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NOVEL MICRO-SCALE STEEL-MAKING FROM MOLTEN CAST IRON PRACTISED IN MEDIEVAL NOMADIC COMMUNITIES OF EAST MONGOLIA*

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Evidence of novel steel-making was found in a number of small cast-iron fragments recovered by the Mongolia–American archaeological survey of eastern Mongolia. These iron artefacts come from medieval period habitation and manufacturing sites and they consistently display irregular surface features characteristic of a solidification reaction from a partially molten state. Their microstructure consists of large near-spherical islands of pearlite spread on a background of fine white cast-iron eutectic. Reflected in this peculiar structure is an extremely small-scale steel-making process where one or more small pieces of cast iron were heated above the eutectic temperature for rapid decarburization in the partially molten state. We provide a detailed account of the technological aspects of this micro-scale steel-making method as observed in the microstructure and chemical composition of the objects examined. This small-scale technology was ideally suited to the pastoral nomadic way of life that characterized medieval eastern Mongolia; however, it probably would not have been appropriate for sedentary communities with access to large-scale urban manufacturing centres. Based on this observation, we discuss the role of nomadic lifeways and associated political environments that likely influenced the development of this innovative steel-making technique.

KEYWORDS: MONGOLIA, MEDIEVAL PERIOD, ARCHAEOLOGY, IRON METALLURGY, STEEL

INTRODUCTION

Mongolia has long been a heartland for the emergence of nomadic states and empires. Some of these are quite well known, such as the Mongol Empire of Genghis Khan (13th–14th centuries CE); while others, such as the Xiongnu state (third century BCE–second century CE) or the Khitan Empire (10th–12th centuries CE), are only now becoming better known from international museum exhibits, recent historical studies and recent archaeological research (Brosseder and Miller 2011, Biran 2012, Kradin *et al*. 2014). Archaeologists place an emphasis on the fact that polities located in Mongolia occupied a pivotal location between Siberia, Central Asia,

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Manchuria and the Central Plain of China, and participated simultaneously in each region and its respective networks (Honeychurch and Chunag 2011). Moreover, within these different geographical areas, contacts, transfers and influence between early groups might best be described as mutually modifying. In other words, the East, North, and Central Asian interaction sphere surrounding the steppes of Mongolia was characterized by multiregional interaction in which no single cultural region could be considered predominant (Rogers 2012, Honeychurch 2015). Based on these recent archaeological assertions, we would expect the history of major technologies within Mongolia likewise to demonstrate a pattern of indigenous innovation in the context of multiregional technological traditions.

The example of metallurgy in Mongolia is a good case in point. Recent analysis of Mongolian bronze and iron objects from a variety of contexts and periods demonstrates that nomadic communities in Mongolia had a long history of indigenous metalwork informed by neighbouring traditions (Park *et al*. 2010, 2011, Park and Reichert 2015). This pattern is clearly evident in the use of bloomery-based iron technology from the Xiongnu period onward, which is fundamentally different from the cast-iron tradition dominant in China. Although the genesis of bloomery iron production in Mongolia is still obscure, it likely has connections to ironworking practices known from southern Siberia and Central Asia (Wagner 2008, Park *et al*. 2010, 2689). This is not to say, however, that cast iron was not used in ancient Mongolia—its use is documented more than 2000 years ago during the period of the Xiongnu state and its frequency and the variety of its uses significantly expanded in the later Khitan and Mongol periods (Eregzen *et al*. 2007, Park *et al*. 2008). Its application, however, was limited to the making of items such as simple domestic tools and farming implements requiring no strict control over the mechanical properties of the materials employed (Park and Reichert 2015).

The nomadic preference for bloomery-based iron-making resulted evidently from its effectiveness for small-scale iron production with low initial investment. This was a key productive aspect required by pastoral nomadic communities removed from the major centres of production, politics and state ritual within the steppe setting. The high investment in workshop infrastructure required to produce cast iron at viable levels was not conducive to the mobile and flexible lifeways of most nomadic communities. Therefore, at the outset of our latest collaborative project, we expected that local bloomery iron production would have characterized community-scale production continuously throughout most of Mongolian history. Interestingly, this expectation was not borne out by our recent study of iron objects recovered from medieval period habitation sites located at Delgerkhaan Uul in eastern Mongolia (Park *et al*. 2017), Figure 1. Metallographic examination reveals that cast iron was involved far more frequently than bloomery iron in the establishment of local iron-working traditions employed in this region. The amount of iron consumption in these local nomadic communities was not high enough to justify investment in cast-iron workshops, but rather their needs for small amounts of cast iron were met by a mixture of recycling and acquisition from distant production centres. Our study suggests that this local metallurgical tradition was encouraged by the relative ease with which cast iron was available as a raw material and, perhaps, also due to a period of restricted access to bloomery iron (Park *et al*. 2017). It is important to note that based on our prior research, the technological landscape encountered at Delgerkhaan Uul is quite different from that documented at the roughly contemporary site of Karakorum, the capital of the Mongol Empire, where fully established bloomery-based technology served as the primary means for iron production (Park and Reichert 2015).

Even in cases where access to cast iron was entirely dependable, the establishment of a cast-iron-dependent tradition would not have been useful without a proper means for producing iron

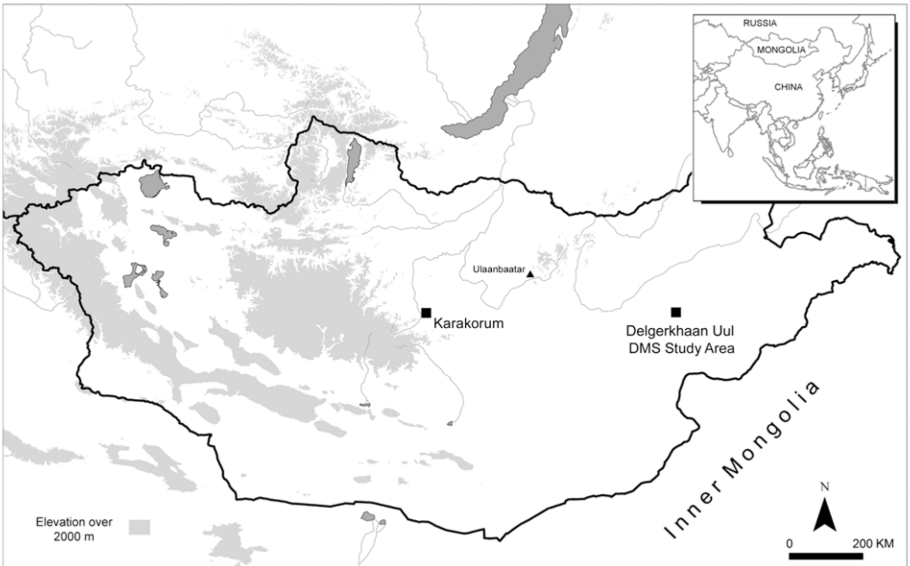

Figure 1 *Mongolia: geography and archaeological sites as mentioned in the text.*

and steel from cast iron. In theory, cast iron can be converted into steel by a variety of decarburization processes. In practice, however, the historically documented techniques for accomplishing this process in preindustrial times often required substantial investment in human and material resources (Rostoker and Bronson 1990, Wagner 2008). It is therefore significant to note an innovative small-scale process employed by our steppe communities for the making of steel directly from cast iron. With this micro-scale steel-making method available, pastoral nomads apparently met a substantial portion of their local demand for steel with only a handful of small cast-iron fragments that were otherwise of little value (Park *et al*. 2017). This paper presents a detailed account of the microstructure and chemical composition observed in a number of steel objects produced using this particular steel-making technique. We then discuss the results and this novel technology in the broader context of medieval Mongolian pastoral nomadic society, politics and interregional interactions.

ARCHAEOLOGICAL CONTEXTS AND COMMENTS ON ARTEFACTS

Most archaeological projects thus far conducted in Mongolia have taken place in the central part of this steppe nation where some of the earliest and most impressive habitation and mortuary sites cluster. Our Dornod Mongol Survey (DMS) is a multi-year survey and excavation project located in Sukhbaatar province of eastern Mongolia. The DMS study area includes major centres of ancient habitation and mortuary activity around the area of Delgerkhaan Uul where the initial focus of field research has been concentrated (Chunag and Honeychurch, 2016). More than 100 km^2 of systematic pedestrian survey has revealed a dense landscape of pastoral nomadic campsites, cemeteries, ritual and rock art sites, and areas of metallurgical craft production. The materials analyzed for this study were recovered from five artefact scatters suggesting seasonal nomadic habitations, two slag and metal scatters interpreted as metalworking sites, and a sample from an isolated surface find (Table 1). In addition to slag and metal artefacts, many of these sites also contain household remains such as pottery fragments, grinding stones and small items including glass beads and coins. These artefact types, and especially instances of decorated pottery and coins, are indicative of the later medieval periods and in particular those of the Khitan and Mongol empires (*c*.950–1400 CE).

The external appearance of the 12 objects under consideration is shown approximately to scale in Figure 2. The iron assemblage consists of small fragments displaying irregular surface features characteristic of a solidification reaction, demonstrating a thermal treatment applied at high temperatures. Most of these maintain a substantial portion of their original profiles, suggesting that the temperature was not high enough to offer full fluidity to the molten alloy. Given their small size and unique shape, it is evident that the objects were treated individually in an extremely small-scale process. The distinctive configuration shown in object numbers 1 and 4, where a small metallic patch is found attached to the surface of a larger metal plate underneath, confirms that two or more fragments of varying sizes were combined and treated together. This arrangement would have allowed partially molten metal to flow between the constituent metal pieces, causing them to be welded upon cooling. In object number 4, for example, the bonding between the top and bottom piece was so complete that no evidence suggesting their former boundary was visible. Although not clearly apparent in Figure 2, object numbers 3, 5 and 11 were also found to consist of two or more pieces welded together. In addition, small pieces of charcoal embedded in object numbers 3, 5 and 12 reveal that the treatment was provided in a charcoal-fired environment. It should be

Table 1 *Summary information for the iron objects examined from the medieval sites in eastern Mongolia and their chemical composition*

Number	*Find spot*	*Period**	*Weight (g)*	*Composition (weight %)*			*Comments*
				Si	*P*	*S*	
1	Q-find	–[†]	83	–[‡]	–	0.3	
2	DMS248	M/EH	16	–	–	–	
3	DMS374	K/M	25.5	0.2	0.2	0.3	0.2 Mn
4	DMS397	K/M	11.3	0.1	0.3	0.2	
5	DMS477	–	15.3	0.2	0.2	0.2	
6			11.0	0.2	0.2	0.2	Slag attached
7			6.0	0.2	0.3	0.2	
8			9.3	–	–	–	Slag attached
9			1.4	0.2	0.3	0.2	Forged plate
10	DMS493	K/M	14.1	0.1	0.1	0.2	0.8 Cu
11	DMS710	–	76.7	0.1	0.2	0.3	0.2 Cu
12	DMS748	K/M	15.8	–	–	0.2	0.5 Cu; ore particles included; steel area with little Si, P and S

Numbers labelling the objects are consistent with those in Figure 2. (The widely varying microstructures ranging from almost pure iron to hypoeutectic white cast iron makes it almost impossible to determine their average carbon concentration. Nevertheless, the carbon level after treatment was found in most cases to fall in the neighbourhood of 2.0%).

*K, Khitan; M, Mongol; EH, Early Historic (post-1400 CE) periods.

[†]Not determined.

[‡]None detected.

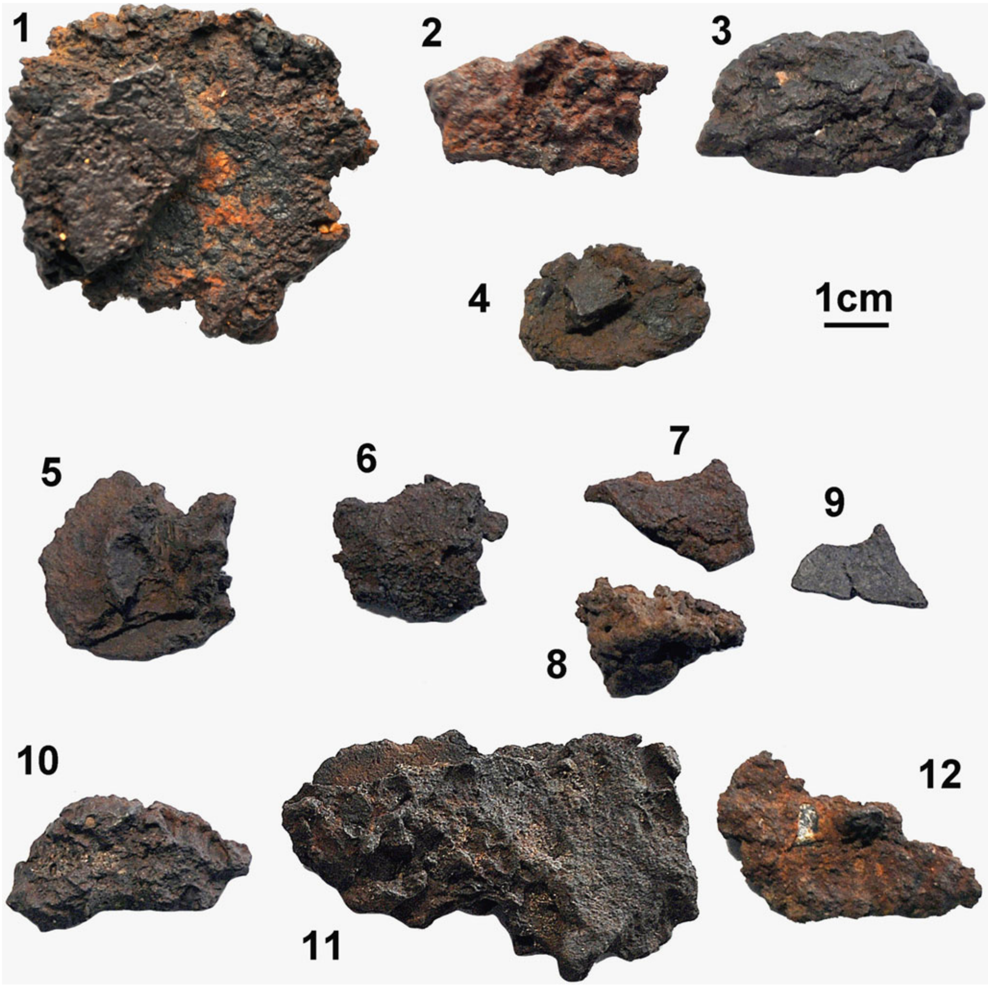

Figure 2 *General appearance of the iron objects under consideration. All objects bear in their irregular surface topography clear evidence of a solidification reaction from the partially molten state, with the exception of number 9 which was forged to take the form of a thin, flat plate. Note that the artefacts are given the same labels as those used in Table 1. [Colour figure can be viewed at wileyonlinelibrary.com]*

emphasized that the objects under consideration are not complete or finished products but are partially processed fragments meant to serve as an intermediary for further metallurgical treatments.

The above discussion provides key information about the raw materials employed and the conditions of the thermal treatments provided. First, the metal flow evident in these peculiar surface profiles is indicative of the ease with which the pertinent metal reaches the molten state. Of the iron materials, cast iron may be the best candidate for that purpose. It should be noted, however, that even with cast iron, the temperature must be 1148 °C or above, which can only be achieved in a contained environment with proper insulation. The best way to attain this high-temperature condition would have been to build an adequate furnace, although the construction and operation of such a furnace would presumably require a relatively high infrastructural investment. Given the micro-scale of the process in question and the small objects in Figure 2, such an investment does not seem warranted. Details about the exact environment employed for this thermal treatment have yet to be uncovered archaeologically, but we expect that such information will be forthcoming as a result of continuing field research. In the meantime, however, we can ascertain that these objects were processed in some kind of a furnace-like contained structure having sufficient air supply and insulation, but designed at an extremely small scale.

There is also little doubt that the treatment above was intended to convert the cast iron into steel by lowering its carbon concentration through decarburization. In this respect, object number 9, which is in the form of a thin plate, is significant because it is indicative of a substantial amount of plastic deformation caused by the application of mechanical working. Deformation to such an extent can never be obtained with regular cast iron and is an unmistakable sign of the carbon level having been greatly reduced to the range of steel, which was then forgeable.

BRIEF REVIEW OF THE IRON-CARBON PHASE DIAGRAM

A brief review of the iron-carbon (Fe-C) phase diagram presented in Figure 3 (ASM 1973) will be of benefit to the discussion below of the analytical results. We focus attention on the reaction

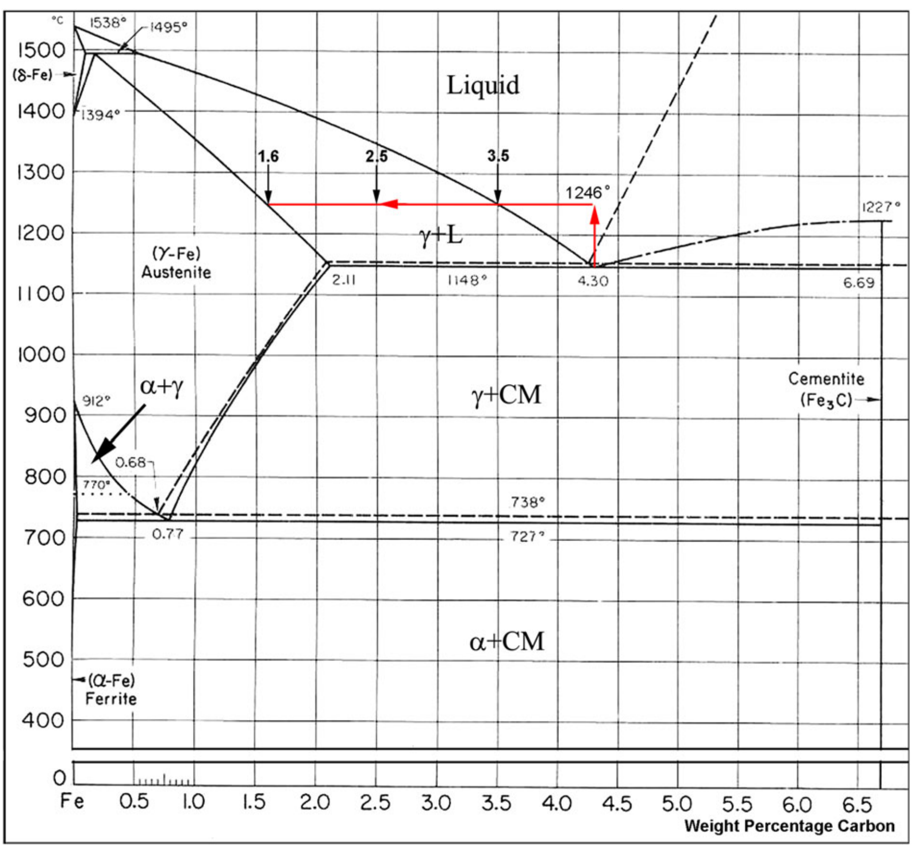

Figure 3 *Iron-carbon (Fe-C) equilibrium phase diagram. The dashed lines represent the Fe-graphite equilibrium diagram, except where coincident with the Fe-cementite diagram. L, liquid; CM, cementite. Source: ASM (1973). [Colour figure can be viewed at wileyonlinelibrary.com]*

that occurs when cast iron of near eutectic composition (i.e., 4.3% carbon, based on weight fraction) is subjected to a decarburization treatment above the eutectic temperature of 1148 °C to take advantage of accelerated carbon diffusion in the liquid state. For the sake of later discussion, suppose the treatment is carried out on eutectic alloys at 1246 °C, as illustrated in Figure 3. At this case, rapid decarburization will occur from the specimen in the molten state reducing the carbon level to approximately 3.5%. At this point, the molten alloy begins to solidify by precipitating solid nuclei of austenite. With the progress of decarburization, the molten alloy gradually transforms into austenite by nucleation and growth mechanisms until the solidification reaction is completed at the overall carbon level of around 1.6%. During this process, the respective carbon concentration of the solid and liquid phases is fixed at the left (1.6% carbon) and right (3.5%) end of the tie line at 1246 °C.

If uniform carbon concentration is assumed in the liquid part, the growth of austenite in the isothermal treatment of near eutectic cast iron, as discussed above, may proceed equally in all directions. This uniform growth may then lead to the solid austenite phase precipitated in roughly spherical forms. If the treatment is prematurely terminated, say when the carbon content reaches 2.5%, solidification of the remaining liquid, which is a little less than 50% of the specimen, proceeds by precipitating first proeutectic austenite in the form of dendrites and then white cast-iron eutectic in the space between them. The final microstructure of the specimen is then expected to comprise large spherical islands of austenite surrounded by relatively small-scale dendrites of austenite with the inter-dendritic space filled with white cast-iron eutectic. It should be noted that the formation of eutectic might be absent depending on the degree of the isothermal treatment and the conditions given during the subsequent cooling stage. The eutectoid transformation at 727 °C then replaces austenite with pearlite, which is observed in microscopic examination at ambient temperatures.

LABORATORY EXAMINATION AND RESULTS

One or more specimens were taken from each of the objects presented in Figure 2 for metallographic examination. The specimens were prepared following standard metallographic procedures and then etched using a solution of 2% nitric acid by volume in methanol, for investigation using an optical microscope and a scanning electron microscope (SEM). The microstructural data obtained were used to assess the carbon concentration, which was reported based on weight fraction to 0.1%. As for other minor elements such as silicon (Si), sulfur (S) and phosphorus (P), their presence was assessed using the energy-dispersive X-ray spectrometer (EDS) included with the SEM, the nominal detection limit of which is within a few tenths of 1%.

The structures typical of those observed in the majority of the specimens are presented in Figures 4 (a, b): optical micrographs of the respective specimens from object numbers 7 and 12. The structures in these micrographs are similar and consist of large dark areas of pearlite in backgrounds of white cast iron. Individual pearlite areas are precipitated in the form of near spherical particles isolated by the network-like white cast iron filling the space between them. The clear contrast between the two constituents, which may be more readily observed in Figure 4 (c), an SEM micrograph covering approximately the same area as Figure 4 (a), gives the impression that the pearlite particles were mostly derived from the growth of separate nuclei. Some may have originated from a single nucleus and are connected in the third dimension. In either case, the roughly spherical shape of the particles displaying little directionality suggests that their growth occurred almost uniformly in all directions. Such a nearly isotropic pattern of growth most likely resulted from a slow solidification reaction occurring at a fixed temperature.

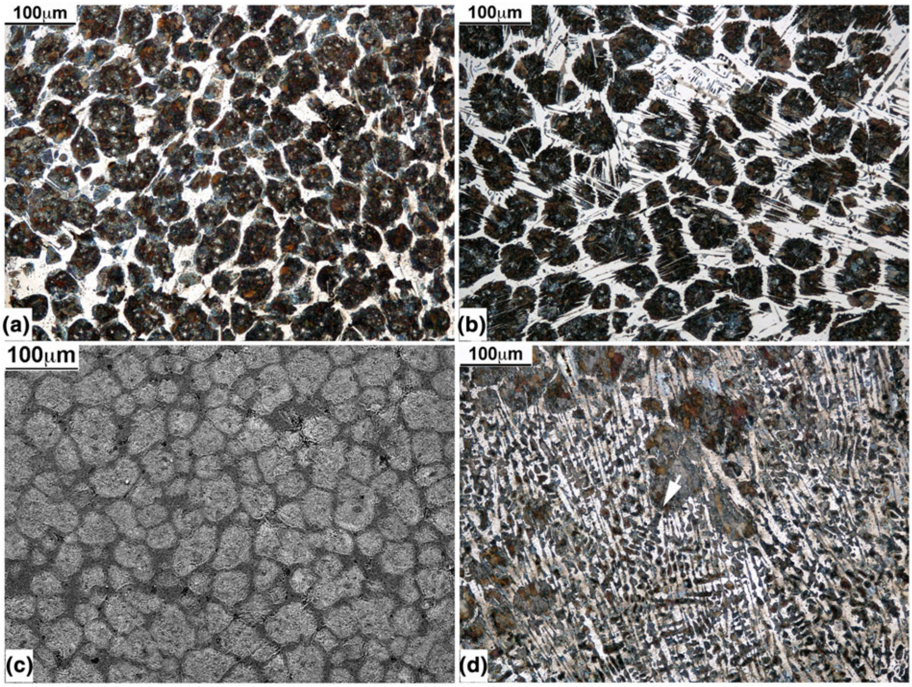

Figure 4 *Micrographs: (a, b) optical micrographs showing the structure of object numbers 7 and 12 in Figure 2 respectively; (c) scanning electron microscope (SEM) micrograph covering approximately the same area as shown in (a); and (d) optical micrograph showing the structure of object number 3 in Figure 2. [Colour figure can be viewed at wileyonlinelibrary.com]*

The driving force for this isothermal transformation in cast iron can be provided by a decrease in carbon concentration when, for instance, a specimen is subject to decarburization in the two-phase region.

Figure 4 (d), an optical micrograph taken from one specimen of object number 3, illustrates a structure that is clearly distinguished from that shown above in terms of the fine scale of the micro-constituents, pearlite and cementite, and their preferential growth in a particular direction. A similar fine structure was observed in two of the four specimens from object number 3, while a coarse structure nearly identical to that of Figures 4 (a, b) was observed in the others, indicating that the reaction rate during the isothermal treatment was not uniform over the entire object. The observed fine structure patterns are distinctive evidence of a rapid liquid-to-solid phase transition whereas the directionality is indicative of a growth guided by the direction of heat flow. The few large dark areas in Figure 4 (d), however, must have been the result of a uniform growth under the isothermal treatment. Evidently, the process in this region was prematurely terminated while the local carbon concentration was still high as compared with that in the rest of the object. It is evident that the remaining liquid transformed to a solid by precipitating a fine structure roughly parallel to the direction of heat flow. The transition from the isothermal mode of solidification to that driven by thermal flux is illustrated in Figure 4 (d), as indicated by the arrow where the planar growth front suddenly becomes dendritic. The carbon level of the area solidified subsequent to this transition may be determined from Figure 4 (d) as ranging between 3.0% and 3.5%, suggesting that the isothermal treatment was applied at temperatures between 1250 and 1300 °C.

Figure 5 (a) is an optical micrograph taken within one specimen from object number 8. The structure consists primarily of pearlite with a few dark areas that correspond to cavity porosities suggestive of a process involving solidification, whether after the re-melt treatment under consideration or during the initial casting of the given object. The arrow near the upper edge of Figure 5 (a) indicates a thin layer of non-metallic materials of special significance in assessing the thermo-chemical treatments given to the object. This layer, appearing similar to rust oxidation formed on iron, was given little attention until its unusual micro-constituents were noticed inadvertently during the microscopic examination. The layer in Figure 5 (a) is not continuous but shows substantial variation in thickness. Figure 5 (b), an optical micrograph enlarging the vicinity of the arrow in Figure 5 (a), provides a better view of the layer's primary constituent precipitated in the form of dendrites against a dark background. Figure 5 (c, d), EDS spectra from arrows 1 and 2 respectively, demonstrate that the primary phase is essentially an iron oxide, while the inter-dendritic space is filled with complex mixtures of various metallic and non-metallic oxides. In terms of microstructure and chemistry, therefore, the constituents of the non-metallic layer in question are similar to those found in slag from iron smelting, indicating that the phase in dendrites corresponds to wüstite (FeO) containing some other minerals (Figs 5, b–d). The formation of such mineral phases from solidification reactions may then place the treating temperature in the neighbourhood of the melting point of the wüstite phase, 1369 °C (Rostoker and Bronson 1990, 195).

Figure 5 (e), an optical micrograph taken within one specimen from object number 12, displays a unique structure containing cast iron, steel and almost pure iron within a limited area of approximately 1 mm^2. In the white layer along the bottom edge is located a cast-iron structure consisting of large pearlite particles embedded in white cast-iron eutectic. This layer is in contact with the grey area of steel whose carbon concentration decreases as one moves away from the boundary toward the interior. Figure 5 (f), an optical micrograph enlarging the area near the arrow in Figure 5 (e), shows the presence of a white layer of ferrite enclosing a dark region inside of which is filled with non-metallic materials. This peculiar grouping of structures arranged according to decreasing carbon content indicates a process given in the two-phase region (Figs 4, d, and 5, e) wherein molten metal gradually transformed into solid steel and then into iron enforced by a reduction in carbon concentration.

Figure 5 (g), an SEM micrograph providing a highly magnified view of the spot marked by the arrow in Figure 5 (f), reveals the presence of large particles in that area. Figures 5 (h, i), EDS spectra from arrows A and B respectively, confirm that the particles are made of almost pure iron oxide while the space between them is filled with a material whose major component is fayalite (Fe_2SiO_4). Given their unique shape and chemical composition, the oxide particles likely originated from iron ores or hammer scale, while the fayalite-based material between them resulted from a reaction that occurred there. It appears that the fayalite material was in liquid form and progressively filled the space between the solid particles during the thermal treatment. The presence of such oxide particles in contact with ferrite grains, as seen in Figure 5 (f), suggests that the oxygen-rich non-metallic region served as a sink draining the incoming carbon atoms from the higher carbon structures, thereby enhancing decarburization (Rostoker and Bronson 1990, 139–48).

Table 1 provides summary information on site chronologies and the approximate weight of the objects examined along with their silicon, phosphorus and sulfur levels, using the same numbers as those in Figure 2. However, no average carbon concentration could be specified as representing a given object because of the widely varying microstructures from almost pure iron to hypoeutectic white cast iron. Nevertheless, the carbon level after the treatment was found in most cases to fall in the neighbourhood of 2.0%.

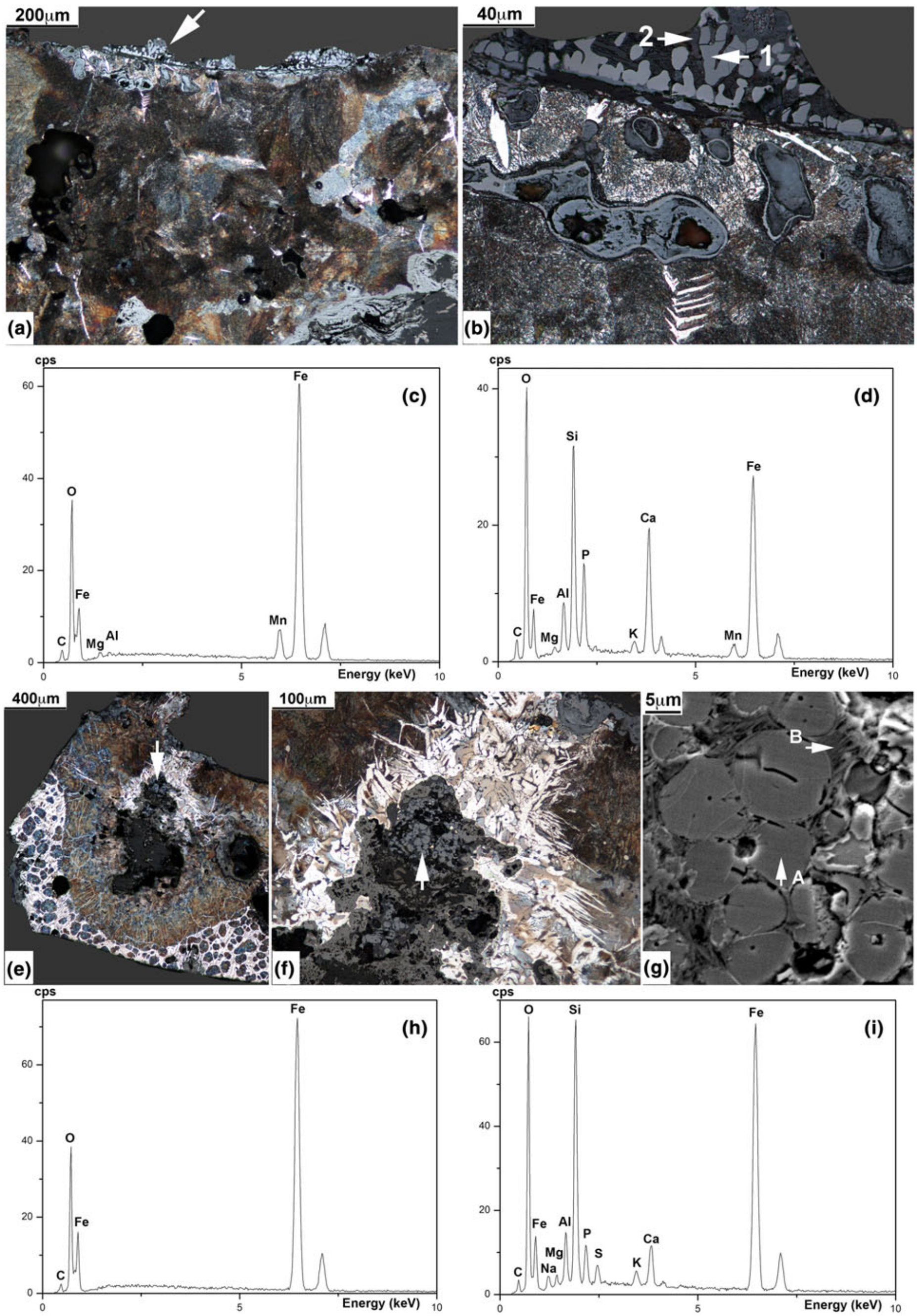

Figure 5 *Micrograph and energy-dispersive X-ray spectrometer (EDS) spectra: (a) optical micrograph showing the structure of object number 8 in Figure 2; (b) optical micrograph magnifying the area marked by the arrow in (a); (c, d) EDS spectra from arrows 1 and 2 in (b) respectively; (e) optical micrograph showing the structure of object number 12 in Figure 2; (f) optical micrograph magnifying the area marked by the arrow in (e); (g) SEM micrograph magnifying the area marked by the arrow in (f); and (h, i) EDS spectra from arrows A and B in (g) respectively. [Colour figure can be viewed at wileyonlinelibrary.com]*

DISCUSSION

Evidence of a special re-melting treatment applied to cast-iron alloys was consistently confirmed in the visual and microscopic investigation of the 12 small metallic fragments under consideration. Macroscopic observation of these pieces argues for a process involving cast iron in liquid or semi-liquid form based on signs of a solidification reaction. The fact that the approximate original shape of these objects was still maintained suggests that the processing temperature was not high enough for the flow properties of the molten alloy to be fully developed against surface tension effects. In this particular case, no container would have been required to hold the samples during the respective treatment. Another line of evidence for this process derives from the unique microstructures of these samples which consist primarily of large near-spherical particles of pearlite in the background of various white cast-iron structures. This particular structural pattern portrays a solidification reaction in which the proeutectic phase grows uniformly in all directions. In a normal casting operation, however, phase transformation is driven by cooling and the proeutectic phase grows in the form of dendrites and the remaining liquid between them solidifies last in the form of eutectic. It is not possible, therefore, to imagine that the peculiar structure described above was the result of a reaction enforced by normal cooling. On the other hand, this structure conforms quite well to expectations for an alternative mode of solidification occurring in an isothermal treatment whereby the reaction proceeds in step with a gradual reduction in carbon concentration.

The small pieces of cast iron presented in Figure 2 therefore all indicate an isothermal treatment applied at temperatures above the eutectic point of the iron-carbon alloy system. Given the overall carbon concentration of approximately 2.0% as determined from their typical microstructure, this treatment was evidently intended as a method for decarburizing cast iron into steel. The most significant aspect of this particular steel-making method is associated with its extremely small scale, which is evident in the size of the objects examined. All objects are in the form of fragments mostly weighing less than 20 g. Their appearance suggests the objects were treated individually rather than as a group or as parts of a large feedstock. The data in Table 1, showing the 12 objects recovered from eight different sites, also point to a small-scale process implemented independently at each site. Even in those artefacts recovered from a single site, no sign was found that they had been processed together and then later separated. More importantly, some objects retain in their appearance visible evidence of two or more fragments processed together, with their overall size not necessarily greater than those objects derived from treating a single fragment. This observation demonstrates that the raw materials to be treated were in fact intentionally prepared from various combinations of small pieces with a target size in mind.

The reaction in the above treatment would presumably have begun with the fully or partially molten cast iron depending on the initial carbon level and the processing temperature. With the carbon level progressively lowered through decarburization, the solidification reaction would have proceeded with no significant change in temperature until the process was terminated. The remaining liquid would then have been transformed to a solid during the subsequent cooling stage, producing a structure clearly distinguished from that developed previously in the nearly isothermal conditions. This difference in solidification patterns was confirmed in the analysis of some of the specimens examined. Furthermore, structural variations observed in some of the objects reflect uneven decarburization over the entire specimen under treatment. Given that the rate of decarburization was determined by the oxygen potential of the reaction environment, the mineral phases such as fayalite, wüstite and particles of iron oxide found in certain specimens should be understood as purposeful additions intended as sources of oxygen. These oxygen-rich minerals, added as agents to promote the removal of carbon atoms from cast iron in the form of carbon dioxide and monoxide, were in fact alluded to in a 17th-century Chinese text quoted and interpreted by Rostoker and Bronson (1990, 148). The minerals were likely in existence as key constituents of iron ore or iron oxide-rich silicate slag such as those derived from the bloomery process. Therefore, the objects in which these minerals were detected constitute valuable archaeological evidence for the use of oxidizing additives in pre-industrial steel-making from liquid cast iron.

Still another line of evidence for the role of these oxygen-rich minerals is the fact that the carbon content is particularly low in the metal parts located in their vicinity. In one case, the metallic area in contact with a thin layer primarily of wüstite was found to consist entirely of pearlite, i.e., steel containing 0.77% carbon. Here the presence of wüstite is a direct indication of the oxygen potential that was high enough to enforce such an enhanced decarburization. In another case, particles of iron oxide were located in an area surrounded by a layer of almost pure iron, i.e., ferrite. It is not difficult to imagine that this area of ferrite initially remained in a liquid state just like the rest of the specimen. With the progress of the treatment, however, the area underwent a series of phase transformations ahead of the other parts until it became an almost pure iron. Evidently, the oxygen-rich minerals served to draw carbon atoms from their immediate neighbourhood, enabling this kind of preferentially accelerated decarburization. The microstructural evolution in such a directional carbon flow is graphically illustrated in the given specimen. As observed, the ferrite layer surrounding the oxide particles was positioned inside the steel region of increasing carbon content toward its periphery, which borders the cast-iron area and which solidified last upon termination of the treatment.

As for the range of processing temperatures, there is no doubt that the lower limit was above the eutectic point of the iron-carbon alloys at 1148 °C. In some specimens, the approximate temperature at which they were treated could be inferred as in the range of 1250–1300 °C based on the structure that developed following the termination of the process. In another specimen, the presence of the wüstite phase in the form of dendrites placed the processing temperature at *c*.1350°C (Rostoker and Bronson 1990, 195). It seems reasonable, therefore, to presume that the treatment was given within a few hundred degrees Celsius above the eutectic point. This temperature range can be achieved only in a well-insulated contained environment with an adequate air supply. It is unreasonable, however, to believe that such a fine-scale process as described above was carried out in a full-furnace structure where the high temperatures required were readily maintained for a long time. It is more likely, instead, that a structure not much different from a crucible was employed with effective insulation and possibly a miniature tuyere system that could provide sufficient airflow to the exact location required. It would also seem reasonable that there were very few workers involved in the operation of such a small-scale structure. In this particular context, where most work would have been done manually using a limited amount of fuel in a single burn, the treatment in question could not have lasted long and likely was completed within about 30 min. The use of a high temperature environment would therefore have been a key requirement to this end.

Despite the widely varying microstructures from almost pure iron to hypoeutectic white cast iron, the carbon content after the treatment was found in most cases to fall in the neighbourhood of 2.0%. This carbon level, belonging to the range of extra-high carbon steel, may still have been too high to make the alloys fully resistant to brittle fracture upon receiving impacts, whether in fabrication or in service. Nevertheless, a clear indication of substantial plastic deformation applied was confirmed in an object that was forged into a thin plate with no visible or microscopic sign of brittle fracture. This would never have been possible without the application of a sufficient treatment, confirming the effectiveness of the given technique as a practical means for converting small cast-iron fragments into steel. With this technique available, every cast-iron object, even in a fragmentary form and otherwise of little use, would have been a valued resource to be recycled as raw material for steel-making.

Evidence was found from radiocarbon analysis that cast-iron fragments of widely varying chronological contexts were in fact collected and reused in later periods as inputs for this steel-making process (Park *et al*. 2018). This aspect is also noted in the chemical composition of the objects examined, which, according to the data in Table 1, may be classified into two groups based on the presence of silicon. Such silicon-contaminated cast iron began to appear in Mongolia during the Khitan period (10th–12th centuries) in association with the use of mineral coal in smelting (Park *et al*. 2008). Cast-iron alloys from coal-based smelting generally contain a substantial amount of phosphorus and sulfur in addition to silicon (Park and Reichert 2015, Park 2015). The presence of silicon along with phosphorus and sulfur in the Mongolian samples, therefore, can be understood as pointing to a coal-based smelting event, roughly contemporaneous with the periodization of the site contexts based on diagnostic pottery, coins and other material culture indicators. On the other hand, the absence of these additional elements would have indicated charcoal-based smelting operations characteristic of earlier periods. It is important to note, however, that the level of these elements in the specimens, whether originating from charcoal- or coal-based smelting, was much lower than that observed in coal-smelted cast-iron alloys (Rostoker and Bronson 1990, Park and Reichert 2015, Park *et al*. 2018) and that evidently was a result of the steel-making treatment itself.

CONCLUSIONS

The above method for making steel from cast iron may best be characterized by its extremely small-scale production, high processing temperatures, the addition of various oxygen-bearing minerals for control of the reaction environment and the use of charcoal as a fuel. The exact nature of the technique, however, has yet to be discovered and so too its origins and geographical distribution. From a comparative perspective we are aware of other small-scale production methods for obtaining steel, for example, based on bloomery methods. It is certainly possible to obtain products of varying carbon content in the bloomery process and there is substantial evidence from African iron metallurgy for the production of steel and low-carbon wrought iron derived in this way. In African contexts, expert smiths were knowledgeable enough to distinguish differentiated products after the smelt by crushing the crude blooms and then sorting the contents visually and by weight into high- and low-carbon fractions. These products would then be worked separately afterwards (e.g., David *et al*. 1989, Serneels *et al*. 1997). In our case, however, the development of the unique microstructures observed requires a substantial amount of treatment at temperatures high enough to produce a partially molten state in the respective cast-iron fragments. The solidification proceeds by the reduction of the carbon level and a coincident increase in the melting temperature rather than by the removal of heat (i.e., by heat flow in which solidification produces microstructures showing a clear orientation in the direction of heat flow). Therefore, we propose that small-scale steel-making from cast iron was the primary objective of the medieval smiths at Delgerkhaan Uul and their use of this particular process was quite unique as well as innovative.

Based on our field collections at multiple sites, this technique was routinely practised among nomadic communities in the Delgerkhaan Uul region as a way to meet local or, perhaps, subregional levels of demand. While at present we cannot know how widespread this technique was in other parts of Mongolia, we do know that its requirement for cast iron as a raw material must have meant that local communities were reliant on a range of sources and networks for these materials. As mentioned above, the recycling of older cast-iron scrap was certainly one source of this supply. Cast iron was present in steppe contexts from at least 200 BCE and we have documented Medieval period steel-making sites containing recycled cast-iron fragments dating to these much earlier periods for use as a raw material (Park *et al*. 2017). Besides scrap fragments, however, there is still no archaeological evidence for cast-iron smelting or finery production at the local community level, even though historians and archaeologists have hypothesized this as a possibility (Perlee 2001).

Moving beyond the scale of the local steppe community, other sources of cast iron may have included the many urban centres of Mongolia and Inner Mongolia. These impressive walled sites were located across the eastern steppe region and contained infrastructure for major craft production during the periods of both the Khitan and Mongol empires (Perlee 1961, Honeychurch and Chunag 2006, Waugh 2010). Although numerous cast-iron artefacts have been recovered at these sites, as well as what seem to be cast-iron ingots intended as intermediary materials, there is again no definitive archaeological evidence for cast-iron production at these centres (Park and Reichert 2015, 50). Compared with other archaeological site types, however, little attention has been paid to these large centres and the amount of excavation work carried out to understand better urban craft production capacities has been informative but still relatively small (Erdenebat and Pohl 2009, Kradin *et al*. 2014). Quite a bit less survey and excavation has been conducted in the peripheral areas around these centres where we might expect to find the remains of workshops for cast-iron processing. At least one major find of an outlying iron-working area to the south-west of the Mongolian imperial capital of Karakorum is under study and demonstrates the importance of greater attention to such 'off-site' sectors in the peri-urban landscape (Pohl *et al*. 2012).

Given the key role of cast iron in China's iron industry, the final possible source of cast iron for the steppe region may have come from the industrial scale workshops of northern and central China. The transfer of raw materials from areas to the south of the steppe during these periods would be expected as part of the political economy of these two empires, both of which integrated all or parts of the eastern steppe and parts of China as well. In fact, the movement of cast iron from China to the northern steppe has been hypothesized as the reason behind the discovery of iron ingot bars mentioned above at major Mongol period centres (Osawa 2005). The bars are compact and portable and could have been easily transformed into steel for weapons, armour, tools, equestrian equipment and daily implements. China, as a primary source for cast iron, remains a strong possibility, although more evidence is required to ascertain the exact provenance of these intriguing iron ingots. However, we expect that future research into this question will reveal that cast iron on the steppe was the result of diverse supply networks and multiple sources in use simultaneously.

Another important observation is that these cast-iron ingots are not known from urban steppe centres built by the Khitan Empire; so far, they have only been recovered at urban sites dating to the Mongol Empire. The historical records of the Khitan Empire indicate that iron was produced and transferred in the form of ingots and also that the Khitan administration put strict controls on iron export, taxed it as a commodity, and used forced labour to mine and smelt iron in the south-eastern regions of the empire (Atwood 2004, 389, Kradin and Ivliev 2008, 439, Hu 2009, 225). Without doubt, iron was an equally strategic resource for the Mongol Empire, but the archaeological record suggests that the steppe region was more liberally supplied with iron than it was during the earlier Khitan period. Evidence for this comes from the geographical distribution of the cast-iron ingot bars that have been found not only at major urban and secondary centres but also at the seasonal campsites of pastoral nomads at the local scale. These latter sites presumably belonged to commoners or perhaps to local elite and are the same kinds of sites having evidence for the small-scale steel-making technique documented in the present study (Park *et al*. 2017).

This different pattern of iron circulation would indeed make sense given that the Mongol Empire emerged as a steppe-oriented polity and maintained the steppe regions as its political core. In contrast, the Khitan Empire emerged from the south-eastern regions of Manchuria and eastern Inner Mongolia and imposed a contested frontier across the north-western sections of Mongolia's steppe lands (Kradin and Ivliev 2008). Yet another reason for this difference may have been due to the nature of the Mongol military. Mongol cavalry soldiers of the early imperial period were a self-supplied force. Their weapons and armour were not provided by a central authority but instead were made locally, individually specified and brought into military service by each individual warrior (Atwood 2004, 350). In this context, political support for the broad circulation of bloomery or cast iron as intermediary raw materials for steel production would have provided distinct benefits to the building and expansion of the empire.

The steel-making technique under consideration here may have been an innovation devised during the Khitan period as a means to circumvent restrictions and tight controls on the circulation of bloomery iron to steppe communities whose loyalty may not have been fully ensured. With the implementation of this novel technique, steppe communities were certainly able to acquire steel in almost any situation as long as a small quantity of cast iron in some form were available. With the advent of the Mongol Empire 80 years after the fall of the Khitan, this micro-scale steel-making method became one of several different pathways to obtaining high-quality steel based on a variety of supply options and involving a range of scales of production, from the local community to the imperial centre. Such multi-path functionality is characteristic of the cultural emphasis that steppe nomads placed on flexibility in their lifeways, economics and politics (Honeychurch 2014). In this respect, it is intriguing to note parallels between the cultural ideals of nomadic communities and their expression in the technologies and material culture related to steel-making.

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REFERENCES

Atwood, C., 2004, *Encyclopedia of Mongolia and the Mongol Empire*, Facts On File, New York.

ASM, 1973, ASM metals handbook, 8th ed., ASM, Metals Park, OH.

Biran, M., 2012, Kitan migrations in Eurasia (10th–14th centuries), *Journal of Central Eurasian Studies*, **3**, 85–108.

Brosseder, U., and Miller, B. (eds.), 2011, *Xiongnu archaeology: multidisciplinary perspectives of the first steppe empire in Inner Asia*, Rheinische Friedrich-Wilhelms-Universität, Bonn.

Chunag, A., and Honeychurch, W., 2016, Mongol-Amerikiin khamtarsan 'Dornod Mongol: Arkheologiin Khaiguul Sudalgaa' tosliin kheeriin shinjilgeenii angiin 2016 ony tailan [Report of the 2016 Mongol-American Joint 'Dornod Mongol Archaeological Survey' Field Project], Institute of History and Archaeology, Ulaanbaatar.

David, N., Heimann, R., Killick, D., and Wayman, M., 1989, Between bloomery and blast furnace: mafa iron-smelting technology in North Cameroon, *African Archaeological Review*, **7**, 183–208.

Erdenebat, U., and Pohl, E., 2009, The crossroads in Khara Khorum: excavations at the center of the Mongol Empire, in *Genghis Khan and the Mongol Empire* (eds. W. Fitzhugh, M. Rossabi, and W. Honeychurch), 137–45, Arctic Studies Center, Smithsonian Institution, Washington, DC.

Eregzen, G., Chunag, A., Gordon, R. B., and Park, J. S., 2007, Transitions in cast iron technology of the nomads in Mongolia, *Journal of Archaeological Science*, **34**, 1187–96.

Honeychurch, W., 2014, Alternative complexities: the archaeology of pastoral nomadic states, *Journal of Archaeological Research*, **22**, 277–326.

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

Honeychurch, W., and Chunag, A., 2006, States on horseback: the rise of Inner Asian confederations and empires, in *Archaeology of Asia* (ed. M. T. Stark), 255–78, Blackwell, Malden, USA, Oxford, UK, Victoria, Australia.

Honeychurch, W., and Chunag, A., 2011, Timescapes from the past: an archaeogeography of Mongolia, in *Mapping Mongolia: situating Mongolia in the world from geologic time to the present* (ed. P. Sabloff), 195–219, University of Pennsylvania Press, Philadelphia, PA.

Hu, L., 2009, Urban landscape and politics: the making of Liao cities in southeast Inner Mongolia, Ph.D. thesis, University of Chicago, Chicago, IL.

Kradin, N., and Ivliev, A., 2008, Deported nation: the fate of Bohai peoples of Mongolia, *Antiquity*, **82**, 438–45.

Kradin, N., Ivliev, A., Ochir, A., Vasiutin, S., Satantseva, S., Kovychev, E., and Erdenebold, L., 2014, Emgentiin Kherem: a fortress settlement of the Khitans in Mongolia, *Silk Road*, **12**, 89–97.

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 *The Avraga site—preliminary report of the excavations of the palace of Genghis Khan in Mongolia 2001–2004* (ed. S. Kato), 45–62, Kokugakuin University, Shibuya.

Park, J. S., 2015, The implication of varying ^{14}C concentrations in carbon samples extracted from Mongolian iron objects of the Mongol period, *Journal of Archaeological Science*, **63**, 59–64.

Park, J. S., Chunag, A., and Gelegdorj, E., 2008, A technological transition in Mongolia evident in microstructure, chemical composition and radiocarbon age of cast iron artifacts, *Journal of Archaeological Science*, **35**, 2465–70.

Park, J. S., Eregzen, G., and Yeruul-Erdene, C., 2010, Technological traditions inferred from iron artefacts of the Xiongnu Empire in Mongolia, *Journal of Archaeological Science*, **37**, 2689–97.

Park, J. S., Honeychurch, W., and Chunag, A., 2011, Ancient bronze technology and nomadic communities of the middle Gobi Desert, Mongolia, *Journal of Archaeological Science*, **38**, 805–17.

Park, J. S., Honeychurch, W., and Chunag, A., 2017, Iron technology and Medieval nomadic communities of East Mongolia, *Archaeological and Anthropological Sciences.*, https://doi.org/10.1007/s12520-017-0553-y.

Park, J. S., Honeychurch, W., and Chunag, A., forthcoming 2018, The technological and chronological implication of ^{14}C concentrations in carbon samples extracted from Mongolian cast iron artifacts, *Radiocarbon*.

Park, J. S., and Reichert, S., 2015, Technological tradition of the Mongol Empire as inferred from bloomery and cast iron objects excavated in Karakorum, *Journal of Archaeological Science*, **53**, 49–60.

Perlee, Kh., 1961, Ancient and prehistoric towns and settlements of Mongolia, Mongolian Academy of Sciences, Ulaanbaatar. [in Mongolian]

Perlee, Kh., 2001, A study on the metallurgical work of Mongolian nomads, in *Collection of Perlee's research papers*, vol. 2 (ed. Kh. Perlee), 55–293, Ulaanbaatar. [in Mongolian]

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

Rogers, J. D., 2012, Inner Asian states and empires: theories, data, and synthesis, *Journal of Archaeological Research*, **20**, 205–56.

Rostoker, W., and Bronson, B., 1990, Pre-industrial iron: its technology and ethnology (Archaeomaterials Monograph No. 1), University Museum Publ., Philadelphia, PA.

Serneels, V., Huysecom, E., and Fluzin, P., 1997, Inagina iron: slags and eutectoïd steel, in Early ironworking in Europe, archaeology and experiment, vol. II: *Experimental and technical studies* (Proceedings of the International Conference, Plas Tan y Bwlch, UK, September 19–25, 1997) (eds. P. Crew and S. Crew), 104–10, Snowdonia National Park Study Centre, Plas Tan y Bwlch.

Wagner, D. B., 2008, *Science and civilization in China: Joseph Needham, vol. 5: Chemistry and chemical technology Part 11: Ferrous metallurgy*, Cambridge University Press, Cambridge.

Waugh, D., 2010, Nomads and settlement: new perspectives in the archaeology of Mongolia, *Silk Road*, **8**, 97–124.