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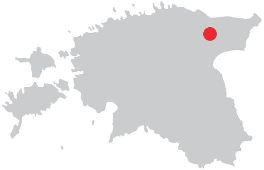

The Iron Smelting Complex of Rihula

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INTRODUCTION

The iron smelting sites of Rihula are located in Lääne-Viru County, west of the Sirtsi mire. The discovery was made in 2016 by Kaarel Sikk during fieldwork for the LIFEME project (Sikk 2017). Altogether three new iron smelting sites were found (Fig. 1). All of the smelting sites were located on a SE–NW directional esker which was formed by the retreating Scandinavian ice sheet. The area provided suitable conditions for establishing iron smelting sites near the mire which most likely held suitable bog ores for the smelting process.

In July 2022, archaeological excavations took place at the iron smelting complex, led by Ragnar Saage and Sander Jegorov. The sites were first inspected to determine which one holds the most scientific value. The preliminary research questions were the following: which site has the highest concentration of slag? Which kind of furnaces were used for smelting iron? Could there have been a smithy in the vicinity of iron smelting sites?

The aim of this article is to give a more comprehensible grasp of the iron smelting site complex – most importantly, when was it used. Moreover, the article investigates metallurgical analysis of slag and unprocessed iron found from the Rihula II smelting site.

LOCATION OF THE SMELTING SITES

The Rihula II iron smelting site was discovered during a survey conducted in the Sirtsi mire as part of the wetland restoration project LIFE Mires Estonia (‘Conservation and Restoration of Mire Habitats’, LIFE14NAT/EE/000126). The first indications of iron smelting activities were identified in the vicinity of a historic hideout used by Estonian Forest Brothers during World War II.

To gain a better understanding of the extent of iron production practices in the area, further metal detector surveys were carried out on the neighbouring hills. This investigation led to the identification of three distinct iron smelting sites, all situated at elevations ranging between 76.5 and 78.5 metres above sea level. The sites were located on different landforms: the first found site, Rihula I, is on a small sandy elevated area; the excavated Rihula II site on an even more prominent hill; and the Rihula III site is almost flat. The distance between the I and II smelting sites was about 200 metres and about 350 metres between sites I and III. In the northern part of the surveyed area, at the same elevation of 77 metres above sea level, sandy areas with potential iron ore were found.

As metal detector surveys were carried out on relatively large areas, these observations suggest that the iron smelting activities in the region were likely concentrated around specific elevations. Such location choice could be related to the natural features of the landscape, such as suitable conditions for smelting processes or the availability of raw materials as suggested by the variation in the local-level landforms of these sites (Rihula I–III).

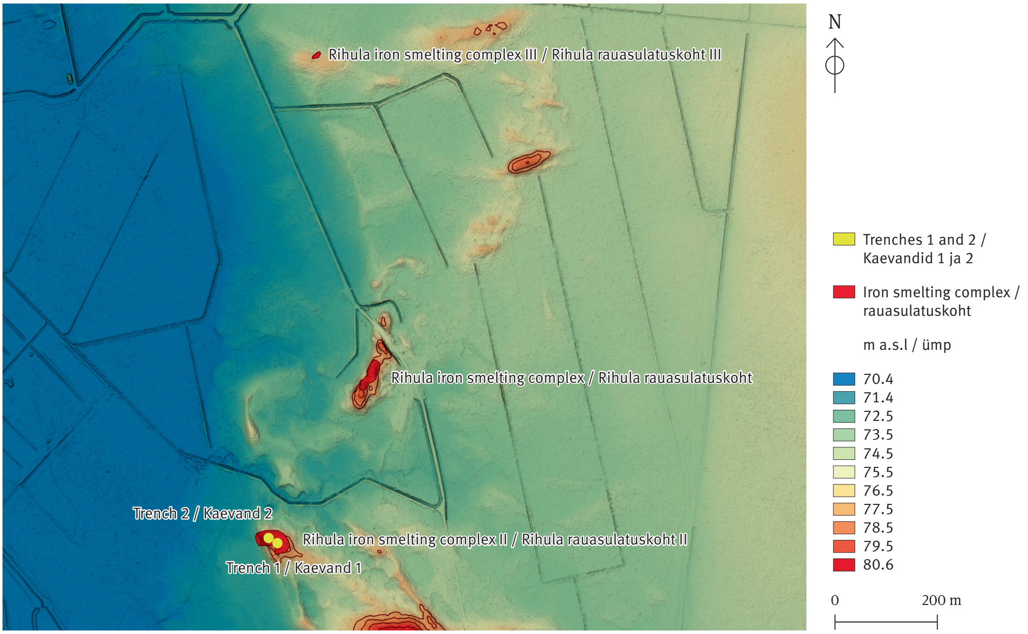

Fig. 1. *Rihula iron smelting complex and trenches.*
Jn 1. *Rihula rauasulatuskompleks ja kaevandid.*
Base map / Aluskaart: Estonian Land Board / Maa-amet
Additions/ Täiendused: Sander Jegorov, Kaarel Sikk

FIELDWORK

First, a thorough examination of the smelting sites was executed. Small test pits were dug on all three sites to identify which has a higher slag concentration and therefore may be of interest. Sharp iron rods were also used to probe the soil for slag heaps. Finally, the Rihula II site was chosen due to it yielding the most slag and pieces of furnace lining.

Two trenches were dug, 4 × 1 and 2 × 2 m in size, which were placed at the second highest point of the esker. The soil was sieved by using meshes of 5 mm eye size. Measurements were done with GNSS device Trimble R8 and total station Trimble S5. Photogrammetry was used for the documentation of the trenches. Agisoft Metashape Pro was used for the creation of 3D models.

The aim of the first trench was to make a cross-section of a presumed slag heap and possibly find a base of an iron smelting furnace. It turned out that most of the top soil of the esker was covered by a slag heap which is in a sense similar to Tuiu, a smelting site in northern Saaremaa (Peets 2003, 104). Confirmed by the cross-section, the slag heap consisted of multiple layers (Fig. 2). At first brown sand was consistent throughout 20–30 cm, filled with slag particles. Underneath laid multiple layers of dense alternating depositions of slag and furnace lining. It is therefore likely that iron smelting took place for a long time or quite intensively at the II site. The slag heap contained other finds as well, namely bloomery iron and pottery.

The aim of the second trench was to find a supposed base of a furnace discovered by Kaarel Sikk during the initial fieldwork. The trench was geolocated using photos taken during the fieldwork of 2016. At first the second trench did not seem to be different from the first in terms of the upper layers (Fig. 3). Most dominant was the brown sand which contained slag in large quantities. The differences started at about 40 cm. It was discovered that the eastern part of the trench contained uneven intensely burnt red-violet sand which had roasted iron ore particles in it. It is possible that some of the area of the trench was used for roasting ore. Ore roasting has been a common procedure in the *chaîne opératoire* of iron smelting and such sites have been found before in previous excavations (Pleiner 2000, 109). Roasting could have been done above the ground or in pits (Moilanen 2015, 36), but it is not certain which one was used in this context. Under the red layer of sand, a 13 cm thick intense black sooty layer started to appear, which is associated with burning. The layer seemed to have a dugout in the eastern profile which may mean that ore was indeed burned in a pit. Another explanation may be that before roasting ore, burning charcoal took place at the same spot. Such development has also been recorded in other sites like Tuiu (Peets 2003, 105). In the charcoal layer, slag concentration was minimal which indicates that not much iron production took place at that location at the time when the charring and ore roasting took place.

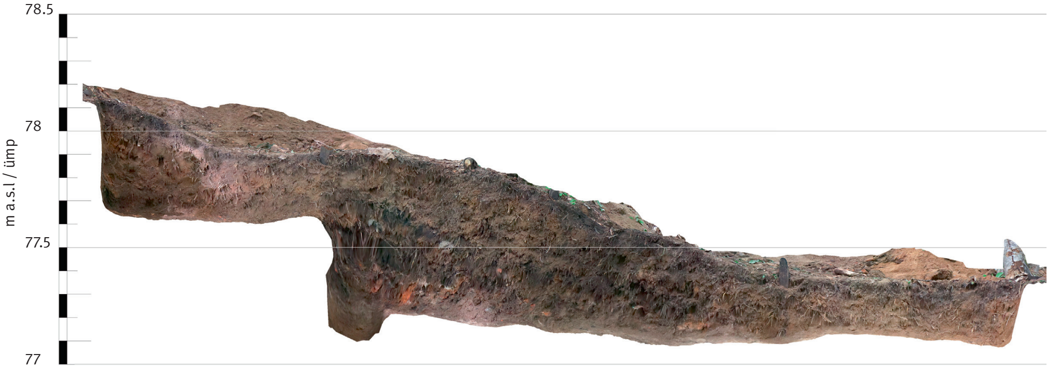

Fig. 2. *The eastern profile of the first trench.*
Jn 2. *Esimese kaevandi idaprofiil.*
Photo / Foto: Sander Jegorov

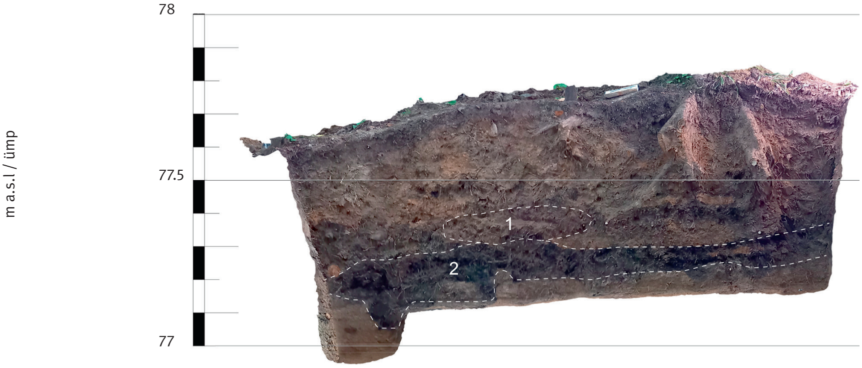

Fig. 3. *The eastern profile of the second trench. 1 – Roasted ore horizon, 2 – sooty horizon with traces of intense burning.*
Jn 3. *Teise kaevandi idaprofiil. 1 – Röstitud maagi horisont, 2 – söene intensiivse põlemise jälgedega horisont.*
Photo / Foto: Sander Jegorov, editing / töötlus: Ragnar Saage, Sander Jegorov

Finds

The majority of the finds consisted of different types of slag and furnace lining. During excavation a lot of unprocessed bloomery iron and a few pieces of pottery were also found from the site. Pottery was hand-made and aligns well with the Viking Age radiocarbon dates.

Slag was by far the most numerous find from the II iron smelting site. Most of the slag was not collected, but it probably amounted up to a several hundred kg-s. There seemed to be at least three types of slags – tap, furnace and clay-rich slag. Considering the differences in appearance, a metallographic study could give more insight into the matter. The amount of slag found from the trenches gives an indication of the scale of iron production at the Rihula II smelting site. Slag was weighed from the three topmost layers of both trenches and the average amount was 41 kg per cubic metre of soil. The deeper layers had a higher concentration of slag averaging at 104 kg/m^3. As we are not certain, what the slag concentration for the unexcavated part of the whole refuse heap is, it is safer to take the lower value of 41 kg/m^3 for our calculations. The refuse heap itself was approximately 250 m^3 cubic meters, which means it contains at least 10000 kg of slag. The ratio of smelting slag to iron depends on the iron ore used in the process, but recent experiments have yielded a compact 5.24 kg iron bloom and 35 kg of slag, which is a 1:7 ratio. If we use the same iron to slag ratio, it may be concluded that at least 1400 kg of iron was produced on the II smelting site.

Furnace lining was one of the more common finds from both trenches. It usually appeared as small fragmentary pieces but larger chunks were also common. The minimum size was about 1 × 1 cm and the maximum up to 16.5 × 7 cm (Fig. 4). According to the most complete lining piece the furnaces might have been about 6.5–7 cm thick. The inner side was covered by a layer of magnetic iron pieces, which had been reduced from the ore and had stuck to the furnace. Beneath the magnetic layer there was clay, which had been heavily fired and turned into purple glassy slag-like material. The outer side was bright red which means the temperature had been much lower than on the inner side, probably around 1000–1100°C. Some pieces of furnace lining were not fired as heavily, since clay seemed like it had been fired at around 600–800°C.

Fig. 4. *A wall fragment of the iron smelting furnace: left – cross section, right – inner surface with metallic iron particles.*
Jn 4. *Rauasulatusahju seina fragment: vasakul läbilõige, paremal ahju sisepind metallilise raua osakestega.*
Photo and editing / Foto ja töötlus: Ragnar Saage

Bloomery iron was present among the bulk finds. The pieces were not larger than 7 × 6 cm on average. At first glance the blooms were rich in slag which was visible on the outer surface. The iron did not seem to have been forged. Instead, some pieces were potentially disregarded and later on thrown to the slag piles. The chemical composition of bloomery iron was investigated metallographically (see below).

Pottery was prevalent among the finds from the iron smelting site (Fig. 5). In total 15 sherds of hand-made pottery were found. About six pieces seemed to belong to the same vessel, considering the surface finish and burning temperature. No rim pieces were found so there were limited possibilities for dating the vessels. A base and two shoulder pieces were also identified. Exterior and interior surfaces of the vessels were slightly smoothed. Just one small piece was polished. No ornamentation was found on any of the pieces. Macroscopic investigation of the clay matrix revealed that rock debris was used as a temper which is standard for the local hand-made pottery for the Late Iron Age (Tvauri 2005, 26). A well burnt clay plaster was identified among the finds which may originate from a building.

Fig. 5. *Hand-made pottery from the Rihula II iron smelting site.*
Jn 5. *Käsitsikeraamika Rihula II rauasulatuskohalt.*
Photo / Foto: Ragnar Saage, editing / töötlus: Sander Jegorov

METALLOGRAPHIC ANALYSIS

In order to determine the physical and chemical properties of the iron and the slag recovered from the site three iron pieces (no. 37, L4 and L17) and three tap slag pieces (no. 37, P9 and P23) were chosen for metallographic analysis (Fig. 6).[1]

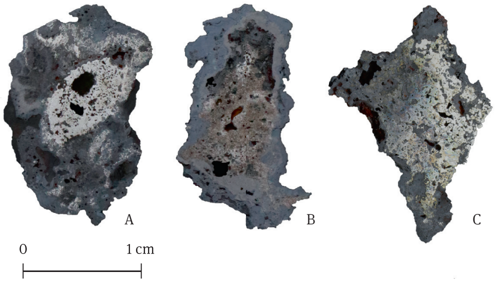

Fig. 6. *Cross-sections of different slag and bloomery iron samples taken from each trench. A – L4, B – L17, C – L37.*
Jn 6. *Ristlõiked mõlema kaevandi šlaki ja toorraua proovidest. A – L4, B – L17, C – L37.*
Photo / Foto: Kristo Oks

The cross-section of the bloomery iron no. 37 was porous and corroded but lacked slag inclusions. Etching with nital revealed different microstructures which indicate different chemical properties of iron. Carbon content (hereafter C content) was best revealed as hypoeutectoid structures where the C content was lower than 0.8%. Areas with large ferrite grains where pearlite in the grain-boundaries was hardly visible indicated a high phosphorus content (hereafter P content) of iron. This was further examined by etching the sample with Klemm's II reagent and measuring the microhardnesses[2] to calculate the P content by using an equation $P = (-0.919 + (0.0083\ HV)) \pm 0.13$, developed by Thiele & Hošek (2015, 122). Hardness measured from the large ferrite grains reached from 229 up to 306 HV which sets the P content of iron from about 0.85 to 1.75 wt%. The phosphorus content of iron is worth noting already from 0.1 wt% (*ibid.*, 114). Phosphorus increases the hardness of iron but reduces its toughness and ductility, making the iron brittle (*ibid.*, 114–115), thereby making it difficult to forge.

Sample no. L4 revealed a harder (HV0.5: 125–208) ferritic-pearlitic structure in the middle of the cross-section and was partly surrounded by soft iron (HV0.5: 94–96). The sample itself was porous and heavily corroded (Fig. 7). Sample no. L17 was steely and revealed a porous and corroded cross-section poor in slag. The high C content was indicated by eutectoid and hypereutectoid microstructures with C content higher than 0.8%. In the pearlitic matrix cementite needles were formed which were preserved even in the corrosion. Interestingly the C content was higher around the biggest pores in the cross-section indicated by cementite

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[1] The samples were cut with a precision saw, mounted in phenolic thermoset resin, grinded with diamond suspensions (45, 9, 3 and 1 μm), polished with aluminium oxide and colloidal silica paste. Iron samples were etched in a 3% nital solution for 6 seconds. All samples were examined with an optical metallographic microscope.

[2] The microhardness was measured with Wilson Tucon microhardness measurer under pressure of 500g (HV0.5).

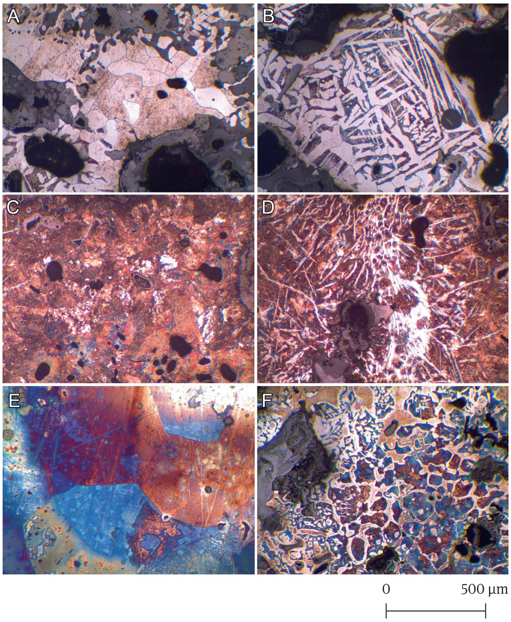

Fig. 7. *Microstructures of slag and bloomery iron. A – L4: iron, slag and corrosion, B – L4: widmanstätten ferrite and pearlite, C – L17: eutectic steel, D – L17: hypereutectic steel with cementite needles, E – 37: phosporous iron, F – 37: steel and phosporous iron.*
Jn 7. *Šlaki ja toorraua mikrostruktuurid. A – L4: raud, šlakk ja rooste, B – L4: widmanstätteni ferriit ja perliit, C – L17: eutektoidne teras, D – L17: hüpereutektoidne teras tsementiidi nõeladega, E – 37: fosforirikas raud, F – 37: teras ja fosforirikas raud.*
Photo / Foto: Kristo Oks

needles. The microhardnesses measured from the hypereutectoid area varied from 259 to 316 HV. The microhardness of steel was measured from both eutectoid (HV0.5: 206–304) and hypereutectoid steel (HV0.5: 259–351).

All chosen slag pieces were tap slag that was removed from the furnace either during the smelting process or after it. The slag piece no. P9 was porous and contained large clusters of glass. Wuestite was mostly dendritic, and often partially covered the glass assemblages. Granular wuestite was also present. In the background fayalite was often irregularly shaped and contained very little glass between the fayalite laths which was visible in the inner part of the cross-section. Alternation of fayalite laths and glass was better visible on the edges of the cross-section where fayalite laths radiate away from the cooling soil below (see Buchwald 2008, 32). The slag also included a few small iron particles. The cross-section of slag sample no. P23 revealed a porous and very distinctive microstructure. Inside the fayalite matrix with multi-directional fayalite laths the wuestite was mainly dendritic and very small. Interestingly the wuestite had formed large granular concretions diffusely over the entire cross-section. More informative is the chemical composition of the slag. The slag sample no. 37 was analyzed with SEM-EDS to determine its bulk chemical composition. The P content varied from 0.25 to 1.04% which aligns with the high P content in iron. The manganese (Mn) content varied from 1.73 to 2.67% which is a positive indicator, for manganese causes the slag turn more fluid thus making it easier to purify the iron bloom from slag.

A radiocarbon analysis was performed on 2 charcoal samples – P4[3] and P11[4] (Fig. 8). The first was collected near the bottom sand layer from the first trench and the second from the

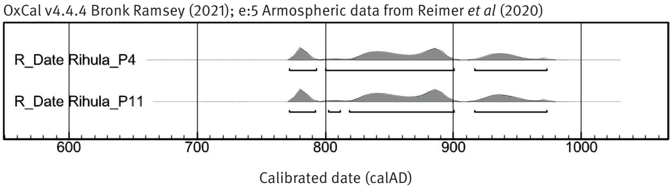

Fig. 8. *¹⁴C results from charcoal found in the I and the II trench just above the natural soil.*
Jn 8. *¹⁴C analüüsi tulemused söest, mis leiti I ja II kaevandist loodusliku pinna pealt.*

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[3] UBA-50398; 1167±23 BP; 774-791, 801-811, 819-899, 918-961, 966-973 calAD; Reimer *et al.* 2020.
[4] UBA-50399; 1166±23BP; 774-790, 802-811, 819-900, 917-974 calAD; Reimer *et al.* 2020.

sooty layer under the roasted ore. The dates are extremely close which might hint to very intense production of iron during a very short time.

DISCUSSION

The information gathered from the excavations has offered a lot of thought for discussion. No furnace bases were found but the abundance of furnace lining confirms that they must have existed. For the discovery of furnaces, additional test pits have to be dug in the area. Most likely an ore roasting place or charring pit was found which was confirmed by an intense red layer of small ore pieces and an intense sooty layer below it. That could indicate just an ore roasting pit or an ore roasting and a charring pit separately. Considering the sheer amount of slag that was collected, the II smelting site most likely was definitely very productive. Although approximate calculations can be made about the quantity of iron produced, they most likely cannot be very accurate due to different unknown factors. The production may have been several tonnes of iron, as concluded from the size of the slag heaps.

The finds give some information about the potential date of the iron smelting site, which is likely not much further that later Iron Age. One piece of pottery had a polished surface which could be indicative of the fine-grained pottery of the Viking Age, especially for example Iru-type (Tvauri 2012, 71), but not too many conclusions could be drawn from that.

The ^{14}C analysis revealed that the Rihula II smelting site can definitely be dated to the late pre-Viking Age and Viking Age, precisely 774–973 calAD. That confirms expectations from the lack of tuyeres and the smoothed pottery which hinted at the fact that the Rihula II site at least is from the Viking Age. However, that cannot be interpolated to other sites.

Metallographic analysis revealed the composition of the slag and bloomery iron. Firstly, the slag, in which the microstructure was standard, contained iron minerals almost always present in the slag. The chemical composition provided more insight, confirming a high P and Mn content. The Mn content has been important in some iron production sites (Hjärthner-Holdar *et al.* 2018, 19). Secondly, the bloomery iron seemed to be of high quality since there was not much slag inclusion in the iron. The carbon content was higher than 0.8%, which is good for using as cutting edges as it can be heat treated. The phosphorus content was low in slag and iron, but it might have been sufficient to make the iron rather brittle. That might have not made it suitable for producing every type of artefacts, but only for specialized types of forged objects. However, it may have also been the reason why they were discarded.

CONCLUSION

The excavations at Rihula II smelting site dated the complex to the Viking Age, which is confirmed by the absence of tuyeres and the radiocarbon dating. The site yielded many finds familiar to similarly dated smelting sites, especially Saunakünka, which is one of the few iron smelting sites in Estonia, dated to the Viking Age. The excavations confirmed previous opinions, like tuyeres belonging to the 12th and 14th centuries, but also brought some new information along with it to the discussion pool since there are not many Viking Age iron smelting sites found in Estonia.

ACKNOWLEDGEMENTS

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RIHULA RAUASULATUSKOMPLEKS

Sander Jegorov, Kristo Oks, Kaarel Sikk ja Ragnar Saage

2016. aastal avastas Kaarel Sikk Lääne-Virumaalt, Sirtsi soost läänes paiknevatel pinnavormidel 3 uut rauasulatuskohta, mis said nimeks Rihula I, II ja III (jn 1). Rauasulatuskohad paiknesid soost kõrgemal asuvatel mineraalmaaküngastel; näha on tugevat seost kõrguste vahemikuga u 76,5–78,5 m ü.m.p.

2022. aasta juulis toimusid arheoloogilised väljakaevamised Rihula II rauasulatuskohal, mis valiti sealse šlakikontsentratsiooni intensiivsuse tõttu. Rajati kaks kaevandit, millest ühega üritati kohalikust maastikust paremini aru saada ja teisega leida Kaarel Siku avastatud hüpoteetilise rauasulatusahju põhi. I kaevand peegeldas rauasulatuskoha jääke, millest oli moodustunud 30 cm kiht (jn 2), mis sisaldas palju räbu, toorraua- ja ahjude tükke. II kaevandist (jn 3) avastati punane maagikiht, mis osutab maagi röstimisele. Selle all lasus 13 cm paksune söekiht, mis võib olla seotud varasema söe miilamisega. Mõlema kaevandi põhjast võetud radiosüsinikdateeringud osutasid viikingiajale (jn 8). Kuna eri kaevandite dateeringud olid väga sarnased, võisid rauasulatusega seonduvad tegevused toimuda lühikese ajavahemiku jooksul.

Leiud peegeldasid rauasulatust, mille mahud olid arvatavasti suured. Šlakikuhjad sisaldasid suurtes kogustes šlakki, toorrauda ja rauasulatusahjude tükke (jn 4), mis näitab, et rauda on Rihula II alal sulatatud mitmel korral. Suured toorrauakogused kinnitavad, et vähemkvaliteetsed tükid heideti kõrvale ja eelistati puhtamat toodangut. Vähesel määral leiti ka keraamikat (jn 5), millest suurem osa olid silutud pindadega ja üks katke oli kiilapinnaline.

Metallograafilise analüüsi raames tehti kahest šlakitükist ja kahest toorrauakamakast mikrolihvid (jn 6). Toorraua mikrostruktuur peitis endas hüpoeutektoidseid struktuure ja perliidi maatriksis tsementiidinõelasid. Šlakis tuvastati tüüpilised mineraalid nagu vüstiit ja fajalliit. Keemiliselt koostiselt olid proovid üsna sarnased, sisaldades palju fosforit ja mangaani. Seetõttu võis raud kohati olla suhteliselt rabe, sobides vaid valitud esemete sepistamiseks. Kõrge mangaanisisaldus aga muudab šlaki eemaldamise raualt hõlpsamaks, mistõttu oli toodetud raud suhteliselt puhas.

Võib öelda, et Rihula II tootmiskohal toimus viikingiajal suuremahuline rauasulatus, mis katkes hilisrauaajal. Kindlamate järelduste tegemine kogu rauasulatuskompleksi kohta nõuaks järgnevaid uuringuid, et selgitada, kas ka teised Rihula rauasulatuskohad kuuluvad viikingiaega või pärinevad teisest ajast.