Evidence for the use of the bow-and-arrow technology by the first modern humans in the Japanese islands

Katsuhiro Sano
The University Museum, The University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo, 113-0033, Japan

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ABSTRACT
Manufacturing bow-and-arrow is an intricate procedure requiring multistage planning. Because of the high complexity of this innovation, the distribution of bow-and-arrow technology reflects a dispersal of human groups that possessed the technology rather than multiple independent origins. Although indirect evidence for bow-and-arrow technology prior to 60 ka has been recovered from Middle Stone Age levels at Sibudu Cave, South Africa, additional evidence from marine isotope stage (MIS) 4 and early MIS 3 in both Africa and Eurasia is absent. Because bow-and-arrow technology possessed significant advantages, it is crucial to determine whether the first modern humans to move out of Africa were equipped with this technology. The first modern human groups that migrated into the Japanese islands adapted to the forest-rich environment and produced edge-ground axes and small-sized trapezoids that are assumed to be transversely hafted arrowheads. The delivery modes of early Upper Palaeolithic trapezoids from the Tohoku region in Japan were examined on the basis of proxies from projectile experiments and morphometric analysis. The results of both macrofabric and morphometric analyses suggest that the early Upper Palaeolithic (EUP) trapezoids were definitely delivered mechanically and some were probably used as arrowheads.

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1. Introduction

In the Japanese islands, the number of Palaeolithic sites abruptly increases after c. 38 kcal BP (Kudo and Kumon, 2012; Izuho and Kaifu, 2015). The lithic technocomplex between 38 and 30 kcal BP, assigned to the early Upper Palaeolithic (EUP), is characterized by trapezoids, edge-ground axes, and pointed blades (Fig. 1). Owing to the acidity of the Pleistocene sediments on the Paleo-Honshu Island (Fig. 2A), neither human nor faunal remains are associated with the EUP sites. Only the Ryukyu Islands, where karstic caves and fissures are abundant, have preserved paleontological records and have yielded several modern human fossils. These human remains temporally coincide with the Japanese EUP sites but are not associated with archeological materials (Kaifu and Fujita, 2012; Kaifu et al., 2015b). However, the characteristics of the EUP technocomplex, including systematic production of blades (Yoshikawa, 2010; Morisaki, 2012) and edge-ground axes (Tsutsumi, 2012), trap-pit hunting (Sato, 2012, 2015), and maritime transport of obsidian (Ikeya, 2015), suggest that the lithic assemblages were left behind by modern humans (Izuho and Kaifu, 2015).

The concept of “modern human behavior” was mainly established on the basis of archeological records from Africa and Europe (Mellars, 1989; McBrearty and Brooks, 2000; Bar-Yosef, 2002; Henshilwood and Marean, 2003; Klein, 2008), but subsequently great regional diversity has been confirmed in Asia (Kaifu et al., 2015a). The oldest evidence for the use of edge-ground axes, trap-pit hunting, and maritime transport of high-quality raw materials observed in the Japanese islands may reflect a regional adaptation to the temperate island environment (Izuho and Kaifu, 2015).

The trapezoid is a specific tool type in the Japanese EUP, which has not thus far been recovered from EUP sites in neighboring East Asian countries. Oda (1969, 1971) assumed that, similarly to European Mesolithic trapezes, “trapezes” from the Japanese islands were used as transversely hafted arrowheads because of their “small” size, although Japanese trapezoids are larger than European trapezes and should not be classified as microliths. Use-wear analyses of EUP trapezoids indicated that, although some of the trapezoids functioned as cutting tools for soft materials (Midoshima, 1991; Kanomata, 2005; Denda, 2009; Kanomata and Denda, 2009; Kanomata, 2011; Tsutsumi, 2012), some trapezoids were used as hunting weapons (Kanomata, 2005, 2011; Yamaoka, 2012). Previous microwear studies on EUP pointed blades showed no distinctive use-wear, with the exception of a few pieces showing traces of sawing of relatively hard materials (Denda, 2009; Kanomata and Denda, 2009; Kanomata, 2013), though the EUP massive pointed blades were traditionally assumed to be hunting weapons on the basis of their
pointed morphology (Sudo, 2007). Nevertheless, use-wear studies on EUP assemblages are still limited and a comprehensive study is required for quantitative demonstration of the functions of trapezoids and pointed blades in the Japanese EUP.

As the use of spearthrowers or bows-and-arrows provides significant advantages over thrusting or hand-cast spears in terms of efficiency, risk minimization, and the variety of game able to be effectively exploited (Shea and Sisk, 2010), it is important to detect the delivery
modes of the EUP hunting weaponry used by the first modern human groups in the Japanese islands. Morphometric analysis of North American dart tips and arrowheads suggested that mass, tip cross-sectional area (TCSA), and tip cross-sectional perimeter (TCSP) are useful proxies for distinguishing dart tips from arrowheads (Hughes, 1998). TCSA and TCSP analyses of African, Levantine, and European stone tips determined that modern humans may have equipped themselves with spearthrowers when they expanded out of Africa (Shea, 2006; Shea and Sisk, 2010; Sisk and Shea, 2011). The morphometric values of quartz segments and backed pieces from Sibudu Cave, South Africa, fall within the range of North American ethnographic arrowheads (Wadley and Mohapi, 2008) and the distributions of impact fractures and residues of these stone tips indicated that they were transverselyhafted armatures. These results indicate that the emergence of bow-and-arrow technology may have occurred prior to 60 ka in South Africa (Lombard and Phillipson, 2010; Lombard, 2011; Lombard and Wadley, 2016). Consequently, modern humans who expanded into Western and Eastern Eurasia may have potentially possessed knowledge of both spearthrower and bow-and-arrow technologies.

In order to assess the projectile systems of the first modern human groups in the Japanese islands, macrofabric analysis of EUP assemblages recovered from the Tohoku region of Japan was conducted in order to identify hunting stone tips (Fig. 2B). The impact fracture patterns were compared to those observed in projectile experiments. A morphometric analysis of these stone tips was also undertaken to examine the potential projectile capability. Finally, the delivery modes of the EUP hunting weapons were discussed.

2. Context

This paper focuses on the early phase of the Japanese EUP, which coincides with the warm, forest-rich period.

2.1. Radiometric chronology of the EUP technocomplex

The geographical distribution of the EUP technocomplex is limited to the Tohoku region of Japan (Fig. 2A), and temporally is mostly restricted to below the Aira-Tn (AT) tephra, which has been dated to c. 30 kcal BP (Smith et al., 2013). The long stratigraphic sequences found at numerous Upper Palaeolithic sites on the Musashino Terrace in the Kanto region allow reconstruction of a detailed Upper Palaeolithic chronology based on distinctive natural layers (X–III) of the Tachikawa loam bed (Yamaoka, 2010), which are principally composed of volcanic deposits derived from several volcanoes of the Fuji–Hakone region (Takai and Tsuchi, 1963). The EUP Musashino chronology consists of three phases: Layer (hereafter L X, LX, and LVI in chronological order (Sato, 1992). As LVII has been only occasionally recognized in the Tachikawa loam bed, no archeological Phase for LVIII has been established. The EUP technocomplex has been found below Phase LVI, but not within and above it, which always includes the AT tephra. Although abundant trapezoids and edge-ground axes as well as some pointed blades have been recovered between Phases LX and LXI in the Kanto region, the abundance of backed points (Fig. 1: 12–13) progressively increases during the subsequent Phase LVII, before being replaced with pointed blades.

Pointed blades were made on a thick blade that possessed a natural pointed tip. Most pointed blades exhibit only marginal retouch on the base. In contrast, backed points were mostly made on a standardized thin blade. Backed points bear blunting on the base and lateral side and the pointed tip was produced by lateral retouching.

Twenty-nine radiocarbon measurements were obtained for 12 EUP sites in the Kanto region (Table S1). All samples were charcoal associated with EUP lithic assemblages. Because of the absence of organic materials from Pleistocene deposits in the Japanese islands, except for the Ryukyu Islands, no bone specimens were available for radiocarbon dating. The radiocarbon determinations were calibrated using the INTCAL13 curve (Reimer et al., 2013) and a Bayesian model for Phases LX, LIX, and LVII was built using OxCal 4.2 (Bronk Ramsey, 2009). The Bayesian model indicates that Phase LX started at c. 36 kcal BP and there was a gradual transition to Phase LIX between 34 and 33 kcal BP (Figs. 3 and S2). The transition from Phases LIX to LVII is placed at around 32 kcal BP and Phase LVII between 32 and 30 kcal BP. The Musashino chronology can be accurately correlated to the Upper Palaeolithic chronostratigraphy in the Mt. Ashitaka region (Nakamura, 2014). A total of 72 radiocarbon determinations from nine EUP sites at Mt. Ashitaka are examined (Figs. 3 and S3). The Bayesian model for EUP chronology in the Mt. Ashitaka region indicates that Phase LX started around 37 kcal BP, ~1000 years earlier than in the Kanto region. Also similarly to the Kanto region, although there are no significant changes in the lithic assemblages between Phases LX and LIX, backed points are increasingly abundant from Phase LVII onward. As there is only one site assigned to Phase LIX in the Mt. Ashitaka region, the age range for Phase LIX in this region is uncertain. Therefore, the timing of the transition between Phase LIX and Phase LVII is still ambiguous, though the Bayesian model suggested it to be around 32.5 kcal BP.

The stratigraphy of the Shinhu region is much shorter than that in the Kanto and Mt. Ashitaka regions, because this area is located away from the thick volcanic deposits derived from the Ashitaka, Fuji, and Hakone volcanoes. Despite this fact, the lithic assemblages in the Shinhu region are roughly comparable to those in the Kanto region on the basis of their techno-morphological aspects. A total of 20 radiocarbon determinations from the early phase (Phases LX–LIX) of the EUP provide Bayesian model range from ~37 to ~32 kcal BP (Figs. 3 and S4).

The thin Upper Palaeolithic stratigraphy in the Tohoku region makes comparison with the Musashino chronology difficult, though several EUP sites have yielded large numbers of backed points that are technomorphologically comparable to the Phase LVII assemblages in the Kanto and Tokai regions. The Bayesian model for two EUP sites with backed points shows that these assemblages appear at around 32 kcal BP (Fig. 4), like Phase LVII in the Kanto region. There are only three radiocarbon determinations from the Phase LVII sites in the Tohoku region, which are all relatively old. Therefore, the end age of the Tohoku Phase LVII assemblages is still unknown. Compared to the Kanto and Mt. Ashitaka regions, pointed blades are much more abundant in the Tohoku EUP assemblages, which should be assigned to the early phase (Phases LX–LIX). Radiocarbon dates from the Sasayamahara site, from which numerous pointed blades were unearthed, suggest that an EUP systematic blade technology was already dominant at around 34 kcal BP in the Tohoku region (Figs. 4 and S1), probably coinciding with the start of Phase IX in the Kanto and Mt. Ashitaka regions. The Bayesian model for three EUP sites with abundant trapezoids and edge-ground axes yields age ranges of ~35–34 kcal BP. Two radiocarbon determinations from the Kaminohagamori site are older than those from the Togeyama IA-1 and Jizouden sites (Table S1). Although the unmodeled calibrations are dated to c. 36.4 kcal BP and c. 35.8 kcal BP, the Bayesian model provided a younger age range (Fig. S1).

From the results above, the EUP sites in the Mt. Ashitaka and Shinhu regions, Central Japan, appear around 37 kcal BP, coinciding with the warm period after the extremely cold and dry Heinrich Event (HE) 4 (Fletcher and Sánchez Goñi, 2008; Svensson et al., 2008). Further to the west, the EUP occurs later, at c. 36 kcal BP in the Kanto region and at c. 35 kcal BP in the Tohoku region. In contrast, the Phase LVII assemblages reflected by an increase in backed points may appear in the Mt. Ashitaka region just slightly earlier, at around 32.5 kcal BP, but at almost the same time in the Kanto and Tohoku regions, at approximately 32 kcal BP. The typical EUP technocomplex represented by numerous trapezoids and edge-ground axes, and circularly arranged basecamps (Hashimoto, 2006) was dominant during the early phase (Phases LX–LIX) of the EUP.

2.2. Paleoecology of the Japanese islands during MIS 3

After HE 4, the relatively warm climate lasted until 32 kcal BP (Svensson et al., 2008; Müller et al., 2011; Kudo and Kumon, 2012).
temporally corresponding with the early phase of the Japanese EUP. Thirty-nine pollen records for MIS 3 from the Japanese islands indicate a considerable proportion of deciduous broadleaf trees in many regions of the Paleo-Honshu Island (Takahara and Hayashi, 2015), suggesting a relatively warm, temperate climate which is supported by the large number of edge-ground axes, which would have been used for felling trees (Tsutsumi, 2012). Furthermore, a cluster of small lithic concentrations exhibits circular distribution patterns ranging from 11 to 80 m in diameter (average 20 m diameter; Hashimoto, 2006; Shimada, 2012; Izuho and Kaifu, 2015). The circular lithic clusters probably represent the EUP basecamp arrangement of circularly arranged small huts. The frequent association of the circular lithic clusters with edge-ground axes suggests that edge-ground axes were used for the procurement of wooden materials, e.g., to construct huts, as shown by use-wear analysis (Tsutsumi, 2012). Accordingly, the archeological records from the EUP, especially the early phase of the EUP, support a deciduous-forest-rich environment.

The Japanese EUP sites are all open-air sites and are not associated with faunal remains. However, some localities, such as caves and lakeshores, have yielded mammal remains, though not archeological assemblages (Kawamura and Nakagawa, 2012). The dominant fauna during MIS 3 in the Paleo-Honshu Island was Cervus nippon (sika deer), Selenarctos thibetanus (Asiatic black bear), Vulpes vulpes (red fox), Lepus brachyurus (Japanese hare), Macaca fuscata (Japanese macaque), and others.
Glirulus japonicus (Japanese dormouse), and Apodemus speciosus (large Japanese field mouse), all of which are extant species.

Recent rigorous evaluation of radiocarbon dates on terrestrial mammal fossils revealed the timing of terrestrial mammal extinction (Iwase et al., 2012; Takahara and Hayashi, 2015). The warm-adapted Palaeoloxodon–Sinomegaceroides complex recovered from the Paleo-Honshu Island, containing *P. naumanni* and *S. yabei*, yielded radiocarbon dates from c. 49 ka to c. 23 ka, suggesting that these species became extinct as a result of the vegetation change from deciduous broadleaf trees to subarctic conifers during the Last Glacial Maximum (LGM). On the other hand, the cold-adapted mammoth fauna, such as *Mammuthus primigenius* and *Bison* sp., were found exclusively on Hokkaido Island, and show two clusters of radiocarbon dates, c. 60–35 ka and c. 25–20 ka. The absence of *M. primigenius* fossils between 37 and 25 ka may reflect the migration of woolly mammoth to the north owing to the vegetation change during this period (Iwase et al., 2012). Consequently, in addition to the MIS 3 dominant fauna above, *P. naumanni* and *S. yabei* are possible candidates for game for the EUP hunters on Paleo-Honshu Island.

3. Material and methods

Many EUP sites have been excavated in the Tohoku region of Japan owing to the large number of rescue excavations undertaken here (Fig. 2B). Material from a total of 12 EUP sites in the Tohoku region were examined in this study (Table 1). First, a macroscopic analysis was undertaken of the EUP trapezoids and pointed blades to identify specimens that had been used as hunting weaponry. Based on a comparative study of the fracture patterns produced in manufacture, use, and post-depositional experiments (Fischer et al., 1984; Sano, 2009) and other projectile experiments (Odell and Cowan, 1986; Rots and Plisson, 2014), crushing, flake-like fractures, burin-like fractures, transverse fractures with step, hinge,...

**Table 1**
The numbers of trapezoids and pointed blades from EUP sites in the Tohoku region analyzed for this study.

<table>
<thead>
<tr>
<th>#</th>
<th>Site</th>
<th>Trapezoids</th>
<th>Pointed blades</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nawateshita</td>
<td>7</td>
<td>21</td>
<td>28</td>
</tr>
<tr>
<td>2</td>
<td>Konokakesawa Loc.2</td>
<td>0</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>Ienoshita</td>
<td>0</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>4</td>
<td>Shimotsutsumi G</td>
<td>0</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>5</td>
<td>Jizouden</td>
<td>37</td>
<td>0</td>
<td>37</td>
</tr>
<tr>
<td>6</td>
<td>Matsuikida Loc.2</td>
<td>15</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>7</td>
<td>Matsuikida Loc.3</td>
<td>0</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>8</td>
<td>Kazanashidai Loc.1</td>
<td>1</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>9</td>
<td>Kazanashidai Loc.2</td>
<td>32</td>
<td>1</td>
<td>33</td>
</tr>
<tr>
<td>10</td>
<td>Togeyamabokujo I Loc. A</td>
<td>7</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>11</td>
<td>Togeyamabokujo I Loc. B</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>12</td>
<td>Kamihagimori</td>
<td>15</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>Total</td>
<td>116</td>
<td>93</td>
<td>209</td>
<td></td>
</tr>
</tbody>
</table>

* The numbers correspond to those in Fig. 2.
and feather terminations that obviously formed after lateral retouching, bifacial spin-offs, and unifacial spin-offs larger than 6 mm were considered to be reliable diagnostic impact fractures (DIFs). The DIFs were used as criteria to identify hunting stone tools.

In addition, the impact trace patterns on trapezoids were compared with those confirmed on experimental specimens. Projectile experiments undertaken by the author provided a good correlation between impact trace patterns and impact velocities (Sano and Oba, 2014, 2015; Sano et al., 2016), which can be used as proxies to distinguish mechanically delivered armatures from hand-delivered or thrust spears. As projectile experiments with pointed blades have not yet been undertaken, a comparative analysis with projectile experiments was conducted only for the EUP trapezoids.

The EUP lithic tools from the Tohoku region were most frequently made from siliceous shale (Yoshikawa, 2010). The siliceous shale is a sedimentary rock and a high-quality raw material, similar to flint and chert. The fine-grained texture is also suitable for use-wear analysis. As the projectile experiments were designed to reveal the delivery modes of trapezoids from the Tohoku region, all the trapezoid replicas were made from siliceous shale (Sano et al., 2016). As a statistically large enough sample size is required to identify mechanically delivered armatures, microscopic analysis was performed only for selected sites: these results will be presented elsewhere.

A morphometric analysis of the TCSA, TCSP, and mass of the EUP trapezoids and pointed blades showed DIFs was also conducted to confirm the potential capability of these specimens as hunting weaponry. The TCSA, TCSP, and mass of these lithic artifacts were compared to those of ethnographic North American dart tips and arrowheads (Thomas, 1978; Shortt, 1997). The TCSA, TCSP, and mass values may indicate the potential projectile capability of stone tips (Hughes, 1998), whereas the validity of the TCSA and TCSP proxies have been challenged because of the much larger Aboriginal dart tips (Newman and Moore, 2013). Indeed, the large stone tips may not necessarily indicate use as thrusting or hand-casting spear points, as significantly large arrowheads were used in Papua New Guinea (Watanabe, 1975). However, the considerably small-sized North American darts and arrowheads were probably not greatly suitable for use as thrusting or throwing spear tips. Therefore, the small values of TCSA, TCSP, and mass compared to North American darts or arrowheads would indicate the morphological potential of stone tips to be delivered using a spearthrower or a bow.

Nevertheless, a more crucial problem with the TCSA and TCSP analysis is that the results do not indicate the real function of an object. Consequently, the analyzed sample may include non-hunting weapons. As indicated by previous use-wear studies (Sawada and Kanomata, 2004; Yamada, 2008; Denda, 2009; Kanomata and Denda, 2009; Denda et al., 2012; Kanomata, 2013; Sano, 2016), prehistoric “stone points” were not always hunting weaponry, but were also used as knives or for other processing activities. Therefore, morphometric analysis of TCSA, TCSP, and mass was undertaken only for samples that showed evidence for hunting, as DIFs.

Because of the trapezoidal form, EUP trapezoids have their maximum width at the tip, which does not represent the width of the shaft. Therefore, the width at a half position on the specimen was used for the TCSA and TCSP analysis.

4. Results

Macroscopic analysis of a total of 116 EUP trapezoids and 93 backed points indicated that approximately one third of both types exhibited fractures (Table 2). Although this means that nearly one fracture was observed per piece, almost half of the fractures were not diagnostic as impact fractures; hence, it is uncertain whether they are impact fractures caused by hunting. Nevertheless, 19 trapezoids (16.4%) show DIFs and a total of 57 DIFs (0.49 DIFs per piece) were observed. The frequency of DIF occurrence of the pointed blades does not significantly differ from that of the trapezoids. Eighteen pointed blades (19.4%) exhibit typical DIFs, with a total of 48 DIFs (0.52 DIFs per piece), including flute-like fractures (Fig. 5A, D), burin-like fractures, (Fig. 5C), transverse fractures with step termination (Fig. 5F), crushing (Fig. 5D), and spin-offs (Fig. 5B, E).

Compared to projectile experiments with trapezoids, the frequency of DIF occurrence on the EUP trapezoids is much higher than that obtained in thrusting and throwing experiments (Table 3). A considerable number of the trapezoids show flute-like fractures on the tip (Fig. 6A–E) and crushing on the lateral edges (Fig. 6A–C). The high frequency of these fracture types could be owing to the morphology of the trapezoids. Crucially, four trapezoids bear transverse fractures that obviously occurred after lateral retouching (Fig. 6F). In addition, a total of 12 spin-offs were observed on five trapezoids. The projectile experiments with trapezoid replicas made from siliceous shale created transverse fractures and spin-offs only when they were delivered at the velocity of a bow (Table 3). One trapezoid from the jizouden site retains only the base owing to an oblique transverse fracture (Fig. 6I), indicating significant impact energy.

Another trapezoid from the jizouden site bears a burin-like fracture measuring 29.2 mm in length, representing three quarters of the entire volume (Fig. 6G). Although the spearthrower and bow experiments produced numerous large impact fractures ~8 mm in size, only two impact fractures from the throwing experiment were larger than 8 mm, and the impact fractures from the thrusting experiment were smaller than 3 mm (Table 3). Moreover, this EUP trapezoid shows a transverse fracture from which spin-offs also occurred (Fig. 6H). One of the spin-offs is significantly large, 9.4 mm long, indicating high impact energy. In addition to the large size of the DIFs, this type of complex fracture pattern was observed only in the bow experiment (Fig. 7) (Sano et al., 2016).

The boxplots of the TCSA and mass of the EUP trapezoids show a similar range to those of North American ethnographic dart tips (Fig. 8). The EUP trapezoids and ethnographic dart tips do not show statistically significant differences in the values of TCSA and mass (Table 4). The TCSP values of the trapezoids are significantly smaller and have a smaller range of that of the ethnographic dart tips. In contrast, the values of TCSA, TCSP, and mass for the EUP pointed blades are larger than those of the ethnographic dart tips and arrowheads: these differences are statistically significant.

Thus, the EUP trapezoids are morphometrically comparable to or smaller than the North American dart tips, but they most probably would not have functioned well as thrusting or throwing spear points. In contrast, the EUP pointed blades are significantly larger and heavier than the North American dart tips and arrowheads. Consequently, their use as a thrusting or throwing spear point cannot be excluded from the morphometric data.

5. Discussion

The results of the present study confirmed that a considerable number of EUP trapezoids were used as hunting weapons. In addition,
although the function of EUP pointed blades has long been unknown owing to a lack of systematic use-wear studies on these artifacts, the relatively large number of DIFs on the pointed blades demonstrated that this tool type was also used as hunting stone tips in the Japanese EUP, as frequently trapezoids were. The delivery mode of EUP pointed blades will be examined in future work based on projectile experiments that have not yet been undertaken.

Previous use-wear studies (Kanomata, 2005; Denda, 2009; Kanomata and Denda, 2009; Kanomata, 2011; Tsutsumi, 2012) demonstrated that trapezoids were also used as cutting tools, in particular small trapezoids with marginal retouching (Type III in the classification of Sato, 1992). Taking into account that the analyzed EUP trapezoids may include pieces that had not been used or used for different functions, the frequency of DIF occurrence on the EUP trapezoids is considerably high, comparable to those in spearthrower or bow experiments.

Projectile experiments with trapezoids indicated that large impact fractures are an indicator of mechanically delivered armatures (Sano et al., 2016). The considerable number of DIFs larger than 8 mm on the EUP trapezoids, especially the presence of significantly large DIFs (>20 mm) and spin-offs larger than 6 mm, suggest that these pieces were delivered at a high impact velocity, as would be the case for spearthrower darts or bows-and-arrows.

The trapezoid experiments further suggested that the presence of diagnostic transverse fractures and spin-offs is indicative of use of a bow (Sano et al., 2016). The EUP trapezoids are thicker and shorter overall than late Upper Palaeolithic backed points from Japan. Therefore, high impact energy is required to break trapezoids transversely. As spin-
offs are often associated with transverse fractures, no spin-offs formed on trapezoid replicas in the thrusting, throwing, and spearthrower experiments. Thus, the presence of diagnostic transverse fractures and spin-offs on the EUP trapezoids may signify that they were delivered at a significantly high impact velocity, such as in bow shooting, but definitely not as slow as the velocities of thrusting or throwing.

A complex fracture pattern and high ratio of reduction due to impact damage were also observed only in the bow-velocity experiments. Sano (2016) reported that the EUP trapezoids from the Tohoku region showing diagnostic impact fractures. A–C: flute-like fractures and lateral edge crushing, D: a flute-like fracture, E: crushing and flute-like fractures, F: a transverse fracture with step termination, G: a burin-like fracture, H: a spin-off, I: a transverse fracture with feather termination. 1–3 are from the Kamihagimori site, 4 from the Kazanashidai II site, and 5–8 from the Jizouden site.
et al., 2016). The complex impact fractures on the trapezoid from the Jizouden site (Fig. 6, no. 7), comprising a transverse fracture with spin-offs and a 29.2-mm burin-like fracture, suggest that this trapezoid was fired using a bow. By comparison with the outline of a fragmented trapezoid from the same site (Fig. 6, no. 8), this fragment retains less than half of its original volume. Such high volume reduction is also a sign of bow use.

All this evidence demonstrates that the EUP trapezoids were mechanically delivered, not used as hand-casting or thrusting spear points. The morphometric analysis of the EUP trapezoids also demonstrated that the size and mass of the EUP trapezoids fall within the range of the North American dart tips or smaller. However, the small size and mass of the EUP trapezoids would not be appropriate for either javelins or thrusting spears. In contrast, the presence of the diagnostic transverse fractures and spin-offs, the complex fracture pattern, and the highly reduced pieces suggest that some of the trapezoids may have been used as arrowheads.

Unlike the spearthrower, the bow has been used in a wide range of environments from tundra, to desert, steppe, and tropical forest (Cattelain, 1997). Hence, the use of bows-and-arrows must have offered early modern humans significant advantages in hunting when they expanded into a variety of biospheres. However, it is difficult to determine the first appearance of the bow-and-arrow, as bows and arrow-shafts are usually made of wood and are therefore preserved only in particular taphonomic contexts.

The oldest remains of arrow shafts and bow-limb fragments were recovered from the Ahrensburgian layers at Stellmoor, Germany (Rust, 1943); the chronological phase of that deposit approximately corresponding to the Younger Dryas (Weber et al., 2011) between c. 12,900 and 11,700 cal BP (Broecker et al., 2010), although that material was lost during the Second World War. Based on the increase of arrow-shaft smoothers (Moreau et al., 2015), the Federmesser-Gruppen hunter-gatherers, who emerged in the Lateglacial Interstadial (Greenland Interstadial [GI]-1c and GI-1a), are believed to have delivered their curve-backed points using a bow (Street et al., 2006; Baales, 2014; Jöris and Street, 2014). The use of bows-and-arrows would already have been practiced at the beginning of the Lateglacial Interstadial (GI-1e), as suggested by morphometric studies of Hamburgian shouldered points (Weber, 2009; Riede, 2010). Given the generally small size of Late Palaeolithic projectile points, bow-and-arrow technology was probably the predominant projectile system during the Lateglacial warm period in Europe.

Bow-and-arrow technology may have originated prior to the Late Palaeolithic in Europe. Macroscopic analysis of Solutrean points, including Parpallo barbed-and-tanged points, showed a significantly high frequency of DIFs, most of which fall within the range of the North American arrowheads (Schmidt, 2015). Thus, Upper Palaeolithic hunter-gatherers may have already possessed bow-and-arrow technology in the Lower Solutrean at around 25 kcal BP (Cascalheira and Bicho, 2015).

Evidence from Sibudu Cave in South Africa, prior to 60,000 years ago, indicates that African modern humans were already using markedly small stone-tipped weapons that may have been projected using a bow (Lombard and Phillipson, 2010; Lombard, 2011; Lombard and Wadley, 2016). However, additional evidence for bows-and-arrows is absent from MIS 4 and early MIS 3 in Africa as well as Eurasia. Therefore, even though stone tips from Sibudu Cave indeed functioned as arrow-heads, it is uncertain whether the bow-and-arrow technology spread to other continents when Homo sapiens first expanded out of Africa.

The results of the present study suggested that at least some of the EUP trapezoids were transversely hafted arrowheads. As the trapezoids appear at the beginning of the Japanese EUP, the first modern humans...
would have already been equipped with the bow-and-arrow technology when they arrived in the Japanese islands. However, the timing and routes of dispersal of bow-and-arrow technology into neighboring parts of East Asia is a subject that requires further investigation, as neither direct nor indirect evidence for bows-and-arrows have been found in this region.

Similarly to Europe, arrow-shaft smoothers appeared in many regions of the Japanese islands in the Lateglacial (Sano et al., in prep.), and most of the bifacial stemmed-points in the Lateglacial fall within the range of North American arrowheads (Hashizume, 2015; Midoshima, 2015). In addition, significantly small barbed stone tips, which are typologically labeled as arrowheads, gradually increase in the Lateglacial Interstadial. Therefore, in the Lateglacial bow-and-arrow technology appears to have become predominant in Japan as elsewhere.

In contrast to the spearthrower that is mostly used in open environments (Cattelain, 1997), the bow is also effective in dense forests. Before the bow-and-arrow technology became predominant in the Lateglacial, this projectile technology would have already played an important role for EUP hunter-gatherers in the Japanese forest-rich environment.

6. Conclusion

A comprehensive TCSA analysis of the Japanese EUP and LUP stone tips indicated that some of the Upper Palaeolithic stone tips from the Japanese islands may have been arrowheads (Tamura, 2011); however, testing by use-wear analysis was required to determine whether the analyzed stone tips were indeed used as hunting weaponry. The present study demonstrated that the EUP trapezoids were indeed used as hunting armatures that were definitely mechanically delivered, and some were probably fired using a bow. Although there is no direct evidence for Palaeolithic spearthrowers and bows in East Eurasia, the fact that the Japanese EUP hunters may have used bows-and-arrows imply that the first modern humans expanded into East Asia together with bow-and-arrow technology. This study does not exclude the possibility that the EUP hunter-gatherers also employed other projectile systems, such as spearthrower-darts and thrusting spears. However, bow-and-arrow hunting was probably an important hunting method in the forest-rich environment during the early phase of the Japanese EUP.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.jasrep.2016.09.007.

Table 4

<table>
<thead>
<tr>
<th>Types</th>
<th>N</th>
<th>Mean</th>
<th>SD</th>
<th>Min</th>
<th>Max</th>
<th>Vs. ethnographic arrowheads</th>
<th>Vs. ethnographic dart tips</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trapezoids</td>
<td>TCSA</td>
<td>20</td>
<td>60.3</td>
<td>33.6</td>
<td>18.8</td>
<td>t = 3.591, p &lt; 0.05</td>
<td>t = 0.298, p = 0.768</td>
</tr>
<tr>
<td></td>
<td>TSCP</td>
<td>20</td>
<td>38.0</td>
<td>10.6</td>
<td>21.1</td>
<td>t = 3.273, p &lt; 0.05</td>
<td>t = 3.357, p &lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>Mass</td>
<td>17</td>
<td>4.3</td>
<td>2.8</td>
<td>1.8</td>
<td>t = 3.118, p &lt; 0.05</td>
<td>t = −0.062, p = 0.950</td>
</tr>
<tr>
<td>Pointed blades</td>
<td>TCSA</td>
<td>18</td>
<td>154.1</td>
<td>77.3</td>
<td>24.5</td>
<td>t = 6.638, p &lt; 0.05</td>
<td>t = 5.215, p &lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>TSCP</td>
<td>18</td>
<td>62.7</td>
<td>15.3</td>
<td>29.7</td>
<td>t = 8.492, p &lt; 0.05</td>
<td>t = 3.997, p &lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>Mass</td>
<td>18</td>
<td>17.8</td>
<td>11.0</td>
<td>2.7</td>
<td>t = 5.960, p &lt; 0.05</td>
<td>t = 4.991, p &lt; 0.05</td>
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</table>


References


