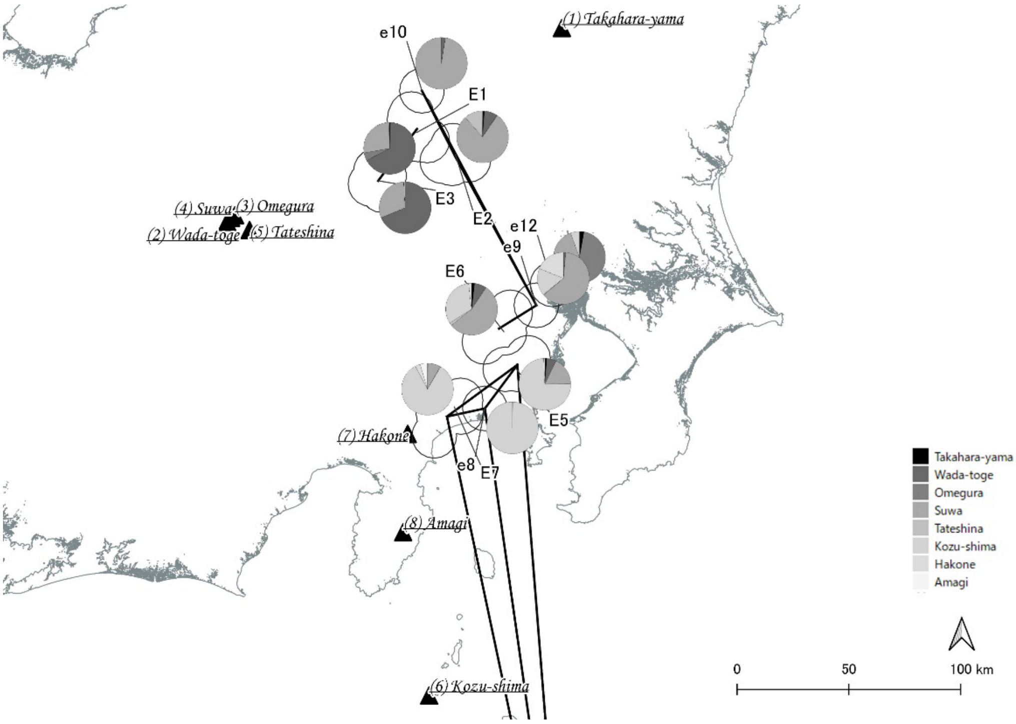

Figure 3 - Network among the consumption areas in Period 2, the early Jomon period (7,000–5,500 years cal BP). Clusters are represented by uppercase characters and single sites by lowercase characters. Pairs with a cosine similarity greater than 0.9 in the composition ratio of each provenance area are linked. White circles indicate clustered areas. Pie charts show the composition ratio of each cluster by provenance.

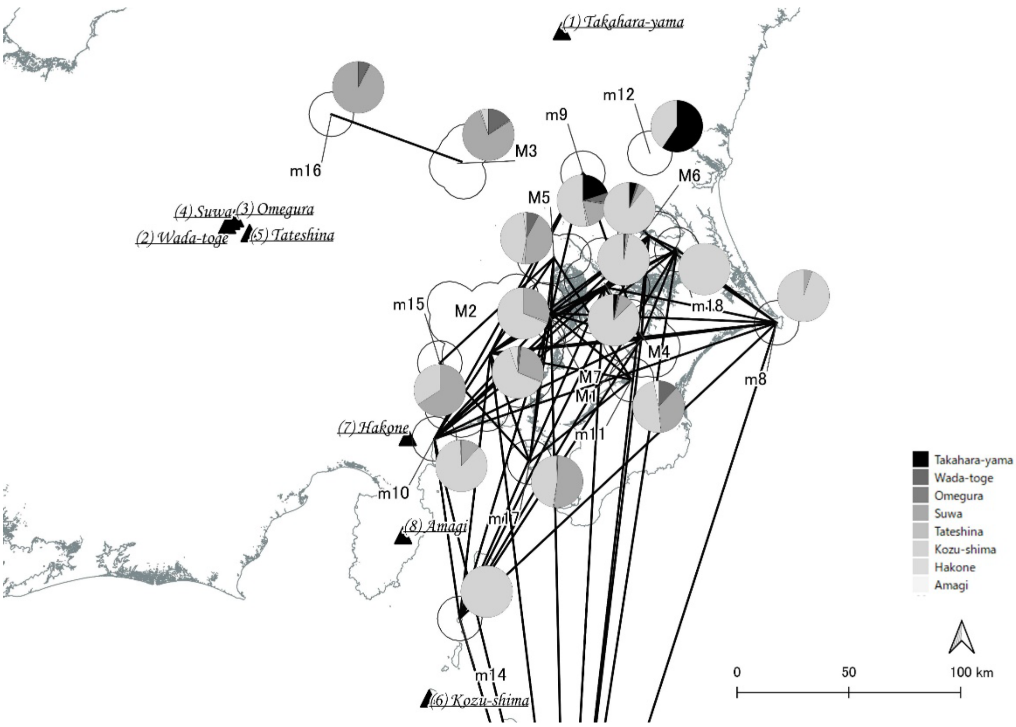

Figure 4 - Network among the consumption areas in Period 3, the middle Jomon period (5,500–4,500 years cal BP). Clusters are represented by uppercase characters and single sites by lowercase characters. Pairs with a cosine similarity greater than 0.9 in the composition ratio of each provenance area are linked. White circles indicate clustered areas. Pie charts show the composition ratio of each cluster by provenance.

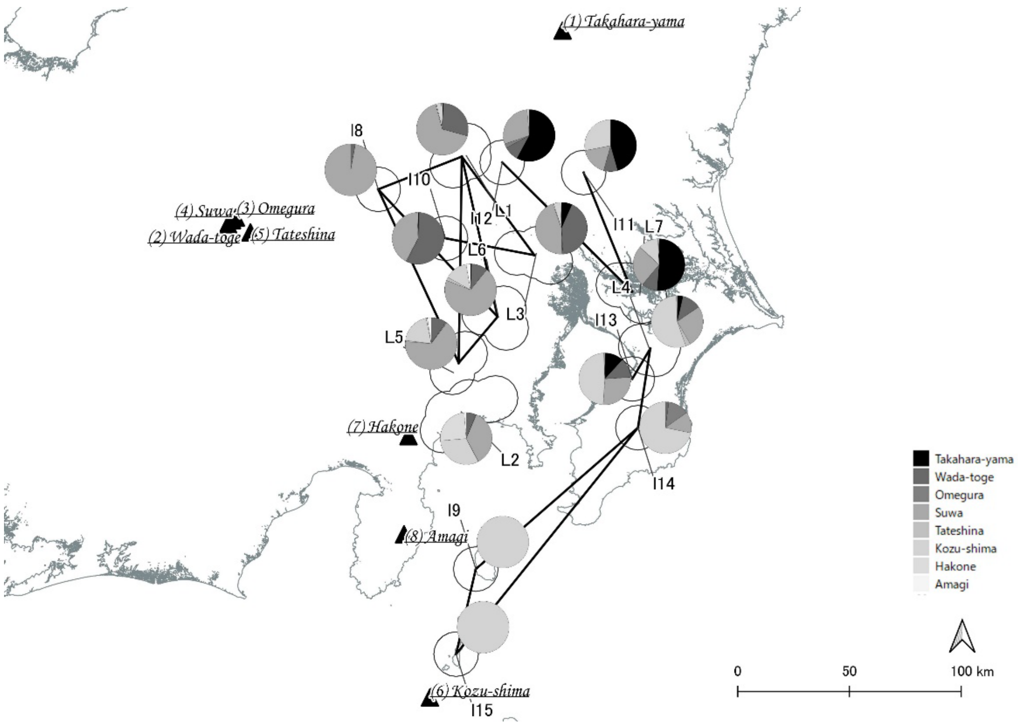

Figure 5 - Network among the consumption areas in Period 4, the late Jomon period (4,500–3,200 years cal BP). Clusters are represented by uppercase characters and single sites by lowercase characters. Pairs with a cosine similarity greater than 0.9 in the composition ratio of each provenance area are linked. White circles indicate clustered areas. Pie charts show the composition ratio of each cluster by provenance.

Bootstrap Simulation

Using the bootstrap method, 100 simulations were conducted to calculate the mean and standard deviation of the cosine similarity and network density obtained from the clustering results using the DBSCAN algorithm. The results showed that the values of cosine similarity and network density obtained from the actual data were within two standard deviations (2SD) of the simulation results (Tables 2 and 3). Moreover, even considering 2SD, the order of magnitude of each index for each period did not change.

These results showed that the social network analysis of the network after clustering using the DBSCAN algorithm had high robustness. The results also confirmed that this study's sampling had little effect on its results. Therefore, it is suggested that the DBSCAN clustering method used in this study is applicable to other archaeological themes where missing data and sampling effects are issues.

Table 2 - Comparison of actual and bootstrap simulation values for cosine similarity between clusters.

Period 1 Beginning and Earlier Jomon		Period 2 Early Jomon	Period 3 Middle Jomon	Period 4 Late Jomon	Period 5 Last Jomon
Average of actual cosine similarity between clusters	0.623	0.411	0.716	0.535	0.508
Average of simulated cosine similarity between clusters	0.619	0.411	0.711	0.533	0.505
Simulated standard deviation	0.017	0.012	0.016	0.014	0.015

Table 3 - Comparison of actual and bootstrap simulation values for network density.

Period 1 Beginning and Earlier Jomon		Period 2 Early Jomon	Period 3 Middle Jomon	Period 4 Late Jomon	Period 5 Last Jomon
Actual network density	0.444	0.200	0.405	0.143	0.256
Average of simulated network density	0.409	0.196	0.412	0.147	0.243
Simulated standard deviation	0.056	0.020	0.039	0.016	0.013

Conclusion and Future Work

This study's social network analysis of obsidian artifacts revealed that the trade networks during the Jomon period were not constant, but rather developed throughout the southern Kanto region during the middle Jomon period and ceased to function in the late Jomon period. The use of DBSCAN clustering improved the readability and interpretability of the large dataset and reduced the bias caused by the small sample sizes of each site, thus confirming the validity of analyzing regional representation. Finally, a bootstrap simulation analysis demonstrated the high robustness of the network in the social network analysis after clustering. The impact of sampling on the results of this study was found to be minimal.

In the future, ancient digital elevation data in GIS should be used to consider the ε value of DBSCAN and the geographical distance between production and consumption areas more accurately, as well as to extract regional clusters and calculate the shortest transportation costs between production and consumption areas. This will enable us to determine the shortest distance or route, taking into consideration geographical features such as elevation differences, slopes, and seas (Ladefoged et al., 2019; Tobler, 1993). We plan to address these points as future research tasks.

Acknowledgments

We would like to thank Prof. T. Terano (Chiba University of Commerce), and Dr. M. Kunigami (Tokyo Institute of Technology) for the useful discussions. We would like to thank Editage (www.editage.com) for English language editing.

Funding

This work was supported by JSPS KAKENHI (Grant nos. 21K21323, 22K18156, and 22H00021), Japan. The funding source was not involved in preparing the manuscript or in the collection, analysis, or interpretation of the data.

Conflict of Interest

The authors declare that they comply with the PCI rule of having no financial conflicts of interest in relation to the content of the article.

Data, Scripts, Code, and Supplementary Information

Our study used the dataset from Nihon-kokogaku-kyokai 2011 nendo tochigi-taikai-jikkoiinkai (2011).

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