Revised: 5 July 2018 | Accepted: 21 September 2018
DOI: 10.1002/arp.1727

RESEARCH ARTICLE

WILEY

Geophysical prospection and archaeological excavation of ancient iron smelting sites in the Barun-Khal valley on the western shore of Lake Baikal (Olkhon region, Siberia)

Nikolay O. Kozhevnikov[1,2] | **Arthur V. Kharinsky**[3] | **Sergey V. Snopkov**[4]

[1] Department of Geophysics, Novosibirsk State University, Novosibirsk, Russia

[2] Laboratory of Geoelectrics, Trofimuk Institute of Petroleum Geology and Geophysics of SB RAS, Novosibirsk, Russia

[3] Laboratory of Archaeology, Paleoecology and the Subsistence Strategies of the Peoples of Northern Asia, National Research Irkutsk State Technical University, Irkutsk, Russia

[4] Department of Geology, Irkutsk State University, Irkutsk, Russia

Correspondence
Nikolay O. Kozhevnikov, Novosibirsk State University, 1, Pirogova str., Novosibirsk, 630090, Russia; Trofimuk Institute of Petroleum Geology and Geophysics of SB RAS, 3, Koptyuga Ave., Novosibirsk, 630090, Russia.
Email: kno48@yandex.ru

Funding information
Russian Foundation for Basic Research (RFBR), Grant/Award Number: 10-05-00263

Abstract

In 1997, an ancient iron production site, Barun-Khal 2, was discovered in the Barun-Khal valley (Olkhon region, near the west shore of Lake Baikal). This discovery initiated studies of the archaeometallurgical potential of the valley. They included magnetometry, resistivity, self-potential (SP) and radiometric surveys, archaeological excavation, analysis of chemical composition and magnetism of slag and other residuals, and radiocarbon dating of charcoal samples. As expected, the most efficient was the magnetometric survey. Despite challenging field conditions such as geology-related magnetic anomalies of large amplitude and contrast, the magnetometer survey in the Barun-Khal valley resulted in the discovery of another iron production site, Barun-Khal 3. Using the magnetometry, the general structure of the sites was studied and the places of excavation were determined. The resistivity, SP and radiometric techniques, as well as magnetic survey were useful in studying near-surface geology and recent geological history. Excavations have found well-preserved slag-tapping bloomery furnaces built into the sides of a large pit (Barun-Khal 2) or a trench (Barun-Khal 3). According to radiocarbon dating, iron production began here within the second and third centuries BC and lasted until the seventh to the eleventh centuries AD. The significance of the works in the Barun-Khal valley is determined by the fact that there exist significant gaps in the coverage of Russia (including Siberia) with archaeometallurgical studies. Most available papers on the archaeometallurgical activity in Siberia were not published in English until now. For the first time, the study of ancient iron production sites in the Olkhon region was considered as an independent scientific task and carried out using both geophysical and archaeological methods.

KEYWORDS

ancient iron smelting, archaeological prospection, bloomery, geophysical survey, Lake Baikal, near-surface geology

1 | INTRODUCTION

In 1997, an ancient iron production site, Barun-Khal 2, was discovered at the mouth of the Barun-Khal valley in the mainland of the Olkhon region, near the western shore of Lake Baikal (Figure 1). In addition to the mainland, the Olkhon region includes the Olkhon Island.

The history of the discovery was described in detail in Kozhevnikov, Kharinsky, and Kozhevnikov (2001) and Kozhevnikov, Kozhevnikov, and Kharinsky (1998). Slowly decaying transients were measured during a time-domain electromagnetic (TEM) survey over the mouth of the Barun-Khal valley. When converted to apparent resistivities, the transients resulted in values of about 2 to 5 Ohm m.

FIGURE 1 Lake Baikal overview map. Dashed line shows boundary of the Olkhon region

Because the site geology as well as in-field and laboratory direct current (d.c.) resistivity data did not indicate the presence of highly conductive rocks, the TEM results were confusing. Subsequent laboratory TEM measurements on soil samples have shown that slowly decaying transients were caused by the magnetic viscosity effect. From the hysteresis and Curie temperature analyses of the near-surface material, these effects were to be attributed to the relaxation of magnetization of superparamagnetic iron and magnetite particles. In 1997, investigating the mouth of the valley, we came across soil and loose material that had been thrown out of a ground squirrel's burrow. The soil contained a large amount of slag and charcoal. Inspection of the burrow showed that the slag and charcoal were thrown from a depth of 30 to 50 cm. Being placed into a small coil, the slags produced slowly decaying transients caused by magnetic viscosity effects. In chemical and mineral composition, the slags were identical to those which are known to form during the production of iron in bloomery furnaces. A small-scale excavation resulted in the discovery of a bloomery furnace, much slag, charcoal, and baked clay fragments. On the charcoal, the uncalibrated and calibrated carbon-14 (^{14}C) dates were found (SOAN-3711): 2180 ± 30 BP, and 361–168 cal BC (2σ).

Usually, archaeogeophysical surveys are conducted over areas where archaeologists have already discovered or expect to discover archaeological targets. Therefore, the history of the discovery of the site is not very common, but rather unique.

Along with geophysical data, the paper by Kozhevnikov et al. (2001) describes the archaeological results as of 1999, among which the most important were the well-preserved smelting furnaces located around the periphery of a large pit. The pit and furnaces contained a large quantity of slag, charcoal and burned clay lining. Analysis of the chemical and mineral composition of the slag has shown that it is a by-product of the bloomery process (Kozhevnikov et al., 2001; Kozhevnikov et al., 1998; Kozhevnikov, Kozhevnikov, Kharinsky, & Urbat, 2003). According to the radiocarbon dating of charcoal samples, iron production took place here from 361 to 168 cal BC (2σ) to 5–210 AD cal (2σ).

Evaluating the significance of this discovery, we note that, for the first time in the Olkhon region, a systematic study of an ancient iron production site was carried out. Earlier, the study of ancient iron production in the Olkhon region, as well as throughout western Baikal region (Western Cisbaikalia), was not considered as an independent scientific task. Artefacts which testified to the production of iron in the Olkhon region were only briefly mentioned in the literature in so far as they were found during studies not related to archaeometallurgy and not dated using the radiocarbon method (Aseev, 1980). As for the site Barun-Khal 2, in our studies we used archaeological and geophysical methods, radiocarbon dating, as well as chemical, mineral and magnetic analyses of slag.

Although the article by Kozhevnikov et al. (2001) was published in a geophysical journal, it attracted the attention of archaeologists and historians, because the site Barun-Khal 2 has established a ‘point’ which is supposed to trace the spread of the bloomery smelting technology through the northern part of East Asia (Lochin, 2015; Park, Gelegdorj, & Chimiddorj, 2010; Park & Rehren, 2011; Radtke, Reiche, Reinholz, Riesemeier, & Guerra, 2013; Sasada & Chuang, 2014; Xiongnu Archaeology, 2011) and even Alaska (Gelvin-Reymiller & Reuther, 2010).

The discovery of the Barun-Khal 2 complex initiated the search, discovery and study of other iron production sites in the Olkhon region (Figure 2). Probably, it would not be an exaggeration to say that the discovery of the site Barun-Khal 2 could be regarded as the beginning of the study of the early iron production in the Olkhon region.

Archaeogeophysical surveys in the Barun-Khal valley continued intermittently until 2012. They were carried out to search and explore iron-smelting sites as well as assess the potential of geophysical techniques in archaeometallurgically-related studies. Along with archaeological results, new data were obtained on the near-surface geology of the Barun-Khal valley and its surroundings.

We believe that results of geophysical and archaeological surveys in the Barun-Khal valley may be of interest to all those who are involved in the study of the archaeology, archaeometallurgy, near-surface geology, recent tectonics and landscapes of the Olkhon region. In this respect, it is important that the Olkhon region has the status of a national park and belongs to specially protected natural areas. In presenting the results of surveys in the Barun-Khal valley, we are also motivated by the fact that, as stressed by Pleiner (2000) and Rehren and Belford (2013), there exist significant gaps in coverage of Russia, Siberia included, with archaeometallurgical studies.

In this article we present essential results previously unpublished or published primarily in Russian in conference proceedings and local collections of papers (Agafonov & Kozhevnikov, 1999; Kozhevnikov & Kharinsky, 2003; Kozhevnikov & Kharinsky, 2005; Kozhevnikov et al., 1998; Kozhevnikov, Kozhevnikov, Nikiforov, Snopkov, & Kharinsky, 2000). Initially, we give a brief description of the Olkhon region and the Barun-Khal valley. Then we describe the archaeogeophysical surveys and discuss their results for two survey areas. Along with archaeogeophysical data, we present and discuss results of archaeological excavations.

2 | BARUN-KHAL VALLEY AND ITS SURROUNDINGS: A GENERAL DESCRIPTION

The Barun-Khal valley (Figure 3) is located near the village of Chernorud (Shara-Togot). The valley has a flat bottom gently inclined towards the southeast. The sides of the valley are formed by faults extending approximately at right angle to the Primorsky fault, one of the main faults in the Baikal rift structure (Mats, 1993). To the northwest of the scrap of the Primorsky fault extends the Primorsky Range (see Figure 2) formed by early Proterozoic granites of the Primorsky complex. In the southeast, the Barun-Khal valley joins the valley of the Kuchulga River.

The bedrock of the valley is covered with Quaternary sandy–clayey sediments, underlain by Neogene clays. Below a certain depth, which varies depending on local conditions (such as the thickness of

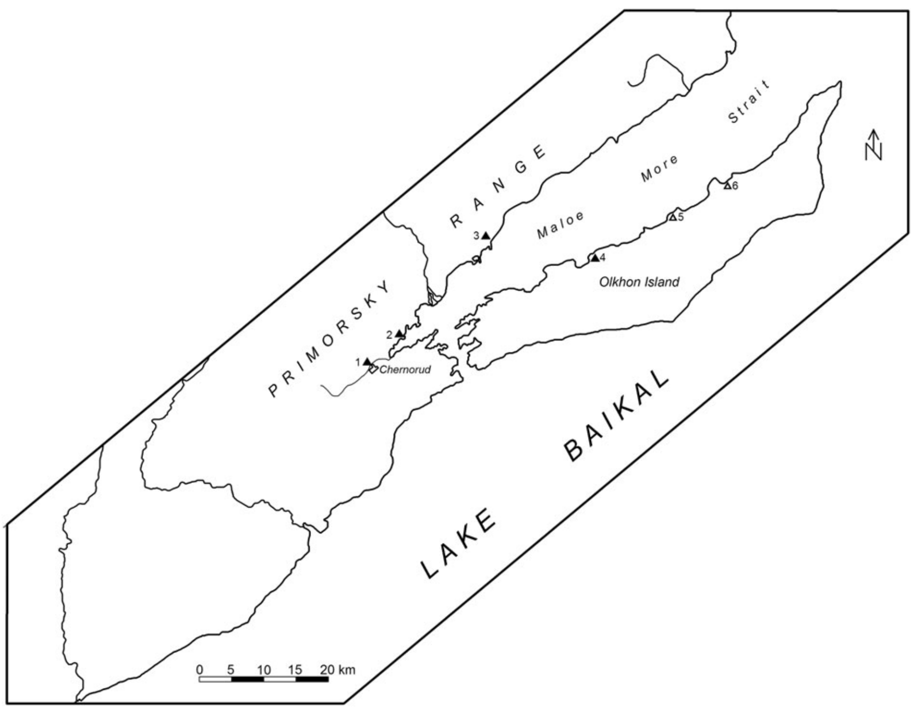

FIGURE 2 Location of iron production sites in the Olkhon region: (1) Barun-Khal; (2) Shida; (3) Kurma; (4) Khungai; (5) Kharantsy; (6) Ulan-Khushun. Solid triangles indicate sites with bloomery furnaces and other metallurgy-related structures. Open triangles show sites where only slag and other residuals of iron smelting were found

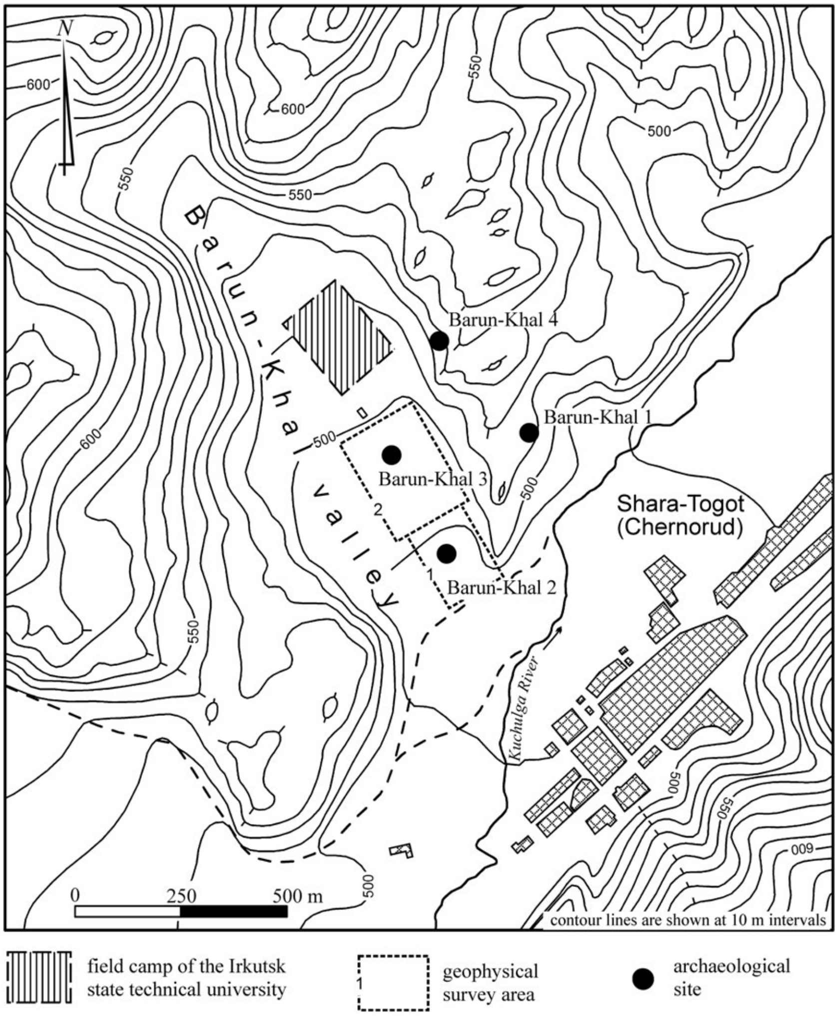

FIGURE 3 Map of the Barun-Khal valley and its surroundings

the soil–vegetation layer, the presence and type of vegetation), the sediments are frozen.

On a regional scale, the site is located within a 2 to 3 km wide band of metamorphic Paleozoic rocks, forming the so-called Chernorud zone (Fedorovsky & Sklyarov, 2010). Rocks exposed on the sides of the valley include marbles, calciphyres, gneisses, pyroxene-carbonate crystalline schists, quartzites, amphibolites, and migmatites. Some marbles, gneisses and quartzite contain significant amount of graphite.

To the northwest of the valley's mouth is located a small settlement (camp) where, since 1976, students of the Irkutsk Technical University have been trained in field geology and geophysics. As a part of training in geophysics, vertical electrical sounding (VES), self-potential (SP) and TEM surveys were carried out on a large scale to study regional structure of the surrounding area (Kozhevnikov, Bigalke, & Kozhevnikov, 2004; Kozhevnikov & Tezkan, 1998).

Surroundings of the Kuchulga River contain a large number of archaeological sites of different age. They are mostly located in valleys descending to the Kuchulga River from the Primorsky range and on ridges that divide these valleys. By now, four archaeological sites are known in the Barun-Khal valley. The first of these, Barun-Khal 1, was discovered by A.V. Kharinsky in 1994 on the left side of the valley, near to its mouth (Zaitsev, Svinin, & Kharinsky, 1996). It included 16 stone mounds with a height of about 25 cm. The mounds are arranged in two parallel rows, directed from the southwest to the northeast. Similar structures were being built in the Olkhon region during the first millennium AD.

In 1997, in the mouth part of the valley, N.O. Kozhevnikov discovered an iron production site, which was named Barun-Khal 2. In 1999, to the northwest of Barun-Khal 2 another archaeometallurgical site, Barun-Khal 3, was discovered. In 2001, on the left side of the valley, A.V. Kharinsky found several Buryat burial sites of the eighteenth–nineteenth centuries (Kharinsky, Avramenko, & Borodina, 2010). They were given the name Barun-Khal 4. Memorial constructions and Buryat graves were not excavated. Excavations were carried out only over areas of iron production sites.

Figure 4 displays a photograph of Barun-Khal valley and its surroundings. The photograph is taken from one of the neighbouring heights.

3 | BARUN-KHAL 2: GEOPHYSICAL SURVEY

After the archaeometallurgical site was discovered in June 1997 during delineating areas of the slag occurrences (Kozhevnikov et al., 2001; Kozhevnikov et al., 1998), we conducted a pilot magnetometer survey along two lines, one of which was oriented across and the other along the valley (Figure 5). To measure the

FIGURE 4 Photograph of the Barun-Khal valley taken from the north. In the background lie the Chernorud settlement and the Valley of Kuchulga River. In the foreground lies the field camp of IRGTU [Colour figure can be viewed at wileyonlinelibrary.com]

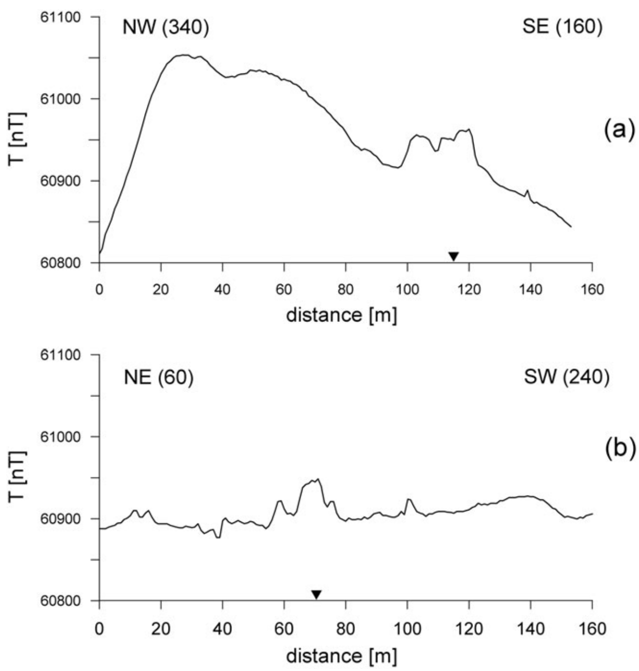

FIGURE 5 Results of the pilot magnetometer survey at the mouth of the Barun-Khal valley. The inverted triangle indicates location of the ground squirrel's burrow and of the trial pit at the intersection of the survey lines. June 1997: magnetometer MMP-203; the distance between sampling points is 1 m

magnitude of the total magnetic field (in tesla), we used a commercially available proton magnetometer MMP-203 providing an instrumental error of the order of ±1 nT. The distance between measurement points was 1 m; the intersection of the profiles was above the trial excavation pit. Against the regional geomagnetic field a smaller-scale anomaly was seen with the amplitude of about 50 nT. The width of the anomaly suggested that the pit was located in the epicentre of a magnetized object with a total area of about 500 to 1000 m^2.

In 1998, we carried out a reconnaissance magnetic survey over an area of 150 by 200 m (area 1 in Figure 3). The purpose of the survey was to assess the overall potential of the site and to locate and delineate areas promising for further excavation work. According to the pilot magnetic survey of Figure 5, the width of the magnetic anomaly associated with the archaeometallurgical site was estimated to be about 20 to 25 m. Therefore, the reconnaissance survey was made along lines the distance between which was 4 m. Measurements were taken at 2 m intervals on each profile.

As during the pilot survey of 1997, we used the MMP-203 instrument. Another magnetometer was used to record variations of the geomagnetic field needed to correct the readings of the main magnetometer. During the survey, the main magnetometer's sensor height above the earth surface was about 2 m.

Figure 6 shows the contour map and three-dimensional (3D) image of magnetic field intensity for the survey area. In the northwest, one can see a linear, step-like anomaly, the amplitude of which decreases from northeast to southwest from 400–500 nT to 200–250 nT. The anomaly strikes in the same direction as that of the main geological structures of the Olkhon region and is due to the bedrock geology. Most likely, the anomaly is associated with a steeply dipping amphibolite layer outcropping on the left side of the valley. Towards the

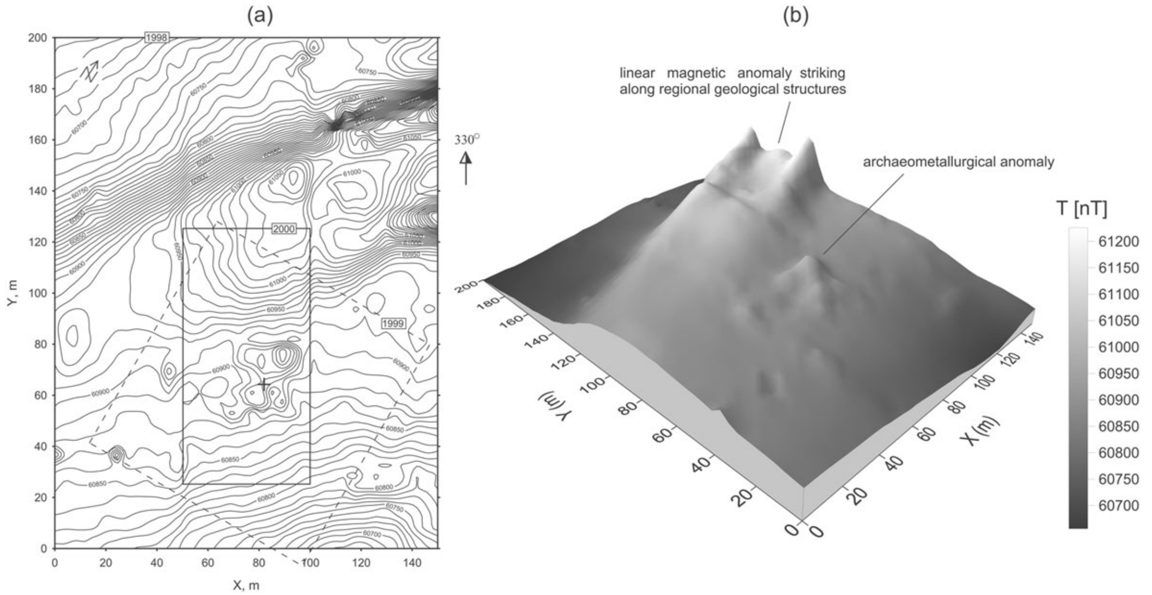

FIGURE 6 Magnetometry results over area 1 of Figure 3: (a) magnetic field contour map; (b) 3D magnetic field image. The rectangles show the geophysical survey areas of 1999 and 2000. The small cross indicates the centre of the excavation. Magnetometer: MMP-203; 4 m by 2 m sampling density

southwest, the step in the magnetic field is smoothed out due to dipping of the upper edge of the amphibolite layer in this direction. This suggests that the thickness of unconsolidated sediments, covering the bedrock, increases towards the right side of the valley.

Against the background of the regional geomagnetic field, the archaeometallurgical site manifests itself as a smaller-scale magnetic anomaly with intensity of 50 to 80 nT. The excavation turned out to be located approximately at the centre of this anomaly. As can be seen, at the reconnaissance stage of magnetic exploration (4 m by 2 m network of observations) the archaeometallurgical site appears as a single anomaly.

In 2000, we performed a magnetic survey over a smaller area (its boundary is shown in Figure 6 by a solid line). The measurements were performed using MMP-203 magnetometer on the observation network of 1 m by 1 m, and with the sensor height of 0.8 m. Figure 7 represents a contour map of magnetic field intensity. A rectangle shown in Figure 7 by a solid line indicates the area of the excavation and of the dump where measurements could not be performed. Within the rectangle area shown by a dashed line, the intensity and gradient of the magnetic field differ sharply from those observed over the most part of the survey area. It is likely that the magnetic field is associated here with a cluster of magnetized objects, such as furnaces, baked clay, slag, etc. Thus, the excavation occupies only a minor part of the total archaeometallurgical site's area.

The pattern of magnetic field reflects the complex structure of the site. The excavation is located in the centre of a magnetic anomaly comprising several smaller-scaled positive anomalies. Most of these anomalies have amplitude of +50 to +100 nT; only one of them has amplitude of about +200 nT. This anomaly is located on a smooth topographic height, at about 10 m to the north of the excavation. In appearance, this elevation resembles a ritual stone mound, but the associated magnetic anomaly indicates the presence of strongly magnetized objects. This place is the most promising for further excavation.

In 2012, within the framework of the Russian Foundation for Basic Research (RFBR) Project Number 10-05-00263, P. G. Dyadkov and D. A. Kuleshov conducted a high-resolution survey of vertical magnetic field gradient using a GEOMETRICS G-858 cesium magnetometer. The lower sensor was located at a height of 30 cm, the upper one at a height of 1 m. The data were recorded in continuous mode over four areas measuring 40 m × 40 m each, as a whole forming a square with a side of 80 m. The area included the excavation and its surroundings.

The measurements were made along lines oriented in the north–south direction. Within 40 m by 40 m square, where the excavation is located, the distance between the lines was 1 m. For the rest of the area, the distance between the lines was 2 m. The time interval between measurements was 0.1 s, which, taking into account the speed of walking, corresponded to the average spacing between the sampling points about 0.1 m.

Figure 8 shows the map of the magnetic field gradient for the overall survey area (80 m by 80 m). A rectangle delineates the area occupied by the excavation and surrounding dump. As seen on the map, the excavation occupies about one-tenth of the area of anomalous magnetic field gradient, in the southwest of the total survey area. In the northeast, there is another cluster of small-scale anomalies. They form a band, or linear zone, which extends in the northwest–southeast direction. This strip is to the right of the road, where the left slope of the valley becomes flat and passes into the bottom. It is not yet clear what exactly this cluster of anomalies is related to. However, there is no doubt that it is not the geology, but the human activity. In 1997, we found here remains of a furnace's bottom (presumably iron-smelting) forming a circle about 60 cm in diameter. The circle was laid out of bricks shaped in the form of arch segments.

Magnetometer surveying is known as one of the main tools of archaeological prospection (Aspinall, Gaffney, & Schmidt, 2008; Linford, 2006; Schmidt, 2007), including the search for and study of

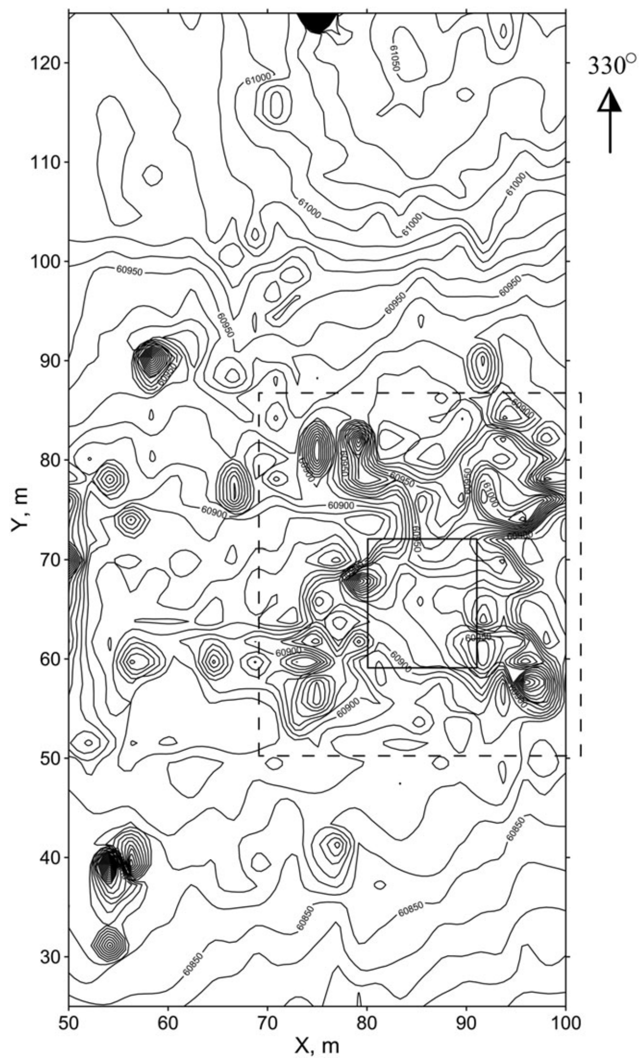

FIGURE 7 Magnetometry results of 2000 represented as contour map of the total magnetic intensity (for location of the survey area, see Figure 6). The contour interval is 10 nT. A rectangle shown by a solid line displays the area occupied by the excavation and the surrounding dump where the measurements could not be performed. The dashed line shows the area promising for further excavation work. Magnetometer: MMP-203; 1 m by 1 m sampling density

ancient iron production sites (Abrahamsen et al., 2003; Crew, 2002; Kulessa, Chiarulli, & Haney, 2004; Powell, McDonnell, Batt, & Vernon, 2002; Smekalova, Voss, & Abrahamsen, 1993; Vernon, McDonnel, & Schmidt, 1998; Vernon, McDonnel, & Schmidt, 1999). However, in archaeometallurgy-related studies one uses also resistivity surveys (Apostolopoulos, 2014; Humphris & Carey, 2016; Vernon, 1995; Walach, Scholger, & Cech, 2011). In the literature on archaeological prospection there are also examples of using SP (Drahor, 2004; Wynn & Sherwood, 1984) and induced polarization (Florsch, Llubes, Téreygeol, Ghorbani, & Roblet, 2011) techniques.

In 1999, we carried out resistivity and SP surveys around the excavation, over an area of 96 m by 100 m. Dashed line in Figure 6 shows the boundary of this area.

The resistivity survey was made with an AE72 instrument designed for measurements of d.c. resistivity and SP. According to the test work (Agafonov & Kozhevnikov, 1999), the Schlumberger A3M2N3B (AB = 8 m, MN = 2 m) array was chosen as suitable for the resistivity profiling. Among other things, the choice of AB = 8 m was motivated by excavation results, which indicated that the depth at which archaeometallurgical findings occurred was no more than 1.5 m. Resistivity readings were taken along survey lines that were oriented north–south. The spacing between lines and between readings was 4 m.

Figure 9(a) displays the apparent resistivity contour map. No less than two-thirds of the survey area has a smooth apparent resistivity relief with resistivity values of about 300 to 400 Ohm m. The excavation is located on the periphery of an area characterized by high (600–1400 Ohm m) resistivities. The most resistive part of the anomaly stretches in the northwest–southeast direction, along the valley and perpendicularly to the regional geological strike.

As the most probable cause of high resistivity one could assume a rise in the permafrost top. However, resistivity profiling using arrays with AB = 4 m and AB = 16 m has shown that the decrease in the spacing between current electrodes resulted in more contrast anomaly, whereas at large spacing the anomaly became smoother (Agafonov Yu & Kozhevnikov, 1999). If the anomaly were produced by permafrost, increasing AB spacing would have resulted in an increase of apparent resistivities. Since this is not the case, the anomaly is related to the near-surface features. Note that earlier in the Olkhon region only linear resistivity anomalies were known trending parallel to the main geological strike (Kozhevnikov et al., 2004; Kozhevnikov & Tezkan, 1998). In this respect, the small-scale isometric resistivity anomaly in the mouth part of the Barun-Khal valley is rather unusual. This, as well as the fact that both the magnetic anomaly and the excavation border on the northwest edge of the resistive area, suggests a possible association of archaeological features and the apparent resistivity high. Obviously, to clarify the actual reason why this part of the site is highly resistive, further excavations are needed.

SP measurements were conducted along five survey lines oriented from the north to the south. The spacing between measurement points was 4 m. They are indicated on the SP contour map (Figure 9(b)) by dots. Non-polarizable Cu–$CuSO_4$ electrodes were used in this survey. One electrode (N) was located at the reference point with coordinates X = 16 m, Y = 0 m, and another electrode (M) moved along the survey lines. At each position of the electrode M, its potential U was measured with reference to the base electrode N.

As shown in Figure 9(b), U changes from −95 to 25 mV. Although the measurement points were distributed over a network not sufficient for a detailed survey, one can see in the southwest of the area a distinct negative anomaly of the SP voltage. The anomaly correlates spatially with the apparent resistivity high (see Figure 9(a)). Currently, the nature of the SP anomaly remains unclear. On a regional scale, the Chernorud zone is traced by northeast–southwest trending negative SP anomalies with amplitudes of 0.5 to 1.0 V (Kozhevnikov et al., 2004; Kozhevnikov & Tezkan, 1998). The source of these anomalies is a geobattery formed by steeply dipping electronic conductors (graphite-bearing layers) and host rocks with ionic conductance (Bigalke & Grabner, 1997). However, the SP pattern of the site is quite different from that associated with a geobattery.

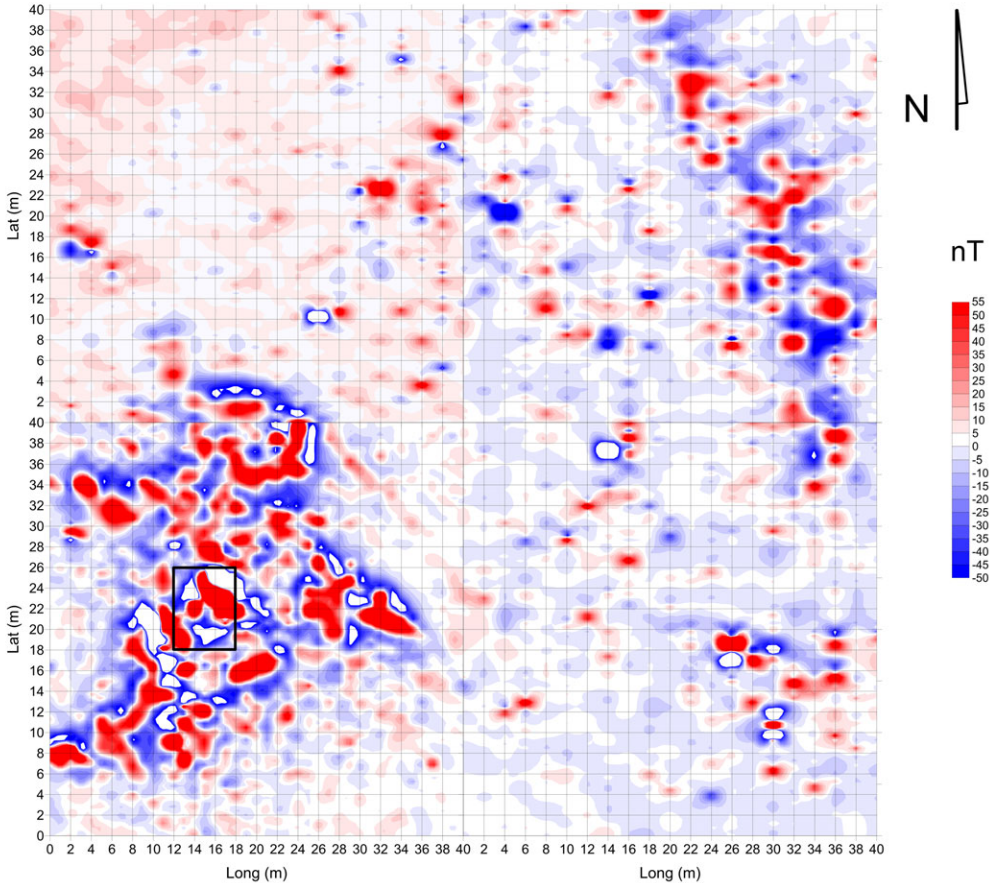

FIGURE 8 Barun-Khal 2 (2012): gradiometer survey results. The rectangle shows the excavation area. Magnetometer: G-858. The lower sensor was located at a height of 30 cm, the upper one at a height of 1 m. Sampling density: 1 m by 0.1 m in the bottom left square, 2 m by 0.1 m in other squares [Colour figure can be viewed at wileyonlinelibrary.com]

4 | BARUN-KHAL 2: THE EXCAVATION

It will be recalled that at the Barun-Khal 2 site a trial pit had indicated ancient metallurgical activity. After that, a pilot magnetometer survey along two transects, crossing the pit, showed that the area occupied by the archaeometallurgical complex was about 500 to 100 m^2. During 1998–2000, the trial pit turned into a full-scale excavation. Simultaneously, geophysical surveys were being carried out around the excavation. Previously, the excavation results were published for intermediate stages of the earthwork only (Kozhevnikov et al., 1998, 2000; Kozhevnikov et al., 2001). Figure 10 displays the most comprehensive plan of the excavation as of today.

The total excavation area was 68 m^2. Depending on the thickness of the loose deposits, the depth of the excavation varied from 0.5 to 2.1 m. In places of the excavation with no signs of ancient earthwork the sequence and thickness of the near-surface layers (from top to bottom), was as follows: (1) dark brown sandy loam with rubble and gruss; (2) light yellow sandy loam with sand and gruss; (3) dark brown sandy loam, turning grey with rubble and slightly rounded pebbles; (4) grey-yellow dense loam with crushed stone and slightly rounded pebbles. In all near-surface layers, iron slag, bricks and pieces of clay lining were found. The most slag-saturated was the layer of dark brown sandy loam.

In 2000, we completely cleared a large, or main, pit dug in a dense grey-yellow loam. The pit has a diameter of 2.8 m and a depth of 2.1 m and is surrounded by three furnaces. They were dug in the dense grey-yellow loam material of the pit's sides. In their lower parts, the furnaces are connected to the pit by underground canals, or tunnels (Figure 11). The bottom of the furnaces and of the pit are at the same level. Being in the pit, one had easy access to the furnace mouths and, thus, to the blooms.

Above furnace #1 there was a flat mound with a diameter of 1.2 m. The mound consisted of one to two layers of stones. The shaft's depth of the furnace #1 is about 1.4 m. In the plan the charging opening on the top of the furnace has an oval shape. The width of the charging opening is 0.95 m and the length is 1.25 m. The underground tunnel, of 1 m in length, connects the furnace's shaft to the main pit.

Furnace #3 was covered with a layer of dense clayey material, stones, bricks, and pieces of slag. The stones, from 2 cm × 4 cm × 9 cm to 12 cm × 15 cm × 20 cm in size, were packed less tightly as those of the mounds covering furnace #1. The bricks, 30 cm in length and 16 cm in width, had the shape of a triangle, with an angle of 30° and the other two of 75°. In plan, charging openings of furnaces #2 and #3 resemble a triangle with one vertex facing the main pit.

In the cross-section, the furnaces are funnel-shaped. The outer opening (furnace's mouth) of the tunnel of furnace #2 measures 0.50 m by 0.75 m and that of furnace # 3 measures 0.60 m by 0.85 m. The sidewalls of the tunnels are parallel to each other, the bottoms are flat and horizontal, and the upper parts are arch-shaped. The shaft of furnace #3 is 1.4 m in depth, whereas the shaft's depth

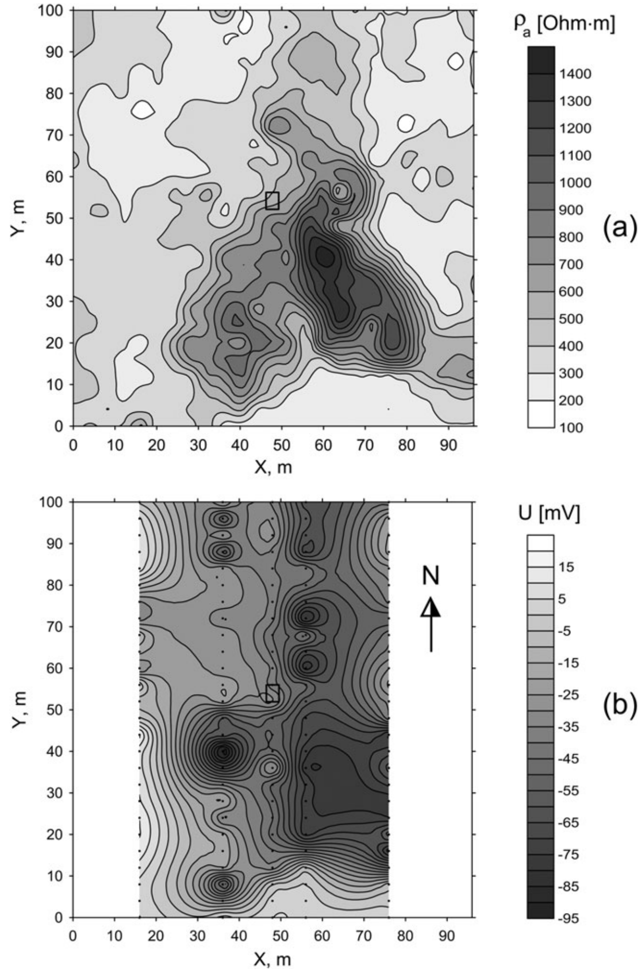

FIGURE 9 Resistivity and SP results of 1999: (a) apparent resistivity contour map for the Schlumberger array A3M2N3B (AM = 8 m, MN = 2 m); (b) SP contour map. The rectangle indicates the position and approximate dimensions of the excavation. For the location of the survey area, see Figure 6. Instrument: AE72. Resistivity sampling density is 4 m by 4 m. SP sampling points are shown in (b) by dots

of furnace #2 is 1.55 m. The furnaces were filled with dark-grey sandy loam with admixture of very fine charcoal fragments. In its upper part (to a depth of about 0.7 m), furnace #3 was filled with bricks and fragments of clay lining. It seems that after the end of the operation, ancient metallurgists have preserved furnaces #1 and # 2.

From the north and east, trenches dug in grey-yellow loam join the main pit. The northern trench consists of two parts, or segments, the southern and northern ones, 4 m and 2.5 m long, respectively. The width of the northern segment varies from 0.7 to 1.8 m. The northern segment, which was not completely cleared, continues beyond the excavation. In the south, a wall of clay-bounded stones and bricks partitioned the northern trench. The height of the wall is 0.7 m and the width is 0.55 m. In the middle of the trench, at the junction of the northern and southern segments, there is a small area measuring 0.6 m × 1.6 m. To the northeast of this area there is another, 1 m wide and 0.8 m high, wall of stone and bricks. The material from the lower part of the trench contained a large amount of charcoal.

At the top, the width of the eastern trench is 0.75–0.85 m, whereas at the bottom it is 0.4–0.5 m. The total length of the trench is 4.3 m; the depth is 1 m. In the southeast, the trench is blocked by a stone wall, beyond which the trench continues in the southeast direction. Sides of the trench and of the main pit retained traces of strong heating. Perhaps, they were burned purposefully: under the action of high temperature loamy material has become harder and thus resistant to destruction.

No artefacts were found during the excavation, so metallurgical activity was dated by the radiocarbon method. The pit was repeatedly used, gradually filling with wastes of metallurgical production. The oldest charcoal from the pit has an uncalibrated ^{14}C date (SOAN-3902) of 2050 ± 35 BP which, taking into account the calibration, gives 171 BC to 168 AD cal (2σ). The order of the construction of the furnaces has not been established. Only one of them, furnace #1, was dated on the charcoal from the furnace's hearth (SOAN-3903). The uncalibrated and calibrated dates are, respectively, 1915 ± 35 BP, and 5–210 AD cal (2σ).

5 | BARUN-KHAL 3: GEOPHYSICAL SURVEY

Along with the study of the area 1 surrounding the site Barun-Khal 2, in 1999 we conducted a reconnaissance magnetometer survey over area 2 (for location, see Figure 3). In the southeast, this area measuring 200 m × 270 m adjoins the north-western border of area 1.

The measurements were carried out over a 4 m × 4 m network using a proton magnetometer MMP-203. During this survey, the sensor height was 2 m. Figure 12 shows a contour map (a) and a 3D image (b) of the total magnetic intensity.

In the southeast part of the area, strong, linear anomalies parallel the strike of the main geological structures of the Olkhon region. Similar to the anomalies in the northwest of area 1, they are due to steeply dipping layers of magnetic rocks. Magnetic field intensity is maximal near the left side of the valley and decreases in the southwest direction. As mentioned earlier, this is because the transverse section of the valley is not symmetrical: the thickness of unconsolidated sediments overlying the magnetic bedrock increases towards the right side of the valley. This asymmetry is due to tectonics: the right side of the valley forms a steep escarp developing along an active normal fault.

In the central part of the survey area, there are round-shaped anomalies which form a cluster, or 'chain', trending northeast–southwest. Two of them are positive whereas the anomaly centred on the north-eastern border of the area is especially remarkable due to its large amplitude (more than 1000 nT) and negative polarity.

In the southwest, the magnetic field pattern is smooth, while in the northwest there are intense positive and negative small-scale, spike-like anomalies increasing in number in the vicinity of the camp. Inspection of this part of the survey area has shown that these spikes of magnetic field are due to the ferromagnetic trash.

With regard to archaeometallurgy, our attention was drawn to a much less pronounced positive anomaly centred at X = 68 m, Y = 188 m. We have taken an interest in this anomaly because its amplitude (+50 nT) and diameter (about 20 m) were close to those of the anomaly that marked the site Barun-Khal 2 (see Figures 5, 6). As in the case of the discovery of the site Barun-Khal 2, a ground squirrel

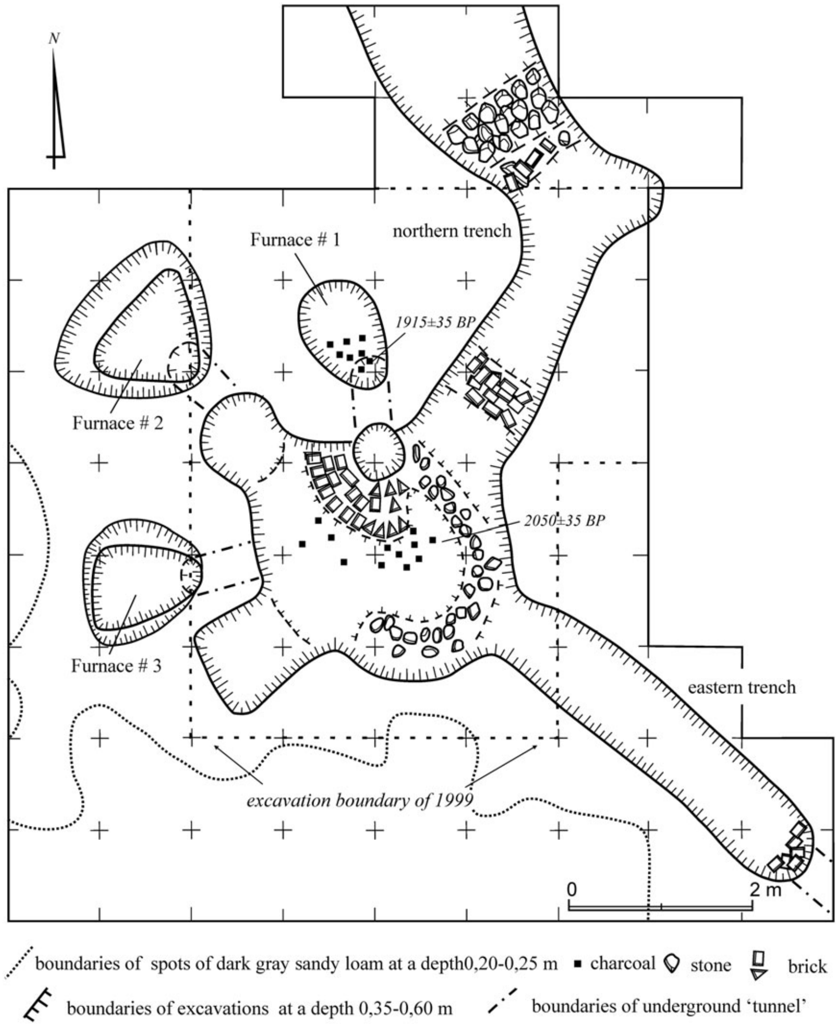

FIGURE 10 Barun-Khal 2: plan of the excavation

FIGURE 11 Barun-Khal 2: furnace # 1 [Colour figure can be viewed at wileyonlinelibrary.com]

played a decisive role here. Inspecting the terrain within and around the anomaly area, we found a burrow and small slag pieces which had been ejected from it. They evidenced directly the presence of an archaeometallurgical site that was given the name Barun-Khal 3.

In 2001, to investigate the anomaly and determine locations for the excavation, we conducted a magnetometer survey over 33 m × 84 m area (labelled as 2001 in Figure 12). Survey lines were oriented parallel to the short side of the rectangle bounding the survey

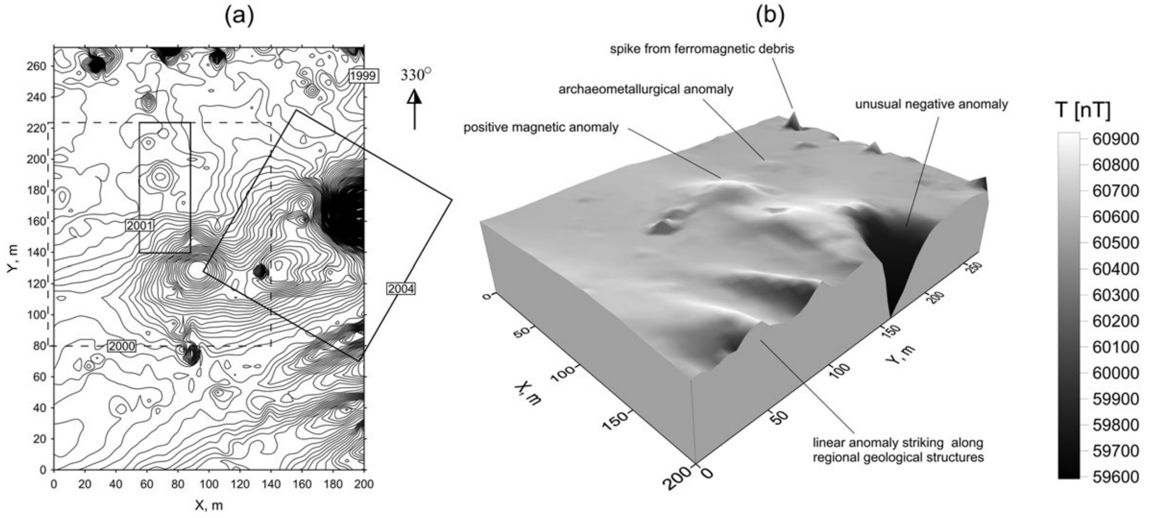

FIGURE 12 Magnetometry results over survey area 2 of Figure 3 (1999). (a) Contour map and (b) 3D image of the magnetic field intensity. Magnetometer: MMP-203; 4 m by 4 m sampling density

area, i.e. approximately across the valley. The distance between survey lines was 2 m, and spacing between readings on each profile was 1 m. During this survey, we used the MMP-203 proton magnetometer with the sensor kept at a height of 0.8 m.

Figure 13 represents results of this magnetometer survey. The overall structure of the anomaly is best seen in Figure 13(a), on the shaded relief map of the magnetic field. Figure 13(b) displays a contour map of the magnetic field. On this map, the contour interval is 5 nT, which is approximately equal to twice the survey error. At such interval, the contours are very close to each other, so for the sake of clarity the values of the magnetic field are not indicated on the map. Increased closeness of contours indicates large magnetic field gradient and marks places with magnetized material located at a shallow depth. A number of small-scale positive magnetic anomalies with amplitude of about several tens of nanotesla cluster into a quasi-linear anomaly directed along the valley.

In the southeast, a general increase in the magnetic field associated with geology is observed. Against a linearly increasing magnetic field, two round shape small-scale anomalies are seen half-cut off by the southeast boundary of the survey area. In the northwest, there is a cluster of isometric anomalies presumably associated with ancient metallurgical activity.

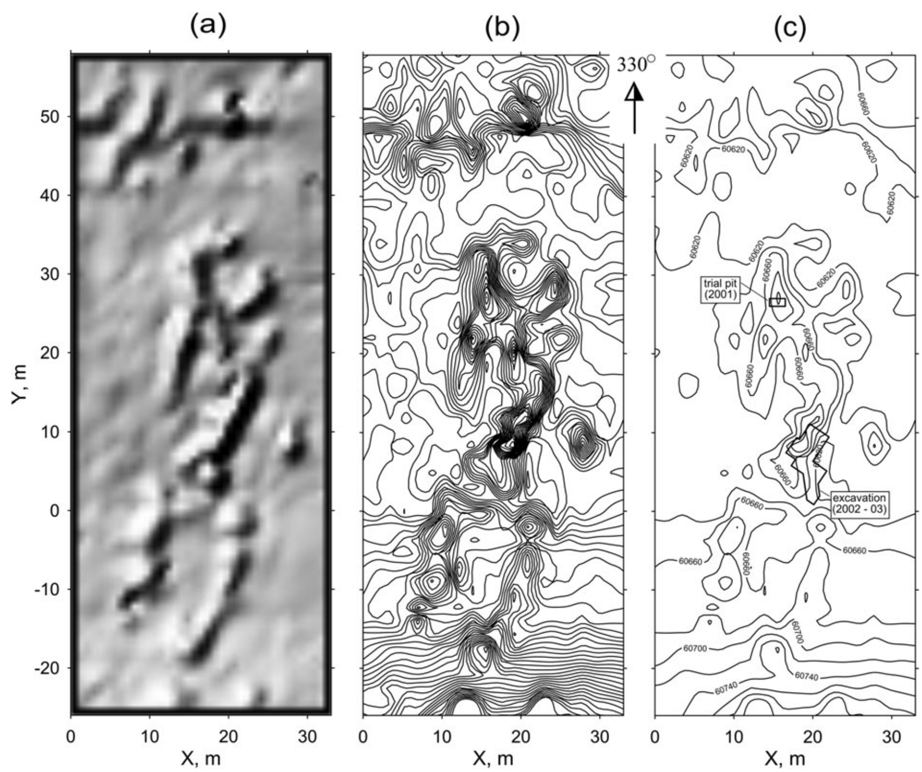

FIGURE 13 Barun-Khal 3: magnetometry results of 2001. (a) Magnetic intensity shaded relief map; (b, c) magnetic intensity contour maps with contour intervals of 5 nT (b) and 20 nT (c). See Figure 12 for the location of the survey area. Magnetometer: MMP-203; 2 m by 1 m sampling density

In 2000, to study the near-surface geology of the Barun-Khal 3 site and of its surroundings, we performed resistivity and SP surveys over an area of 144 m by 144 m. Its boundary is indicated in Figure 12(a) by a dashed line. Both surveys were done on a network of 8 m × 8 m (the distance between profiles, and between observation points was 8 m). The resistivity profiling was carried out using the same array (A3M2N3B) that we used in the study of Barun-Khal 2 site. During the survey, the array was oriented along the *Y*-axis, in the azimuth of 330°.

Figure 14(a) shows the apparent resistivity map. In the southwest, due to shallow permafrost, apparent resistivities are as high as 1150 Ohm m. When creating the apparent resistivity map, we excluded from the processing the data for the profile *Y* = 0. Otherwise, the range of resistivities would be too wide for the map to be visually informative.

Over most of the area, the apparent resistivities vary by about one order of magnitude, from 150 to 1150 Ohm m. In the north, a round shape high resistive ($\rho_a \geq 10^3$ Ohm m) anomaly centres at about *X* = 125 m, *Y* = 125 m. On terrain, this anomaly is located on the most elevated, dry and devoid of vegetation (grass, shrub) part of the site. Surface deposits consist here of stones with gravel and sand filling.

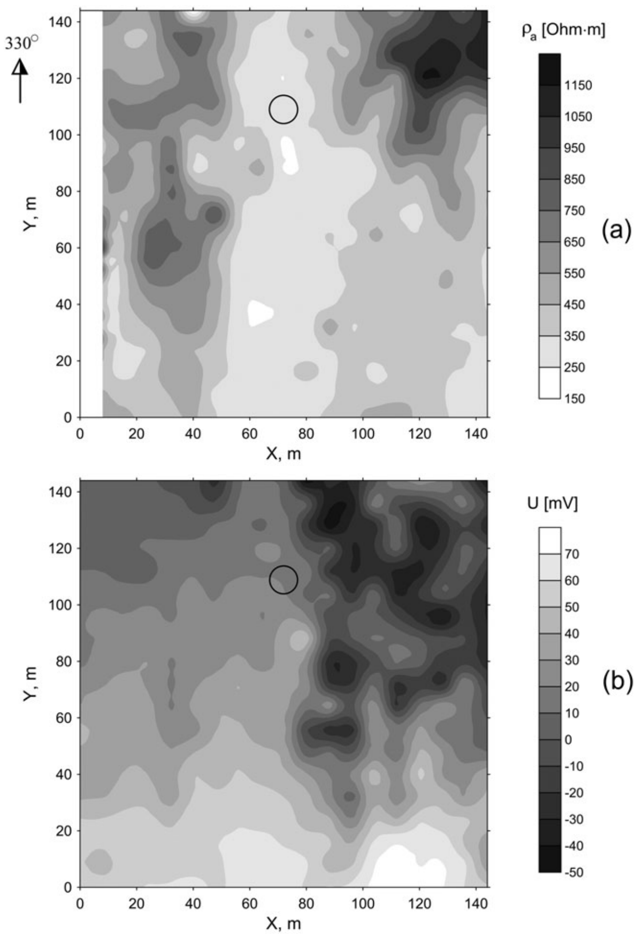

FIGURE 14 Resistivity and SP results of 2000 over the 144 m by 144 m survey area: (a) apparent resistivity map; (b) SP map. The circle indicates the position of the archaeometallurgical magnetic anomaly as determined from the reconnaissance survey data shown in Figure 12 (for the location of the area, see Figure 12). Instrument: AE72; 8 m by 8 m sampling density

The rest of the surrey area is covered with vegetation that changes towards the southwest: a low shrub replaces grass. The archaeometallurgy-related magnetic anomaly (see Figure 12) is located within a linear, 30–50 m wide, low resistivity (150–250 Ohm m) zone extending through the whole survey area in the north–south direction.

During the SP survey, a reference electrode was placed at *X* = 0, *Y* = 144 m. Figure 14(b) displays a contour map of the SP data. A negative SP anomaly is identified in the right upper part of the map. Over most of the area, the potential changes smoothly, increasing towards the southeast. Archaeometallurgical magnetic anomaly is located in the region of a smooth distribution of the potential.

Comparing maps in Figure 14, one can see that high apparent resistivities correlate spatially with negative SP signals. The cause of this correlation remains unclear. Note that a similar correlation is seen also at the Barun-Khal 2 site (see Figure 9 and its comment).

5.1 | Radiometric survey

The radiometric method that measures naturally occurring radioactivity in the form of gamma rays is widely used in geological mapping (Telford, Geldart, & Sheriff, 1990). However, radiometric techniques have found few uses in archaeology (Ruffell & Wilson, 1998; Wynn, 1986). In 1999, in order to clarify the potential of gamma survey in studying geoarchaeological context of the valley, we measured the total gamma ray intensity over survey area 2 (for location, see Figure 3). Measurements were taken on a reconnaissance network of 8 m by 8 m using SRP-68 gamma-ray scintillometer (Larionov & Rezvanov, 1985).

Figure 15 shows the contour map of total gamma radiation intensity (*I*). As can be seen, values of *I* range from 9 to 25 μR/h. The

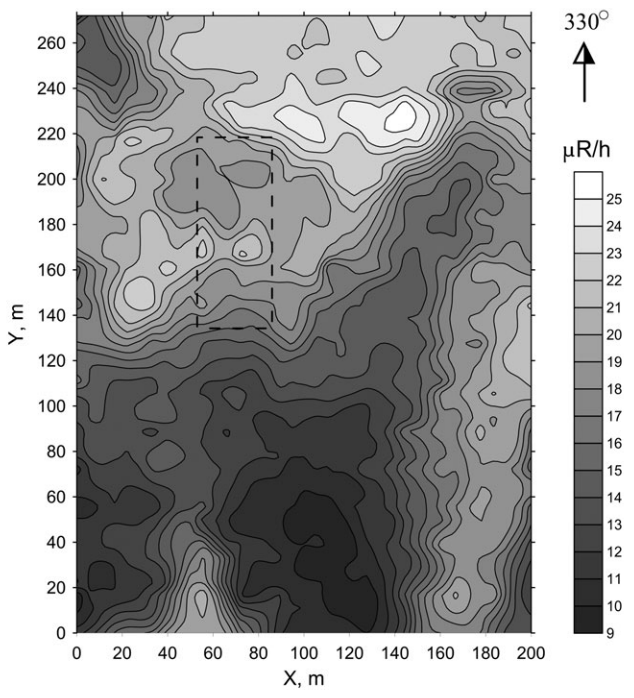

FIGURE 15 Total gamma radiation intensity over area 2 of Figure 3 (1999). The dashed line indicates the boundary of the detailed magnetometry of 2001. Instrument: SRP-68; 8 m by 8 m sampling density

highest intensities are observed in the northwest, most elevated part of the area, covered by stony granite material with gravel and sand filling. The intensity of gamma radiation decreases toward the south-eastern border of the area. The lowest intensities centre at X = 115 m, Y = 40 m. This spot is covered with a bush, while over other parts of the area the soil is matted or, as in the northwest, near to bare.

Previously, no gamma survey was done over the bottom part of the Barun-Khal valley. It has been known only that radioactivity of metamorphic rocks exposed on the sides of the valley do not exceed 11–12 μR/h (Vakhromeev, Dmitriev, Kanaikin, & Kozhevnikov, 1999). Even lower intensities (5–10 μR/h) were observed over diluvium, at the foot of the slopes forming sides of the valley.

The only possible source of increased radioactivity is a material washed down by streams from the Primorsky Range (see Figure 2) which, geologically, consists of a large granite massif. Taken to the foot of the ridge, granite debris formed a proluvium train, whose front reached eventually the mouth of the Barun-Khal valley. Later a non-radioactive soil–vegetation layer covered these radioactive deposits. Obviously, the thicker this layer is, the more gamma-quanta are absorbed, and the lower is the gamma-ray intensity measured on the earth surface. Because of this, the map of gamma radiation intensity mirrors the thickness of the soil–vegetation layer.

It may seem that the results of the gamma-survey are not directly related to the search for and study of such archaeometallurgical targets as smelting furnaces and slag accumulations and thus they are beyond the scope of this article. However, the gamma survey proved to be an effective tool for studying the general geoarchaeological context of the mouth of the valley. The study of ancient geomorphology may be useful in the search for remains of dwellings or places where charcoal was produced. It should also be recalled that the soil–vegetative layer forms an integral constituent of the near-surface stratigraphy that is one of the most important concepts used in archaeology (Gamble, 2001).

It is interesting that between radioactive proluvium deposits with a large amount of granite material and the non-radioactive soil–vegetative layer there is a distinct, sharp boundary (interface). This suggests that at some point in time, due to a rapid climate or water regime change, or other event, the supply of granite material from the Primorsky Range had ceased, and a non-radioactive soil–vegetation layer had formed on the surface of radioactive sediments. On a geological timescale, it happened recently. Thus, radiometric data indicate an event that may be of interest for recent geology and, possibly, geoarchaeology of the Olkhon region.

The earlier mentioned radiometric data suggest that it is advisable to continue gamma surveying over the entire bottom of the Barun-Khal valley, as well over mouth parts of neighbouring valleys, whose structure is similar to that of the Barun-Khal valley. Along with geological efficiency, radiometric surveying is favoured for its low cost and expressiveness.

6 | BARUN-KHAL 3: THE EXCAVATION

In 2001, a trial pit with a size of 1 m × 2 m was dug at the centre of one of the small-scale magnetic anomalies clustering into a complex large-scale anomaly shown in Figure 13. At a depth of about 0.4 m, we found a trench oriented north–south. Its depth was about 0.5 m; the width at the top was 0.9–1.1 m, and at the bottom 0.5–0.6 m. The trench was dug in a layer of dark grey humus sandy loam.

Under the action of high temperature, the trench's sides became orange-red. The trench was filled with a dark-grey humus sandy loam with charcoal and detritus stone material, pieces of slag and clay coating. The uncalibrated and calibrated ^{14}C dates of the charcoal collected at a depth of 40 cm are (SOAN-4595): 1110 ± 80 BP, and 690–1119 AD cal (2σ).

In 2002, we excavated an area of 3 m × 4 m in the centre of one of the intense small-scale magnetic anomalies. The earthwork continued in 2003, and the total excavation area reached 28 m^2 (Kozhevnikov & Kharinsky, 2003). During the excavation, we cleared a trench and two bloomeries (Figure 16). The depth of the trench is 0.7–1.0 m, the width at the top is 1.8–2.1 m, and at the bottom 0.4–0.5 m. In the north, the trench extends beyond the excavation area, and in the southeast joins furnace # 2. In the middle and northern parts of the excavation, the trench is oriented in the north–south direction.

In the middle of the excavation, the trench turns to the southeast. In the place of bending forming a ‘knee’, the trench connects to furnace #1. At 1 m to the north of the junction with the furnace, the trench is crossed by a stone wall with a width of 0.4 m and a height of 0.5 m. Under the action of fire, the trench sides became reddened. The trench contained black loose loam with dispersed charcoal alternating with thin layers of grey sandy loam and grey-yellow loam. In the trench were found fragments of slag, clay lining and charcoal. The radiocarbon dates on the charcoal collected at the trench bottom (SOAN-4883) are: 1770 ± 35 BP, 136–377 AD cal (2σ).

In the north, the depth of the trench is about 1 m. At the top, the width of the trench is 2.2 m, and the sides are not vertical. At a depth of 0.5 m, the trench's width becomes 0.5 m and sides become vertical. The trench was dug in dense yellow loam that is resistant to destruction, so the trench's structure has retained initial proportions and shape. The loamy sides of the trench were fired, which made them even more durable.

Near the western boarder of the excavation, there is furnace #1. In the plan, its shape is triangular. The furnace was dug from a depth of 0.35 to 0.40 m into a dense yellow loam. On the inner surface of the furnace were preserved fragments of a burnt clay coating.

The furnace was overlain by randomly arranged stones and filled with black loose loam with charcoal, pieces of clay coating and iron slag. The depth of the furnace's shaft is 1.1 m. Towards the southeast, the bottom of the furnace is lowered, passing into a working opening that connects to the trench. In the cross-section, the opening is in the shape of a vertically oriented oval with a height of 0.5 m. Radiocarbon dates of the charcoal from the furnace fill are (SOAN-4882): 1820 ± 35 BP, 87–324 AD cal (2σ).

In the southeast, the trench passes into furnace #2. In the plan, the charging opening resembles an oval. Its width is 0.65 m, and the length is 0.90 m. The furnace was dug into a dense yellow loam. At the top, the furnace shaft was filled with dark grey sandy loam with fragments of clay lining and slag. Below there was a dark loam with small stones, slag and fragments of coating. The height of the shaft

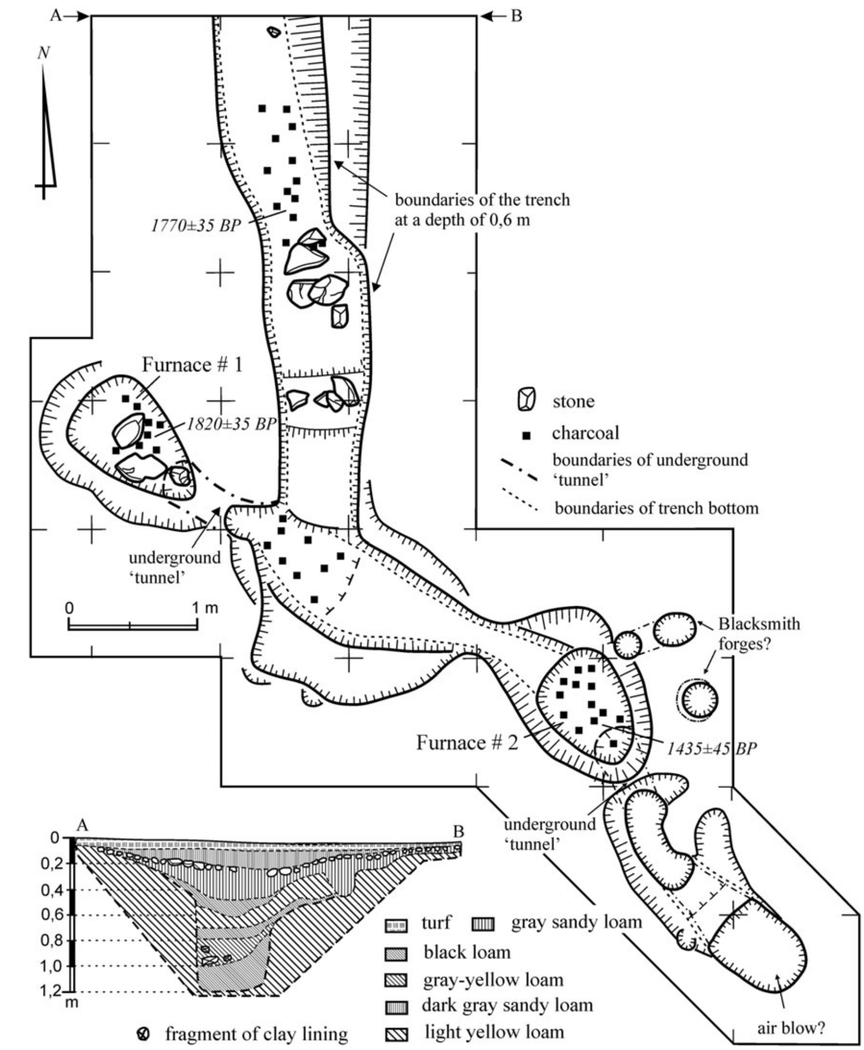

FIGURE 16 Barun-Khal 3: the excavation

is 0.75 m. The bottom of the furnace is lowered in the southeast direction, passing into a tunnel.

The outer part of the tunnel connects to a depression in the floor of the main pit. In the cross-section, the opening has the form of an arch 0.45 m high and 0.4 m wide. Through the underground channel, the opening is connected to another one, which emerges on the earth surface. This opening has the form of an arch with a cross-section of 0.55 by 0.73 m. The curved part of the opening faces the opposite side of the furnace. The uncalibrated and calibrated radiocarbon dates of the charcoal from the furnace fill are (SOAN-5282): 1435 ± 45 BP, 544–665 AD cal (2σ).

7 | DISCUSSION AND CONCLUSIONS

In this article, we described the stages of geophysical and archaeological studies of ancient iron production sites in the Barun-Khal valley. Note again that previously there was no research aimed at a comprehensive study of the ancient iron production in the Olkhon region. Therefore, the scenario of our studies was not known in advance, but was forming in the course of the surveys.

The discovery of the Barun-Khal 2 site was an unexpected result of searching for a solution to a specific geophysical problem (Kozhevnikov et al., 2001; Kozhevnikov et al., 1998). Subsequent archaeogeophysical surveys focused on the area surrounding the excavation. As for the Barun-Khal 3 site, its discovery resulted from the archaeogeophysical survey and was favoured by the experience acquired when studying the Barun-Khal 2 site.

Previously, geophysical surveys in the Olkhon region, including surroundings of the Barun-Khal valley, were aimed at geological mapping of metamorphic complexes and studying regional structure of the region (Kozhevnikov et al., 2004; Kozhevnikov & Tezkan, 1998). In this article, we describe the first experience in applying geophysical methods for studying archaeometallurgical sites and near-surface geology.

When studying the archaeometallurgical context of the Barun-Khal valley, we used magnetometer, resistivity, SP and gamma radiation surveys. They were not aimed at searching for individual bloomery furnaces but predominantly at outlining archaeometallurgical sites and studying their general structure. Along with the data on archaeometallurgical features, the surveys gave new information on the near-surface geology of the Barun-Khal valley and recent geology of the Olkhon region.

As one would expect, the most efficient was the magnetometer survey. At the reconnaissance stage, iron production sites in the Barun-Khal valley are marked by anomalies with amplitude of several tens of nanotesla and an area of about a thousand square metres. Although archaeometallurgical anomalies are observed against anomalies of geological nature with amplitude of up to several hundred nanotesla, they could be identified using an inexpensive proton magnetometer (see Figures 5, 6, 12). Its application proved to be useful also in studying the structure of archaeometallurgical sites (see Figures 7, 13). The gradiometer survey made it possible to recognize details of Barun-Khal 2 site which were unseen when using the proton magnetometer (see Figure 8). Subsequently, similar results were obtained in the search for and study of other iron production sites in the Olkhon region (Kharinsky & Snopkov, 2004; Snopkov, 2017).

Along with the search for and study of archaeometallurgical sites, magnetometer surveys in the Barun-Khal valley revealed some interesting features of the near-surface geology. First, worthy of mention are rounded anomalies, among which the most enigmatic is the negative one near the north-eastern boundary of survey area 2 (seeFigure 12). In 2004, we performed over and around the anomaly area a detailed magnetic survey and found that amplitude of the anomaly is −1500 nT (Kozhevnikov & Kharinsky, 2005). Examination of the terrain showed that the anomalous area forms a very smooth topographic elevation of about 0.5 to 1 m with a diameter of several tens of metres.

Results of resistivity and SP surveys primarily reflect the near-surface geology features, some of which may be, possibly, related to ancient human activity. In order to more fully assess potential of these methods as tools for studying of archaeometallurgical targets, further work is needed.

The results of the radiometric survey were unexpected. The total intensity of gamma radiation mirrors the thickness of the soil–vegetative layer. This layer lies on loose loamy sediments that contain granite material, washed away from the Primorsky Range in the recent geological past.

Previously, in the Olkhon region, artefacts suggesting the early iron production activity were met only as accidental findings of uncertain age. Excavations at the archaeometallurgical sites of the Barun-Khal valley revealed a large amount of charcoal. This made it possible, using the radiocarbon dating, to evaluate the age of iron production at the Barun-Khal 2 and Barun-Khal 3 sites. Radiocarbon dates were obtained by L.A. Orlova in the Laboratory of Geology and Paleoclimatology of the Cenozoic (Institute of Geology and Mineralogy of the SB RAS, Novosibirsk, Russia). In the article we present calibrated, with 95.4% confidence interval, dates obtained using version 4.3.2 of the Oxcal software (Ramsey, 2009) and the atmospheric curve IntCal13 (Reimer et al., 2013).

Chemical, atomic absorption, X-ray diffraction and magnetic analyses of slags have shown that they are a by-product of the bloomery smelting process (Kozhevnikov et al., 2001; Kozhevnikov et al., 1998; Kozhevnikov et al., 2003). For production of iron, ancient metallurgists of the Barun-Khal valley used slag tapping furnaces. At first a large (main, or working), 1.5 m deep, pit or trench, was dug in a dense loam. After that, furnaces were built around the pit by removing 'unnecessary' loam.

The shafts of furnaces are 1.2–1.5 m in height. In the plan they are triangular, resembling a Greek letter Δ. Via an arched tunnel, the lower part of the furnaces is connected to a main pit. Internal diameter of the furnaces decreases downwards, i.e. in the cross-section they have the shape of a funnel or an inverted cone. According to Rehder (2000), this may indicate that instead of charcoal, dry wood was charged into the furnace where it transformed into charcoal. Due to smaller density of dry wood as compared to that of charcoal, its carbonization resulted in a large decrease in volume of a charge that 'had to be manipulated by a pole from the top to ensure adequate mixing of ore and charcoal'.

The inner surface of the furnaces is covered with clay which is fired, sometimes melted. The fill of the pits and furnaces contained many fragments of baked and melted clay. During excavations no tuyeres were found.

The excavations suggest that immediately after stopping the operation of the furnaces the ancient metallurgists filled the pits and the furnaces with earth, stones, slag, charcoal and other material. Due to this conservation, the furnaces and other elements of the smelting sites are well preserved.

Among the filling of pits and furnaces, we did not find traces of ore used by the ancient metallurgists to produce iron. In iron ore occurrences and deposits of the Olkhon region, three genetic types of mineralization have been identified: metamorphogenic, sedimentary (including weathering crust) and endogenous hydrothermal ones (Shulga & Ivanova, 2015). However, the question which ore was used to produce iron in the Barun-Khal valley and elsewhere in the Olkhon region remains open (Matasova, Kazansky, Kozhevnikov, Snopkov, & Kharinsky, 2017; Stepanov, 2012).

The case study of the Barun-Khal sites has shown that slags are the main indicator of the ancient iron metallurgy in the Olkhon region. Prior to the discovery of Barun-Khal 2 site, slags were rarely attended to, and no one suspected that they were evidence of the iron production in antiquity. In the following years, using them as an indicator of archaeometallurgical activity resulted in discovery and studies of other iron production sites (see Figure 2) throughout the Olkhon region (Ivanova, Levitsky, & Kuznetsova, 2006; Ivanova, Levitsky, & Pavlova, 2007; Kharinsky, Kozhevnikov, & Snopkov, 2012; Kharinsky & Snopkov, 2004; Snopkov, 2017).

ACKNOWLEDGEMENTS

The authors thank Yury Agafonov, Natalya Drozhina, Semyon Nikiforov, Piotr Dydkov and Dmitriy Kuleshov for their help in archaeogeophysical survey. In the search for archaeometallurgical objects, we were assisted also by ground squirrels. They are clever and prefer to dig burrows in places of ancient earthworks where the soil is looser than elsewhere. The reported study was partially supported by the Russian Foundation for Basic Research (RFBR), research project No. 10-05-00263: Archaeogeophysical studies of ancient iron metallurgy sites in the Olkhon region. The authors are grateful to Elizabeth Schnieders for having read the article and amended English. The authors also thank anonymous reviewers and Chris Gaffney for their helpful comments and suggestions which greatly improved the paper.

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

ORCID

Nikolay O. Kozhevnikov http://orcid.org/0000-0003-1664-6706
Arthur V. Kharinsky http://orcid.org/0000-0002-4815-6069
Sergey V. Snopkov http://orcid.org/0000-0001-8222-7249

REFERENCES

Abrahamsen, N., Jacobsen Bo, H., Koppelt, U., De Lasson, P., Smekalova, T., & Voss, O. (2003). Archaeomagnetic investigations of Iron Age slags in Denmark. *Archaeological Prospection*, *10*, 91–100. https://doi.org/10.1002/arp.200

Agafonov, Yu. A., & Kozhevnikov, N. O. (1999). Geophysical survey in studying of an Iron Age archaeological site in Chernorud locality (Olkhon region). In G. S. Vakhromeev (Ed.), *Geophysics on the threshold of the third millennium, proceedings of the first workshop* (pp. 215–224). Irkutsk: IRGTU Publishing. (in Russian).

Apostolopoulos, G. V. (2014). Combined geophysical investigation for the detection of ancient metallurgical installations near Keratea City, Greece. *Journal of Applied Geophysics*, *104*, 17–25. https://doi.org/10.1016/j.jappgeo.2014.02.008

Aseev, I. V. (1980). *Transbaikalia in the middle age as inferred from archaeological evidence*. Novosibirsk: Nauka. (in Russian)

Aspinall, A., Gaffney, C. F., & Schmidt, A. (2008). *Magnetometry for archaeologists*. Lanham, MD: AltaMira Press.

Bigalke, J., & Grabner, E. W. (1997). The Geobattery model – a contribution to large scale electrochemistry. *Electrochimica Acta*, *42*, 3443–3452. https://doi.org/10.1016/S0013-4686(97)00053-4

Crew, P. (2002). Magnetic mapping and dating of prehistoric and medieval iron-working sites in northwest Wales. *Archaeological Prospection*, *9*, 163–182. https://doi.org/10.1002/arp.191

Drahor, M. G. (2004). Application of the self-potential method to archaeological prospection: Some case histories. *Archaeological Prospection*, *11*, 77–105.

Fedorovsky, V. S., & Sklyarov, E. V. (2010). The Olkhon geodynamic proving ground (Lake Baikal): High resolution satellite data and geological maps of new generation. *Geodynamics & Tectonophysics*, *1*(4), 331–418. (in Russian), https://doi.org/10.5800/GT-2010-1-4-0026

Florsch, N., Llubes, M., Téreygeol, F., Ghorbani, A., & Roblet, P. (2011). Quantification of slag heap volumes and masses through the use of induced polarization: Application to the Castel-Minier site. *Journal of Archaeological Science*, *38*, 438–451. https://doi.org/10.1016/j.jas.2010.09.027

Gamble, C. (2001). *Archaeology: The basics*. London: Routledge.

Gelvin-Reymiller, C., & Reuther, J. (2010). Birds, needles, and iron: Late Holocene prehistoric Alaskan grooving techniques. *Alaska Journal of Anthropology*, *8*(1), 1–22.

Humphris, J., & Carey, C. (2016). New methods for investigating slag heaps: Integrating geoprospection, excavation and quantitative methods at Meroe, Sudan. *Journal of Archaeological Science*, *70*, 132–144. https://doi.org/10.1016/j.jas.2016.04.022

Ivanova, G. N., Levitsky, V. I., & Kuznetsova, O. P. (2006). Characteristics of the iron production material from the Olkhon Island. In: Proceedings of the Siberian Branch of Russian Academy of Natural Science (Earth Sciences section). Geology, prospecting and exploration of ore deposits, issue 3 (29) (pp. 158–168). Irkutsk: IRGTU Publishing (in Russian).

Ivanova, G. N., Levitsky, V. I., & Pavlova, E. A. (2007). Chemical and mineral composition of iron smelting residuals from the Olkhon Island. In: Proceedings of the Siberian Branch of Russian Academy of Natural Science (Earth Sciences section). Geology, prospecting and exploration of ore deposits, issue 4 (30), (pp. 100–111). Irkutsk: IRGTU Publishing (in Russian).

Kharinsky, A. V., Avramenko, V. N., & Borodina, M. L. (2010). Hipped structures of the Obondoi site (Olkhon region). In: Proceedings of the Laboratory of Ancient Technologies, issue 8, (pp. 235–258). Irkutsk: IRGTU Publishing (in Russian).

Kharinsky, A. V., Kozhevnikov, N. O., & Snopkov, S. V. (2012). Metallurgical centers of the western shore of Lake Baikal in the first millennium AD. In: History and culture of medieval peoples of the steppe Eurasia: Proceedings of the second international congress on medieval archeology of the Eurasian steppes (pp. 65–68). Barnaul: Altai University Publishing (in Russian).

Kharinsky, A. V., & Snopkov, A. V. (2004). Iron production by population of Olkhon region in Elga time. In: Proceedings of the laboratory of ancient technologies, issue 2 (pp. 167–187). Irkutsk: IRGTU Publishing (in Russian).

Kozhevnikov, N. O., Bigalke, J., & Kozhevnikov, O. K. (2004). Geoelectrical surveys in the Olkhon region: Methods, results, and tectonic implications. *Russian Geology and Geophysics*, *45*(2), 253–265.

Kozhevnikov, N. O., & Kharinsky, A. V. (2003). Ancient iron production site Barun-Khal III. In: Sociogenesis of northern Asia: Past, present, future. Proceedings of the Regional Scientific and Practical Conference, (pp. 81–86). Irkutsk: IRGTU Publishing (in Russian).

Kozhevnikov, N. O., & Kharinsky, A. V. (2005). Magnetic field of the Barun-Khal valley and its relationship with ancient metallurgical activity. In: Proceedings of the Laboratory of Ancient Technologies, issue 3 (pp. 38–38). Irkutsk: IRGTU Publishing (in Russian).

Kozhevnikov, N. O., Kharinsky, A. V., & Kozhevnikov, O. K. (2001). An accidental geophysical discovery of an Iron Age archaeological site on the western shore of Lake Baikal. *Journal of Applied Geophysics*, *47*, 107–122. https://doi.org/10.1016/S0926-9851(01)00051-9

Kozhevnikov, N. O., Kozhevnikov, O. K., & Kharinsky, A. V. (1998). How the search for a solution of geophysical problems have led to the discovery of archaeological site. *Geofizika*, *6*, 48–60. (in Russian).

Kozhevnikov, N. O., Kozhevnikov, O. K., Kharinsky, A. V., & Urbat, M. (2003). Chemical composition and magnetism of ancient metallurgical slags from the Chernorud site on the western shore of Lake Baikal. Archaeometallurgy in Europe. Proceedings of the International Conference Milan, Italy, volume 1, pp. 525–534.

Kozhevnikov, N. O., Kozhevnikov, O. K., Nikiforov, S. P., Snopkov, S. V., & Kharinsky, A. V. (2000). Ancient center of iron metallurgy in the Barun-Khal valley. In: Baikal Siberia in antiquity: A collection of scientific papers, issue 2, part 2 (pp. 166–195). Irkutsk: Irkutsk State Pedagogical University (in Russian).

Kozhevnikov, N. O., & Tezkan, B. (1998). The main structure and tectonic features of the Chernorud-Mukhor site on the western shore of Lake Baikal from TEM and SP measurements. *Journal of Applied Geophysics*, *39*, 237–250. https://doi.org/10.1016/S0926-9851(98)00005-6

Kulessa, B., Chiarulli, B., & Haney, S. (2004). Geophysics in support of industrial archaeology in a challenging environment: Shade iron furnace, Pennsylvania, USA. *Archaeological Prospection*, *11*, 181–187. https://doi.org/10.1002/arp.237

Larionov, V. V., & Rezvanov, R. A. (1985). *Nuclear geophysics and radiometric surveys*. Moscow: Nedra. (in Russian).

Linford, N. (2006). The application of geophysical methods to archaeological prospection. *Reports on Progress in Physics*, *69*, 2205–2257. https://doi.org/10.1088/0034-4885/69/7/R04

Lochin, I. (2015). Xiongnu iron production sites in Mongolia. In Y. Murakami, & Y. Esin (Eds.), *Ancient metallurgy of the Sayan-Altai and East Asia* (ed., Vol. 1) (pp. 107–116). Abakan-Ehime: Ehime University Press. (in Russian).

Matasova, G. G., Kazansky, A. Y., Kozhevnikov, N. O., Snopkov, S. V., & Kharinsky, A. V. (2017). A rock-magnetic quest for possible ore sources for the ancient iron-smelting industry in the Olkhon region (Lake Baikal, Siberia). *Archaeometry*, *59*, 511–527. https://doi.org/10.1111/arcm.12260

Mats, V. D. (1993). The structure and development of the Baikal rift depression. *Earth Science Reviews*, *34*(2), 81–118. https://doi.org/10.1016/0012-8252(93)90028-6

Park, J.-S., Gelegdorj, E., & Chimiddorj, Y.-E. (2010). Technological traditions inferred from iron artefacts of the Xiongnu Empire in Mongolia.

Journal of Archaeological Science, *37*, 2689–2697. https://doi.org/10.1016/j.jas.2010.06.002

Park, J.-S., & Rehren, T. (2011). Large-scale 2nd to 3rd century AD bloomery iron smelting in Korea. *Journal of Archaeological Science*, *38*, 1180–1190. https://doi.org/10.1016/j.jas.2010.12.007

Pleiner, R. (2000). *Iron in archaeology: The European bloomery smelters*. Praha: Archeologický ústav AVČR.

Powell, A. J., McDonnell, J. G., Batt, C. M., & Vernon, R. W. (2002). An assessment of the magnetic response of an iron-smelting site. *Archaeometry*, *44*, 651–665. https://doi.org/10.1111/1475-4754.00091

Radtke, M., Reiche, I., Reinholz, U., Riesemeier, H., & Guerra, M. F. (2013). Beyond the Great Wall: Gold of the Silk Roads and the first Empire of the steppes. *Analytical Chemistry*, *85*, 1650–1656. https://doi.org/10.1021/ac3025416

Ramsey, C. B. (2009). Bayesian analysis of radiocarbon dates. *Radiocarbon*, *51*, 337–360. https://doi.org/10.1017/S0033822200033865

Rehder, J. E. (2000). *The mastery and uses of fire in antiquity*. Montreal: McGill-Queen's University Press.

Rehren, T., & Belford, P. (2013). The future of archaeometallurgy and historical metallurgy. *The Crucible. Historical Metallurgy Society News* 83: 6–7.

Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Ramsey, C. B., … van der Plicht, J. (2013). IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon*, *55*, 1869–1887. https://doi.org/10.2458/azu_js_rc.55.16947

Ruffell, A., & Wilson, J. (1998). Near-surface investigation of ground chemistry using radiometric measurements and spectral gamma-ray data. *Archaeological Prospection*, *5*, 203–215. https://doi.org/10.1002/(SICI)1099-0763(199812)5:4<203::AID-ARP96>3.0.CO;2-D

Sasada, T., & Chuang, A. (2014). Iron Smelting in the Nomadic Empire of Xiongnu in Ancient Mongolia. *ISIJ International*, *54*, 1017–1023. https://doi.org/10.2355/isijinternational.54.1017

Schmidt, A. (2007). Archaeology, magnetic methods. In D. Gubbins, & E. Herrero-Bervera (Eds.), *Encyclopedia of geomagnetism and paleomagnetism*. *Encyclopedia of Earth Sciences Series*. (pp. 23–31). Heidelberg: Springer.

Shulga, V. V., & Ivanova, R. N. (2015). Polygenic iron-ore mineralization of the Olkhon crystalline complex (West Baikal Region). In: Proceedings of the Siberian Branch of the Earth Sciences Section of the Russian Academy of Natural Sciences, No. 2 (51), pp. 35–45 (in Russian).

Smekalova, T., Voss, O., & Abrahamsen, N. (1993). Magnetic investigation of iron-smelting centers at Snorup, Denmark. *Archaeologia Polona*, *31*, 83–103.

Snopkov, S. V. (2017). Magnetic prospection method in the search for and study of ancient iron smelting sites on the western shore of Lake Baikal (Olkhon region). In: Proceedings of the third All-Russian Malyshev Conference, ROSA publishing, pp. 45–55 (in Russian).

Stepanov, I. S. (2012). Classification and chemical composition of iron smelting byproducts from Gisbakalia. Proceedings of the Irkutsk State Technical University, issue 12 (71), (pp. 70–76). Irkutsk: IRGTU Publishing (in Russian).

Telford, W. M., Geldart, L. P., & Sheriff, R. E. (1990). *Applied geophysics* (second ed.). Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9781139167932

Vakhromeev, G. S., Dmitriev, A. G., Kanaikin, V. S., & Kozhevnikov, N. O. (1999). Physical properties of rocks of the Olkhon region. In G. S. Vakhromeev (Ed.), *Geophysics on the threshold of the third millennium, proceedings of the first workshop* (pp. 110–127). Irkutsk: IRGTU Publishing. (in Russian).

Vernon, R. W. (1995). Development of geophysical techniques for studying early iron smelting sites (MSc Dissertation). University of Bradford.

Vernon, R. W., McDonnel, G., & Schmidt, A. (1998). The geophysical evaluation of an iron-working complex: Rievaulx and Environs, North Yorkshire. *Archaeological Prospection*, *5*, 181–201. https://doi.org/10.1002/(SICI)1099-0763(199812)5:4<181::AID-ARP95>3.0.CO;2-W

Vernon, R. W., McDonnel, J. G., & Schmidt, A. (1999). Medieval iron and lead smelting works: a geophysical comparison. In A. M. Pollard (Ed.), *Geoarchaeology: Exploration*, *environment*, *resources*, Special Publications (ed., Vol. 165) (pp. 15–34). London: Geological Society.

Walach, G., Scholger, R., & Cech, B. (2011). Geomagnetic and geoelectric prospection on a Roman iron production facility in Hüttenberg, Austria (Ferrum Noricum). *Archaeological Prospection*, *18*, 149–158. https://doi.org/10.1002/arp.412

Wynn, J. C. (1986). Archaeological prospection: An introduction to the Special Issue. *Geophysics*, *51*, 533–537. https://doi.org/10.1190/1.1442107

Wynn, J. C., & Sherwood, S. I. (1984). The self-potential (SP) method: An inexpensive reconnaissance and archaeological mapping tool. *Journal of Field Archaeology*, *11*, 195–204.

Xiongnu Archaeology (2011). In U. Brosseder, & B. K. Miller (Eds.), *Multidisciplinary perspectives of the first steppe empire in inner Asia*. Bonn: Rheinische Friedrich-Wilhelms-Universität.

Zaitsev, M. A., Svinin, V. V., & Kharinsky, A. V. (1996). Hipped structures on the western shore of the Kurkut Bay. In: Archaeological heritage of Baikal Siberia: Study, protection and use (pp. 67–76). Irkutsk: Irkutsk State University (in Russian).

How to cite this article: Kozhevnikov NO, Kharinsky AV, Snopkov SV. Geophysical prospection and archaeological excavation of ancient iron smelting sites in the Barun-Khal valley on the western shore of Lake Baikal (Olkhon region, Siberia). *Archaeological Prospection*. 2018;1–17. https://doi.org/10.1002/arp.1727