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ORIGINAL PAPER

Iron technology and medieval nomadic communities of East Mongolia

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Abstract Numerous iron objects from the medieval sites in Mongolia were metallographically examined for a comparative study intending to probe indigenous and foreign impacts on the establishment of local iron tradition. The artifact assemblage includes iron and cast iron objects recovered during the recent Mongol-American joint expedition to sites in the eastern part of Mongolia. Cast iron objects, dominating the assemblage, were mostly in the form of small fragments or square bars, which would be of little value if they were to be used for casting. However, their greatly varying microstructures reveal evidence of various small-scale steelmaking processes involving cast iron. This observation suggests that most of them were prepared as a practical means to procure steel, a highly valued commodity particularly among nomadic communities. In contrast, other iron objects with microstructures characteristic of inferior bloomery products constituted only a minor part of the assemblage. We discuss the results of our analysis from a comparative perspective and propose that this unique ironworking tradition discovered in eastern Mongolia reflects the distinctive geographical and sociopolitical background of the nomadic groups and periods concerned.

Keywords Mongolian empire · Iron technology · Cast iron · Steel · Nomadic communities

Introduction

The eastern part of the nation of Mongolia played a key role in political and cultural developments of Inner Asia even prior to the rise of the earliest state known as the Xiongnu polity. Little is known, however, of the early history and archeology of this particular region. This lack of information poses a serious difficulty in research intending to understand the development of local material cultures and technology as determined by various internal and external sources of influence. Given limited access to the kinds of documentary evidence that would be required for the study of ancient technologies, the best alternative may be found in archeology. This approach, however, also has limitations in many cases due to environmental and cultural site formation processes that sometimes allow little archeological evidence to survive for examination. In this respect, metallic artifacts and their derivatives including slag and charcoal are of special significance because of their relatively high resistance to weathering in arid steppe environment, allowing them to have a better chance to remain intact. More importantly, bronze and iron technologies have constituted two key elements in the establishment of material cultures throughout the history from the beginning of their use. We therefore pay special attention to the numerous metallic artifacts recently recovered from the joint Mongol-American expedition to the archeological sites at Delgerkhaan Uul in Sukhbaatar province of eastern Mongolia (Fig. 1). The expedition was carried out as part of the long-term project entitled the Dornod Mongol Survey (DMS). Given their abundance and diversity, we focus first on iron and cast

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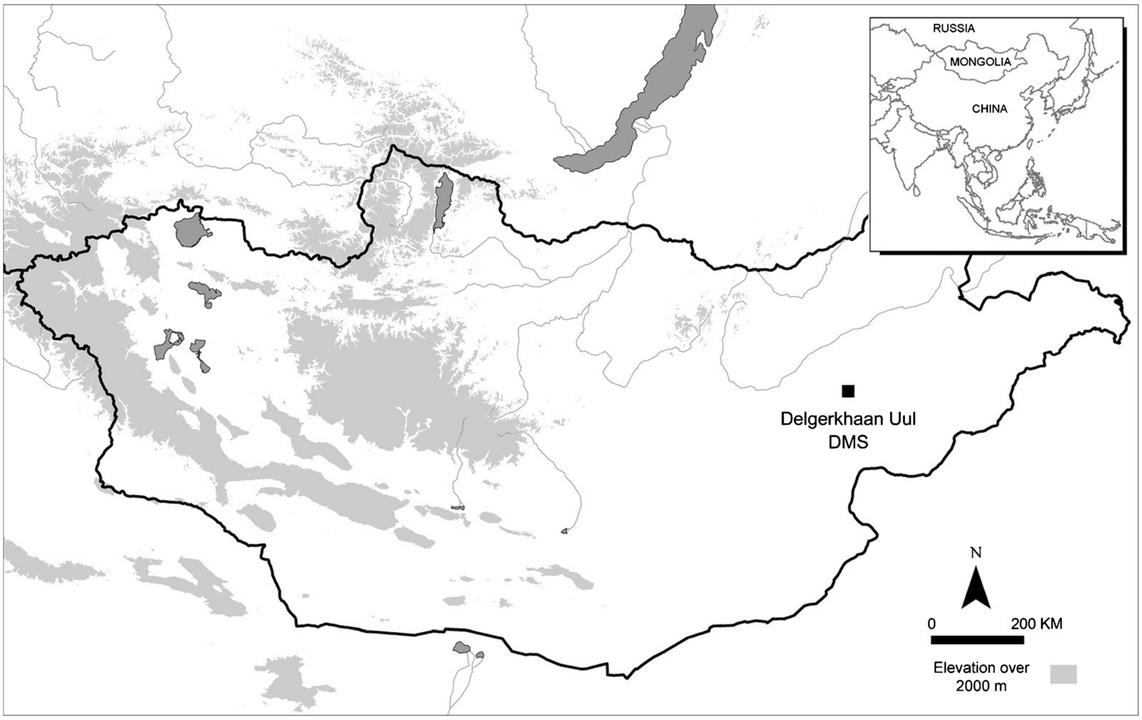

Fig. 1 Map of Mongolia showing the location of the archeological sites mentioned in the text

iron objects from the DMS sites of medieval contexts (500–1400 AD), with the majority of them belonging to the Khitan/Mongol period (ca. 950–1400 AD).

The applicability of Mongolian bronze and iron artifacts as archeological materials with substantial promise for understanding prehistoric and historic steppe communities has been well-attested in recent work by Park et al. (2008, 2010, 2011, 2015, 2016, 2017). Most notable in this body of recent research is evidence that the Xiongnu state established unique metallurgical traditions for the production of both bronze and iron, which were clearly distinguished from Chinese style of technologies. Mongolian bronze technology of the pre-Xiongnu and Xiongnu periods heavily depended on the use of arsenic (As) as the major alloying element, mostly without the addition of lead. Tin (Sn) was also used, but not frequently and in small amounts. This alloy tradition is in strong contrast to traditional Chinese bronze recipe based on the profuse use of both tin and lead without the intentional addition of arsenic. Xiongnu iron technology, based on the smelting of bloomery iron and steelmaking through carburization, was also in strong contrast to that of China, characterized by the production of cast iron and steelmaking through decarburization. Cast iron was also used by Xiongnu people, but on a much smaller scale and only for the fabrication of a few moving parts of horse-drawn carriages. This Xiongnu style of iron technology was largely carried forward to the Mongol period with modification noted only in the increased use of cast iron in its variety of applications.

This resistance to foreign technological influences resulted from culturally governed selection of external ideas and practices in keeping with the unique steppe environments and nomadic lifestyle, in addition to indigenous innovation (Wagner 1996, 2008; Park et al. 2017). It is important to note, however, that the presence of China was reflected in some bronze artifact formulas recovered at certain Xiongnu affiliated sites within the frontier zone (Park et al. 2016).

Scientific research on Mongolian bronze and iron traditions is just beginning, and the pertinent data thus far reported are still preliminary and far from being sufficient for a comparative discussion on developmental processes within different regions. Nevertheless, the available information is adequate to pose questions on the variability of regional metallurgical traditions. This variability has important implications for Mongolian archeology since it reflects input from non-local metallurgical traditions including those of Central Asia, Siberia, and China. Given no notable scientific analyses reported for metal artifacts from eastern Mongolia, our DMS metal assemblage is invaluable first for the characterization of local iron tradition and then for a comparative study focusing on its spatiotemporal variability. We will provide a detailed account of the analytical results and then compare them with data available for the iron tradition established at Karakorum, the capital city of the Mongolian empire established in central Mongolia (Park and Reichert 2015).

Comments on artifacts

The external appearance of the DMS iron objects under investigation is illustrated in Fig. 2 where all the artifacts are shown to scale, each with a number for identification. In this photo, those with the identification number underlined are objects made of bloomery iron but the others were all derived from cast iron. It was almost impossible in many cases to distinguish between these two different types of iron objects without relying on metallographic examination, which is described in detail in a later section. It is surprising to note that there are only 16 bloomery objects out of the 67 examined, demonstrating the domination of cast iron in our DMS iron assemblage. It is strange, however, that the majority of those in Fig. 2 are in the form of small fragments, which would be of little value if they were to be used individually for making a finished cast iron product. Without even mentioning the technological difficulties and substantial material losses associated with the process of re-melting and casting at such a small scale, it would not be sufficient for making one small bowl even if all the materials in Fig. 2 were combined. It is evident therefore that the cast iron objects were not meant to be employed in normal casting but were intentionally prepared for some other specific purpose.

Of the cast iron artifacts in Fig. 2, those in the form of square bars, as seen in objects #33–39, are of special significance for comparative purposes since similar objects have been excavated from Mongol sites in central Mongolia, often in large quantities (Pohl et al. 2012: 53; Shiraishi and Tsogtbaatar 2009: 559). They have been hypothesized to be product intermediaries manufactured for further processing (Osawa 2005: 45). This premise has been confirmed by recent metallographic analysis (Park and Reichert 2015) on bar-type artifacts recovered from the Mongol site at Karakorum.

Another group of important artifacts includes objects #40–46 and 48–51. These are clearly distinguished from the rest in the assemblage by the uniquely irregular surface profiles consistently found associated with them. Such a

Fig. 2 The general appearance of the iron object under consideration. The numbers identifying the objects are consistent with those in Table 1. The objects were all made of cast iron with the exception of those with the identification number underlined. Objects #33–39 are product intermediaries (Osawa 2005: 45) in the form of square bars excavated from other Mongol sites, often in large quantities (Pohl et al. 2012: 53; Shiraishi and Tsogtbaatar 2009: 559). Objects #40–46 and 48–51 are clearly distinguished by the uniquely irregular surface profile, which is characteristic of a solidification reaction from the partially molten state

unique surface feature is characteristic of a solidification reaction from the partially molten state, signifying that the objects were all given a thermal treatment slightly above the liquidus temperature of each artifact alloy. In this temperature range, the metal objects would not have been fully molten, thereby maintaining substantial portion of their original shape. This fact is readily confirmed in objects #42 and 43 where in both cases a small metallic patch is attached to the top surface of the larger metal plate underneath. It is evident in each case that the two separate metal pieces stacked together were treated at elevated temperatures such that their surfaces in contact became partially molten to allow for the attachment upon freezing. Although not clearly visible in Fig. 2, objects #41, 49 and 51 were also found to consist of two or more pieces welded together.

Careful investigation of Fig. 2 in light of this observation suggests that all of these metal objects could have served as an input material, whether individually or in various combinations, for the specific small-scale thermal treatment described above. This is particularly pertinent for cast iron objects that readily melt at relatively low temperatures due to high carbon contents. One may then safely conclude that the small and often fragmentary cast iron artifacts in Fig. 2 did not come into existence fortuitously but were carefully prepared with a certain purpose in mind. In this situation, cast iron in any shape and size must have been a highly valued commodity that could be collected and saved for reuse. Moreover, larger cast iron fragments may have been broken into smaller pieces to be practical for use in such small-scale applications. As such, these DMS sites give evidence for a unique iron tradition depending heavily on cast iron and associated engineering processes. This particular technological landscape is in strong contrast to that of the roughly contemporary Karakorum site where fully established bloomery-based technology served as the primary means for the fabrication of key iron products (Park and Reichert 2015). It is impressive to recognize that even without information available from scientific analyses, the artifact composition alone, as apparent in Fig. 2, can provide significant information about DMS sites and their associated technologies.

Excavation contexts

The Dornod Mongol Survey (DMS) project is a multi-year survey and excavation effort designed to study the prehistory of eastern Mongolia in greater detail. The regional study area includes major centers of ancient habitation and mortuary activity including the area of Delgerkhaan Uul where the initial focus of field research has been concentrated. The local environment at Delgerkhaan Uul marks an ecotone between steppe and arid steppe where a confluence of two seasonal water ways ensures reliable water and pasture to support herd animals. For this reason, Delgerkhaan Uul is rich in pastoral nomadic campsites dating from the Bronze Age up to the twentieth century. Systematic survey of approximately 75 km^2 thus far has documented more than 200 such sites. In addition, evidence at Delgerkhaan Uul for both copper alloy and iron working is extensive and includes the presence of ores, manufacturing remains, and finished products.

The materials analyzed for this study were recovered from surface collections at multiple artifact scatter sites, most of which are interpreted as seasonal habitations sites while a smaller number are considered as metal production areas. In addition to slag and finished metal artifacts, habitation sites also contain household remains such as pottery fragments, grinding stones, and small items such as glass beads and coins. These artifact types, and especially instances of decorated pottery, are indicative of the early to late medieval period and particularly the Khitan/Mongol period. These diagnostic artifacts were therefore used to assign site chronologies prior to radiocarbon analysis.

Analytical results

For metallographic examination, one or more specimens were taken from each of the objects in Fig. 2. The specimens were mounted and polished following standard metallographic procedures and then etched using a solution of 2% nitric acid by volume in methanol. Their microstructures were examined using an optical microscope and a scanning electron microscope (SEM). The microstructures observed were used to infer the carbon level, which was specified according to weight fraction to the accuracy of a few tenths of a percent. The presence of other minor elements such as silicon (Si), sulfur (S), and phosphor (P) was checked using the energy-dispersive X-ray spectrometer (EDS) included with the SEM, whose detection limit is approximately a few tenths of a percent.

Figure 3a–f present optical micrographs taken of the specimens from objects #9, 14, 30, 38, 33, and 45, respectively. The structures in these micrographs were all derived from cast iron and consist of two major constituent phases, ferrite and cementite, existing separately or in combination. The greatly varying microstructures illustrated were determined by the relative amount of these two phases and the mode of their combination. It is known that ferrite can contain carbon up to 0.02% while the carbon level of cementite is fixed at 6.67%. In Fig. 3a–d, f, the bright areas are occupied by the cementite phase while the dark regions comprise ferrite and cementite arranged in alternating layers, though not resolved in such low magnified micrographs. This lamellar structure, named pearlite or eutectoid with its average carbon content set at 0.77%, emerges below 727 °C from the transformation of austenite, a high-temperature metal phase precipitated directly out of

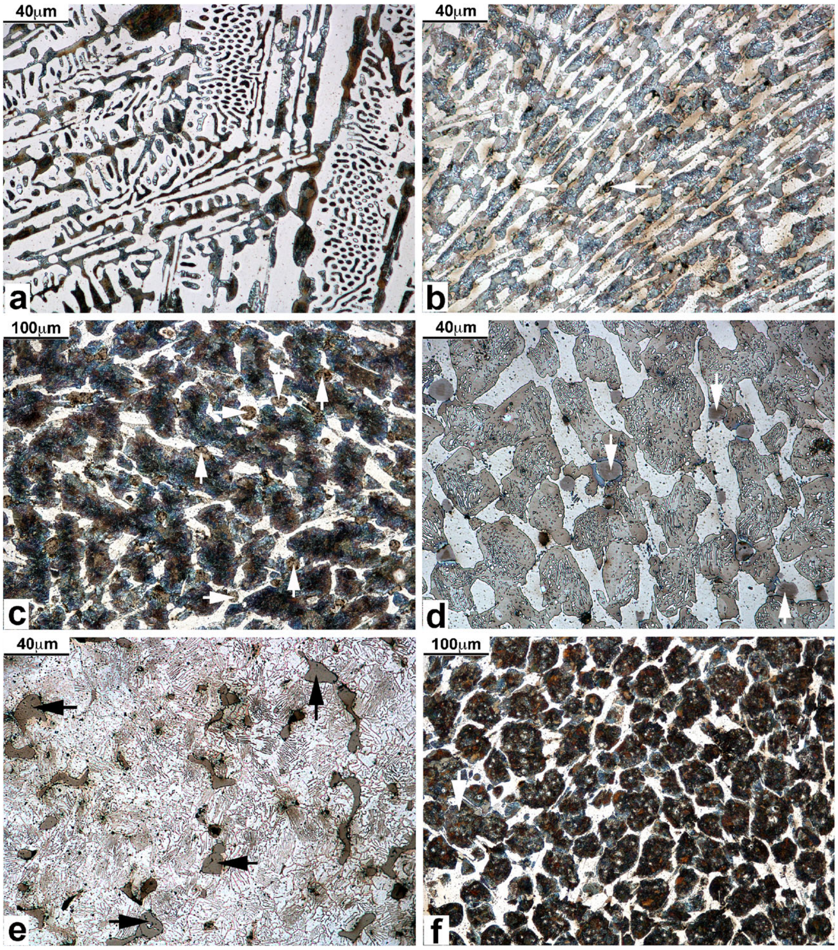

Fig. 3 Optical micrographs showing the structure of objects #9, 14, 30, 38, 33, and 45 presented in Fig. 2, respectively. Microstructures represented by panel a are referred to as type 1, those represented by panels b–e and f are termed type 2 and type 3, respectively, in the text and also in Tables 1 and 2

molten cast iron. Evaluation of the above micrographs in terms of the relative fractions of pearlite and cementite, therefore, allows the approximate carbon level to be determined between 0.77 and 6.67%.

The structure in Fig. 3a is of special significance as a reference since it is formed during the solidification of cast iron containing 4.3% carbon at the temperature of 1148 °C. This particular condition defined by the specific carbon content and temperature is termed eutectic with the associated microstructure named white cast iron eutectic. It is important to remember that molten cast iron of this composition solidifies at the fixed lowest temperature to give the particular structure consisting entirely of eutectic. Structures not much different from this were also observed in objects #1–11, with their carbon content ranging from 3.8 to 4.5%. We will refer to this particular group of microstructures as type 1.

With the decrease in carbon level, the solidification of cast iron begins at higher temperatures and is completed at the eutectic point. In this hypoeutectic case portrayed in Fig. 3b, the austenite phase is first precipitated and grows until the eutectic growth commences at the eutectic temperature. The large dark areas of pearlite seen in Fig. 3b, therefore, roughly correspond to the portion precipitated in the form of pro-eutectic austenite above 1148 °C. The carbon content of this specimen is inferred from the relative fractions of pearlite and cementite to be 3.0%, placing the associated melting temperature at around 1300 °C. The carbon level in Fig. 3c, d may similarly be determined to be about 1.8 and 2.0%, respectively. The greatly increased pearlite fraction in these two micrographs is indicative of such low carbon levels, while the greatly expanded dimension of pearlite areas is characteristic of the pro-eutectic phase solidified at extremely slow rates during casting. In addition, the small particles and ribbons visible in the dark areas in Fig. 3d are those resulting from coarsening of the cementite phase in pearlite. Such coarsening, which is attained by a prolonged thermal treatment of pearlite near 727 °C, suggests that a similar treatment was given to the specimen in Fig. 3d.

A still lower carbon concentration of approximately 0.77% is observed in Fig. 3e, where the entire area is filled with pearlite. In terms of carbon level, this specimen is not cast iron but steel, which is also reflected in the microstructure as seen in Fig. 3e. One conspicuous deviation is the numerous inclusions scattered across this micrograph, some of which are marked by arrows. EDS analysis revealed that these inclusions correspond to particles of iron sulfide. Such sulfide compounds, when present in steel, seriously deteriorate material properties, especially impact resistance (Verhoeven 1975: 195–196). Their presence as seen in Fig. 3e is diagnostic of mineral coal employed in the smelting of parent cast iron (Park et al. 2008; Park 2015) from which the steel was derived. Moreover, their unique distribution pattern confirms that the object was initially cast to shape with no notable mechanical working applied. Similar sulfide inclusions were consistently observed in the majority of the specimens examined, which is also confirmed in Fig. 3b–d where some of such particles are marked by arrows.

The micrographs in Fig. 3b–e illustrate great variation as determined by the widely varying carbon content and different conditions present during casting. It is important to note, however, that casting was the exclusive method of fabrication regardless of the current carbon concentration. Moreover, the raw material employed for initial casting was all smelted using mineral coal, which is evidenced by the consistent presence of numerous sulfide particles in their respective microstructures. In this regard, we will refer to the wide range of microstructures represented in Fig. 3b–e as type 2.

The structure shown in Fig. 3f is not much different from those in Fig. 3c, d and consists of dark pearlite regions outlined by the network of cementite, allowing the average carbon content to be determined at approximately 1.8%. One important variation is found in the peculiar shape of pearlite, which is roughly spherical and displays no such directionality as can be seen in Fig. 3c, d. Given the pearlite areas approximating those solidified first as pro-eutectic austenite, the structure seen in Fig. 3f portrays a specimen nearing the completion of the solidification reaction. The dark areas generally spherical in shape lacking directionality point to the fact that the growth of their parents as pro-eutectic austenite occurred slowly and evenly in all directions. This condition is best achieved in protracted heating at a fixed temperature slightly above the eutectic point 1148 °C (Park et al. forthcoming). In this treatment, the growth of austenite is driven not by the decrease in temperature, which is the case with most other specimens, but by the decrease in general carbon level. This reduced carbon content, caused by decarburization readily occurring in such elevated temperatures, raises the melting point of cast iron and allows for further growth of austenite. Such treatment will eventually lead to the consolidation of two or more such pro-eutectic areas, which can be verified in Fig. 3f at the arrow near the left edge. This particular thermal treatment is also well reflected in the peculiar surface profile of the object in question, #45, as well as many others in Fig. 2. Their consistent and distinctive surface features suggest that they were all re-melted and kept in the partially molten state, evidently for decarburization as a means of steelmaking. This unique structure will be referred to as type 3.

Our artifact assemblage also contains objects made of low carbon iron. Examination of their microstructure consistently reveals ferrite grains containing a number of non-metallic inclusions elongated along the forging plane. This structure, referred to as type 4 in this article, is characteristic of bloomery iron forged to shape.

The analytical results on microstructure and carbon concentration are summarized in Table 1 along with some brief information on the recovery site, typology-based periodization and the mass of each object. The numbers labeling the objects are consistent with those in Fig. 2. For the benefit of later discussion, key data in Table 1 were selected to prepare Table 2, which provides a concise overview of the number and fraction of artifacts in each type, the range of carbon concentration, the method of fabrication and the description of microstructures.

Discussion

The metallographic examination as summarized in Tables 1 and 2 reveals various microstructures derived primarily from cast iron through a wide range of engineering processes including casting, heating, and re-melting. Table 2 shows that the majority of specimens examined are members of type 1, 2, and 3 in the classification of cast structures based on carbon contents, the presence of sulfide particles, and the application of re-melting. Given that the functionality of cast iron is greatly reduced due to its inferior impact resistance from high carbon levels, the treatments implied by these varying microstructures were likely associated with the control of carbon content and microstructure. The visual inspection of the shape and size of the artifacts in Fig. 2 also suggests that they did not come into existence by chance but were intentionally prepared for a specific purpose.

Further support for this hypothesis comes from type 1 objects consisting primarily of eutectic structures, often with a little pro-eutectic phase. Their carbon level of 3.8 to 4.5%, guaranteeing the lowest range of melting temperatures, is evidently optimal for casting. The average mass of type 1 fragments measuring approximately 12 g, however, does not support the claim that they were meant to make new finished cast iron products. In addition, the lack of sulfide compounds in type 1 microstructures is a strong indication that the objects in this group were initially cast during the Khitan period or earlier (Park et al. 2008; Park 2015). Such an early object recovered from a later period site signifies that cast iron, even in small fragmentary forms, was a valuable commodity to be recycled. This fact is confirmed by one of type 1 objects (#1) from a Khitan/Mongol site (see Table 1) that has been dated to the Xiongnu period by radiocarbon analysis (2 sigma, 350–302 BC [18.9%], 226–94 BC [81.1%]) (Park et al. forthcoming).

Type 2 artifacts are distinguished from those of type 1 by their substantially reduced carbon concentration of 0.8 to 3.5% and the consistent presence of numerous sulfide compounds in their microstructures. In addition, the extreme coarseness found in type 2 structures is indicative of unusually slow

Table 1 Summary information on the iron objects examined from the medieval and early historic sites in East Mongolia and their microstructure, approximate carbon concentration and mass. The numbers labeling the objects are consistent with those in Fig. 2

#	Site	Period[a]	Microstructure type[b]	C (%)[c]	Mass (g)	Comments
1	241	K/M	1	4.3	21	
2	241	K/M	1	4.3	12	
3	241	K/M	1	4.3	8	
4	241	K/M	1	4.5	2.5	
5	264	K	1	4.5	9	
6	264	K	1	3.8	1	
7	301	K/M	1	4.3	2.3	Annealed
8	316	-[d]	1	4.0	23	Annealed
9	374	K/M	1	4.0	21.9	
10	748	K/M	1	4.3	34.8	
11	Surface find	-	1	4.0	8	Very fine
12	206	Med	1a	4.3	18	Gray cast iron eutectic
13	236	-	2	3.2	-	
14	236	-	2	3.0	-	
15	248	M/EH	2	1.5	9	Steel; annealed
16	256	K/M	2	3.5	41.5	
17	301	K/M	2	2.0	5.5	Steel
18	301	K/M	2	2.0	-	Steel
19	303	K/M	2	2.0	68	
20	303	K/M	2	2.0	28	
21	303	K/M	2	3.0	13	
22	313	K/M	2	2.0	15	
23	397	K/M	2	3.5	4.4	
24	491	K/M	2	2.0	22.8	
25	705	K/M	2	2.5	34.5	
26	705	K/M	2	1.0	37.4	Steel; annealed
27	705	K/M	2	0.1	13.6	Nail; Hi P
28	705	K/M	2	1.2	16.6	Steel; annealed
29	710	-	2	3.0	23.7	
30	710	-	2	1.8	20.1	
31	748	K/M	2	1.0	10.6	Steel
32	761	T or K/M	2	1.2	72.5	Steel
33	256	K/M	2	0.8	10	Steel; bar
34	256	K/M	2	1.0	7	Steel; bar
35	493	K/M	2	1.0	13.1	Steel; bar
36	493	K/M	2	3.0	10.7	Bar
37	705	K/M	2	1.5	13.9	Bar
38	705	K/M	2	2.0	16.7	Bar
39	748	K/M	2	2.5	13.6	Bar
40	248	M/EH	3	2.5	16	
41	374	K/M	3	2.0–3.5	25.5	Charcoal attached
42	397	K/M	3	2.0	11.3	
43	477	-	3	2.0	15.3	Charcoal attached
44	477	-	3	2.0	11.0	Slag
45	477	-	3	1.8	6.0	
46	477	-	3	0.8–3.5	9.3	Slag
47	477	-	3	2.0	1.4	
48	493	K/M	3	2.0	14.1	
49	710	-	3	2.5–3.5	76.7	

Table 1 (continued)

#	Site	Period[a]	Microstructure type[b]	C (%)[c]	Mass (g)	Comments
50	748	K/M	3	0.8–3.5	15.8	Charcoal attached
51	Surface find	-	3	2.0–2.5	83	
52	222	-	4	--[e]	2	
53	222	-	4	--	1	
54	236	-	4	--	-	
55	256	K/M	4	--	2	
56	256	K/M	4	--	7	
57	263	-	4	--	3	
58	301	K/M	4	--	4	
59	303	K/M	4	--	7	
60	397	K/M	4	--	1.8	
61	397	K/M	4	--	1.7	
62	477	-	4	--	3.2	
63	477	-	4	--	2.2	
64	705	K/M	4	--	18.3	
65	748	K/M	4	--	3.5	
66	761	T or K/M	4	--	5.6	
67	029	-	4	--	6	Fewer inclusions

[a] Period: T) Turk, K) Khitan, M) Mongol, Med) Medieval (AD 500–1400), EH) Early Historic (post-AD 1400) periods

[b] Microstructure type: description of microstructure for each type is presented in Table 2

[c] (%): based on weight fraction

[d] -: Not determined

[e] –: Bloomery iron with little C

cooling rates applied during the solidification and cooling stages of casting. Sulfide particles found in type 2 specimens are significant because they were derived from mineral coal, generally containing sulfur, which was used as a fuel in smelting. There is little doubt that coal-based smelting removed restrictions long imposed by limited access to charcoal and gave added freedom to furnace construction. This freedom in turn would have allowed furnaces to operate at higher temperatures, which is necessary for the production of cast iron with lower carbon. The use of mineral coal evidenced in type 2 objects, therefore, is responsible for their greatly lowered carbon concentrations. Also important to note is that coal-based smelting commenced in Mongolia during the Khitan period and came to dominate during the Mongol imperial period (Park et al. 2008; Park 2015; Park and Reichert 2015). In chronological sequence, therefore, type 2 objects should be dated to the Khitan/Mongol

Table 2 Number and fraction of artifacts in each type, range of carbon concentration, method of fabrication and description of microstructures

Type	Number (fraction, %)	C content in weight %	Fabrication method (fuel)	Microstructures and comments
1	12 (18)	3.8–4.5 (mostly ≈ 4.3)	Cast (charcoal)	All near eutectic white cast iron except one gray cast iron eutectic; all in as-cast conditions except two annealed
2	27 (40)	0.8–3.5 (mostly ≥ 2.0)	Cast (coal)	Varying proportions of proeutectic dendrites with inter-dendritic cementite; mostly in as-cast conditions with some annealed; notable amounts of S and P detected often with a little Si
3	12 (18)	0.8–3.5 (mostly ≤ 2.0)	Cast (charcoal or coal)	Large near-spherical proeutectic islands with their boundaries filled with cementite or white cast iron eutectic; all re-melted using charcoal
4	16 (24)	Negligible	Forged (?[a])	Ferrite grains containing non-metallic inclusions elongated along the forging plane; all bloomery products
Total	67 (100)			

[a] ?: Not known

period in agreement with chronological estimates based on other lines of evidence.

The reduced carbon concentration seen in type 2 objects was a beneficial effect greatly desired for the making of steel directly from smelting. In fact, a substantial fraction of artifacts in this group have carbon concentrations within the range of steel below 2.0%. This is especially true for those made in the form of square bars (see objects #33–35 and 37). This particular kind of artifact has been recovered from many sites across Mongolia, often in large amounts, and was probably produced on a large scale in well-supplied workshops for circulation as product intermediaries. It is important to note, however, that a number of type 2 artifacts, particularly those in fragmentary form, contain 2.5% carbon or more, which is too high to be described as steel and would not allow any significant mechanical working to be applied. Without a practical and reliable method to lower carbon content, therefore, most objects in Fig. 2, with the exception of some of those supposedly from professional production centers, would have been useless for recycling.

Accordingly, we discovered in type 3 artifacts evidence for a novel technology used to transform small pieces of cast iron into steel. The process as inferred from their microstructure and also from their peculiar surface features comprises a protracted heating of recycled cast iron fragments at temperatures slightly above 1148 °C where they remain in a partially molten state. A detailed account of the reactions occurring in this re-melting treatment will be given in a separate paper (Park et al. forthcoming) along with other key technological aspects. It should be noted, however, that accelerated decarburization at this high temperature, especially from the liquid part, reduces the overall carbon level down to 2.0% or below within a reasonable amount of time such that the method is practical as a small-scale steelmaking technique. As can be seen in Table 2, the carbon content of type 3 objects varies significantly but mostly falls within a range of 2.0% and below. More importantly, this method allows the heating time and temperature to be freely adjusted for better control of carbon content, not to mention the ability to remove other unwanted elements such as sulfur and phosphor.

In principle, this particular method is not much different from that employed in modern steelmaking industries where cast iron is first smelted and then, in a separate process, decarburized into steel. This two-step method reflects the difficulties involved in making steel directly from smelting (Rostoker and Bronson 1990). In China, a similar technique had been in practice from antiquity as one of the major means of steelmaking (Wagner 1996, 2008). The process as noted in type 3 objects, therefore, was nothing new in principle. In practice, however, it is a rare example of an industrial scale technique implemented at an extremely small scale. Steelmaking at such a limited scale would never have been attempted in the central areas of neighboring China where mass production of steel from cast iron was practiced at almost an industrial level. As such, the implementation of this technique must have been the result of an educated choice tailored to meet steppe environments where access to iron products was just as important as in early China but subject to a decidedly different cultural and resource setting.

With this unique steelmaking technique available, small pieces of cast iron in fragmentary form and otherwise of little use, became a valuable resource for recycling. Perhaps in certain cases, a cast iron object would have been prized as a potential source for steel making rather than for its original purpose. For example, a small cast iron bowl of a little more than 1 kg, when fragmented, would have produced materials approximately equal in amounts to all those in Fig. 2 combined. A few such bowls would have sufficed to meet the needs of a whole household or even a steppe community depending on the local need for steel. Small-scale steelmaking, therefore, added great flexibility to iron procurement strategies in the steppe region as long as supply chains were accessible for cast iron to be acquired even once in a while. In this situation, no local production of cast iron would have been practical or necessary since most raw materials, apart from those recycled, would likely have been supplied from workshops in other parts of the Khitan or Mongolian empires.

These observations point to an interesting cast iron-dependent local iron tradition founded exclusively on externally supplied raw materials without the need for on-site cast iron production. It has yet to be determined whether this cast iron-dependent tradition was unique to the DMS region during the Khitan/Mongol period or a common technology across a broader portion of eastern Mongolia from antiquity onward. In either case, it is in strong contrast to the iron tradition of central Mongolia as observed in the metal objects from both Xiongnu and Mongol period contexts, which consistently display bloomery-based iron technology dominating local iron industry (Park et al. 2008; Park and Reichert 2015). Cast ion was also used in this region from the Xiongnu period onward with evidence for its use increasing during the Khitan/Mongol period (Park et al. 2008; Park and Reichert 2015; Perlee 1959, 1961, 2001). Its application, however, was limited to making less critical items such as domestic or farming implements requiring no special material properties. Given the influential interaction networks established across Mongolia from antiquity onward and steppe innovations in movement and transportation (Honeychurch 2014), it is unlikely that key technological ideas practiced in one area would have been completely unknown to other areas. This hypothesis is likewise supported by the propensity of steppe people to pursue flexible and adaptable strategies and suggests that this apparent regional difference in iron technology resulted not from a lack of technological information or capacity but from selection among multiple alternatives.

Given the political make-up of the Khitan and Mongol empires and their expansive geographical territories, it is quite possible that the distribution of iron products from imperial workshops was a venue for political negotiation among centralized leadership and outlying political factions. As part of the project of sustaining a large empire, imperial authorities typically devise strategies promoting integration to enfranchise the political center while secondary and tertiary power holders strive to enfranchise their own regional or local agendas (Honeychurch 2015; Rogers 2012; Sinopoli 1994). The response of a local community, such as that at Delgerkhaan Uul, to these political conditions may have been to place emphasis on diverse multiple strategies to access needed iron materials including obtaining products from various centers as well as practicing different methods for local production. One may therefore expect that the cast iron dependency was important as an alternative in reserve to be exploited when bloomery products, for whatever political or organizational reason, were not sufficient. In this particular case, local ironworking was probably deeply enmeshed in the politics among steppe communities and imperial leadership. It is intriguing to note that information as subtle as the degree of external provisioning to a local community within a much larger empire can be inferred from the study of local iron traditions.

Conclusion

A number of iron objects recovered from the medieval sites at Delgerkhaan Uul in Sukhbaatar province of eastern Mongolia were metallographically examined. The assemblage of our metal artifacts consists primarily of small pieces or fragments of cast iron weighing 20 g or less, coming mostly from Khitan/Mongol contexts. Cast iron in such small quantities would generally be considered of little use; however, we detect clear evidence of a unique steelmaking technique observed in some of the cast iron objects examined. The technique as inferred from their characteristic microstructure and also from their peculiar surface profile involves one or more cast iron fragments heated slightly above 1148 °C to reduce their carbon level to the range of steel through decarburization. Steelmaking at such a small scale was evidently instrumental in rendering cast iron, even in fragmentary form, as a valued resource for producing the desired material having superior functional properties. The importance of cast iron fragments was also evidenced by the make-up of our medieval site assemblages which contained cast iron from much earlier time periods as well as contemporaneous specimens. This would suggest the purposeful collection of scrap cast iron for the production of steel.

Given the advantage of the bloomery process for occasional and small-scale production (Wagner 1996), the emergence of a non bloomery-based iron tradition in steppe areas was probably encouraged by variability in the supply and distribution of iron materials from centralized supply chains. Iron acquisition must have depended on the stability of resource networks as determined by the social and political environments surrounding a given steppe region located within the Khitan and Mongol empires. Discovery of this innovatively small-scale method of steelmaking may therefore be understood as reflecting a persistent nomadic propensity to remain flexible, not only in politics (Honeychurch 2014) but also in key aspects of material cultures. With the unique steelmaking technique in their possession, local steppe communities had greater options for how to meet local needs despite unpredictable political conditions beyond their control.

It remains unclear at what point in time the iron metallurgical practices observed in our metal objects were established. There is no question, however, that their implementation allowed local steppe communities to alternate between dependencies on cast iron and bloomery iron as determined by pertinent sociopolitical settings, which must have had a direct impact on the stability of internal interaction networks. The technological conditions present at Delgerkhaan Uul in eastern Mongolia constitute a notable deviation from steppe neighbors in central Mongolia where access to bloomery iron seems to have been much more prevalent (Park et al. 2010; Park and Reichert 2015). A continuing study is necessary to clarify the chronological and geographical frames in which these intriguing regional differences developed. We are especially curious as to whether such technological variations reflected an attempt at imperial management and control over steppe communities and political factions far from the seats of centralized imperial power.

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References

Honeychurch W (2014) Alternative complexities: the archaeology of pastoral nomadic states. J Archaeol Res 22:277–326

Honeychurch W (2015) Inner Asia and the spatial politics of empire: archaeology, mobility, and culture contact. Springer, New York

Osawa M (2005) One of the forms of iron producing in the mongol empire obtained from forge-related objects found at Avraga site. Approach based on metallurgical study, in: Shimpei Kato (Ed.), The Avraga site. Preliminary report of the excavations of the palace of Genghis Khan in Mongolia 2001–2004. Kokugakuin University, pp. 45–62

Park JS (2015) The implication of varying ^{14}C concentrations in carbon samples extracted from Mongolian iron objects of the Mongol period. J Archaeol Sci 63:59–64

Park JS, Reichert S (2015) Technological tradition of the Mongol Empire as inferred from bloomery and cast iron objects excavated in Karakorum. J Archaeol Sci 53:49–60

Park JS, Chunag A, Gelegdorj E (2008) A technological transition in Mongolia evident in microstructure, chemical composition and radiocarbon age of cast iron artifacts. J Archaeol Sci 35:2465–2470

Park JS, Eregzen G, Yeruul-Erdene C (2010) Technological traditions inferred from iron artefacts of the Xiongnu Empire in Mongolia. J Archaeol Sci 37:2689–2697

Park JS, Honeychurch W, Chunag A (2011) Ancient bronze technology and nomadic communities of the middle Gobi Desert, Mongolia. J Archaeol Sci 38:805–817

Park JS, Erdenebaatar D, Eregzen G (2015) Evolution of Mongolian bronze technology with the rise of the Xiongnu State. Archaeol Anthropol Sci. https://doi.org/10.1007/s12520-015-0304-x

Park JS, Honeychurch W, Chunag A (2016) Complicating the frontier: armaments, fortifications, and identities beyond the Great Wall. J Archaeol Sci Rep 6:475–487

Park JS, Erdenebaatar D, Eregzen G (2017) The implication of the metallurgical traditions associated with Chinese style wagons from the royal Xiongnu tomb at Golmod 2 in Mongolia. Archaeol Anthropol Sci. https://doi.org/10.1007/s12520-017-0476-7

Perlee Kh (1959) A study on the Khitan and the Khitan-Mongol relationship. Ulaanbaatar (in Mongolian)

Perlee Kh (1961) A brief study on Mongolian towns in prehistoric and historical time. Ulaanbaatar (in Mongolian)

Perlee Kh (2001) A study on the metallurgical work of Mongolian nomads. In: Kh. Perlee (Ed.), Collection of Perlee's research papers, vol. 2. Ulaanbaatar, pp. 55-293 (in Mongolian)

Pohl E, Mönkhbayar L, Ahrens B et al (2012) Production sites in Karakorum and its environment: a new archaeological project in the Orkhon Valley, Mongolia. Silk Road 10:49–65

Rogers JD (2012) Inner Asian states and empires: theories, data, and synthesis. J Archaeol Res 20:205–256

Rostoker W, Bronson B (1990) Pre-industrial iron: its technology and ethnology. Archaeomaterials monograph 1. University Museum Publications, Philadelphia

Shiraishi N, Tsogtbaatar B (2009) A preliminary report on the Japanese-Mongolian joint archaeological excavation at Avraga site: the Great Ordu of Chinggis Khan, in: Bemmann, J., Parzinger, H., Pohl, E., Tseveendorzh, D. (Eds.), Current archaeological research in Mongolia. Papers from the First International conference on "Archaeological Research in Mongolia" held in Ulaanbaatar, August 19th–23rd, 2007. Bonn Contributions to Asian Archaeology 4. Vor- und Frühgeschichtliche Archäologie, Rheinische Friedrich-Wilhelms-Universität, Bonn, pp. 549–562

Sinopoli C (1994) The archaeology of empires. Annu Rev Anthropol 23: 159–180

Verhoeven JD (1975) Fundamentals of physical metallurgy. Wiley, New York

Wagner DB (1996) Iron and steel in ancient China. E.J. Brill, Leiden

Wagner DB (2008) Science and civilization in China. Joseph Needham. Volume 5. Chemistry and chemical technology part 11: ferrous metallurgy. Cambridge University Press, Cambridge