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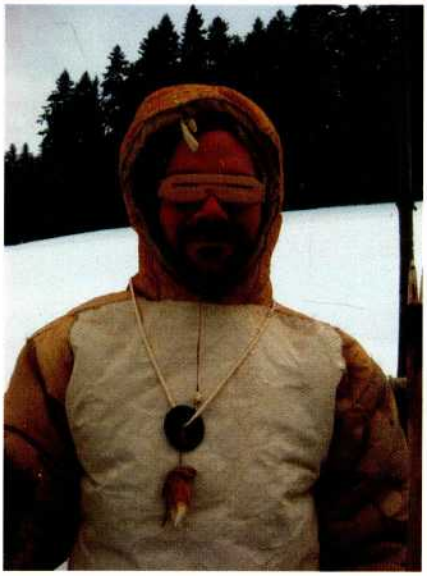

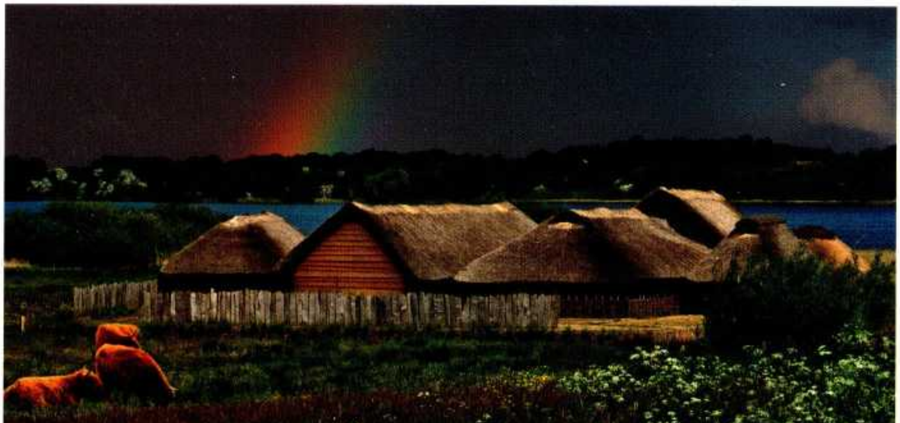

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Reconstructing Bronze Age Copper Smelting in the Alps: an ongoing process

Erica Hanning

Zusammenfassung – *Anhand von archäologischen Befunden, ethnographischen Beispielen und bisherigen theoretischen und experimentellen Untersuchungen wurde eine Reihe von experimentalarchäologischen Versuchen in drei nachgebauten Öfen zur Rekonstruktion ostalpiner bronzezeitlicher Kupfererzverhüttung durchgeführt. Das Ziel dieser Experimentreihe ist nicht nur die erfolgreiche Verhüttung von sulfidischem Kupfererz, sondern auch verschiedene Rekonstruktionsmöglichkeiten des bronzezeitlichen Befundes zu erarbeiten.*

Introduction

During the Bronze Age, both chalcopyrite as well as fahl ore mining districts and copper production centers were spread throughout the eastern Alpine region. Especially during the Middle to Late Bronze Age, the layout and construction of the smelting sites, as well as the external appearance of the slag show a surprising level of conformity, pointing to certain amount of standardization of the sulfide copper smelting process across the eastern Alpine region.

Although there is variation of the archaeological material from site to site, a "typical" middle to late Bronze Age eastern Alpine smelting site is usually located near a source of water and is comprised of three general elements: roasting beds, furnaces and slag heaps. The roasting beds (*Fig. 1a*) were carefully leveled with a clay coated floor and often delimited by stones. The furnaces (*Fig. 1b*) were usually located below the roasting beds, often in pairs, or sometimes as batteries of several furnaces in a row (ex. Acqua Fredda, Trentino: CIERNY 2008). They were typically dug into the slope, with stone-and-clay walls on at least three sides, between 35 and 65 cm in width and a preserved height of up to ca. 90 cm (ex. GOLDENBERG 2004 170-173; ZSCHOCKE, PREUSCHEN 1932, 73-95; NOTHDURFTER, HAUSER 1988, 179). A low clay threshold is usually all that has been preserved of the front wall, which was presumably destroyed in order to extract the smelting products. Remains of clay tuyeres (ex. EIBNER 1993, 34; TÖCHTERLE, SCHNEIDER, in press; CIERNY 2008, 230) point to the use of forced draft, most likely in the form of a simple animal skin bellows.

Slag heaps were situated below the furnaces, whose slag can be roughly divided into three types: slag cakes (Schlackenkuchen), platy slag (Plat-

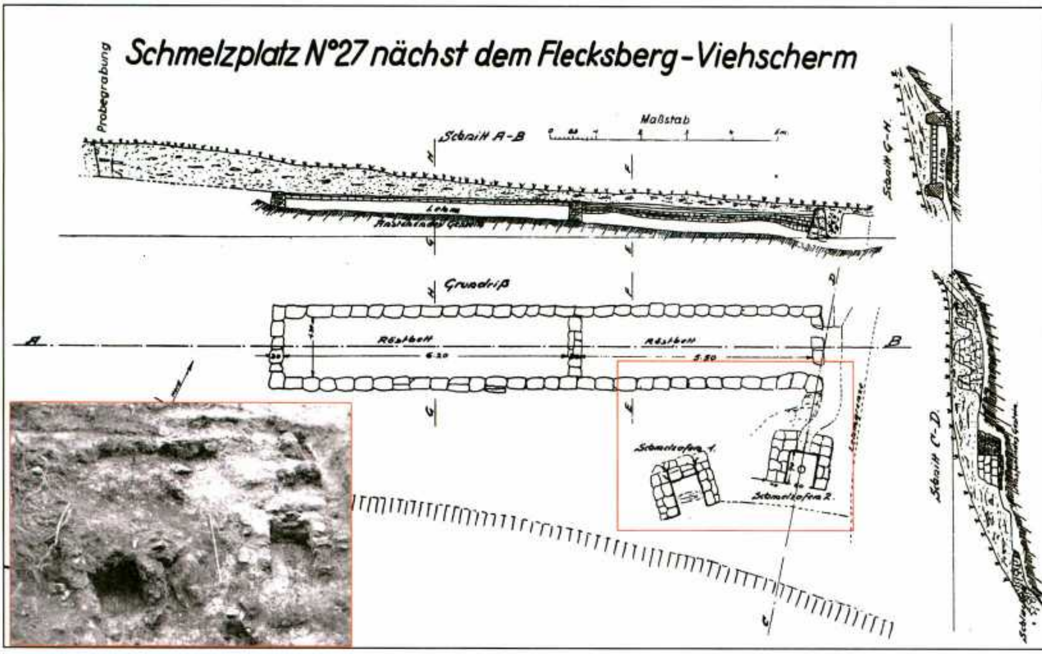

Fig. 1: Plan and photo of smelting site "27", Mitterberg, Mühlbach am Hochkönig, Austria. A: Roasting Beds. B: Furnaces.

tenschlacken), and crushed slag (Schlackensand). While the first two types of slag originate from the actual smelting process, the crushed slag is produced during the mechanical treatment of the slag in order to recuperate entrapped metal and matte (GOLDENBERG 2004, 174). Analyses of the slag make it quite clear that copper sulfides were being smelted and temperatures between 1100 and 1400°C were reached in the furnaces (METTEN 2003, 5; MOESTA, SCHNAU 1982, 542; VIERTLER 2011, 81-83). Additionally, the presence of both roasting beds and furnaces points to the use of an at least two-step smelting process involving a period of oxidation in an open fire (roasting) combined with smelting at higher temperatures in low furnaces.

Due to contrasting interpretations of the archaeological remains and scientific investigations of the slag, several different theoretical reconstructions have been put forward over the years. Several reconstructions are based on an operational sequence similar to those described by Agricola as the "Old German Process" (AGRICOLA 1556, Books 8-9; CZEDIK-EYSENBERG 1958; EIBNER 1982), while others have put forward another smelting operation based on the traditional Japanese Mabuki process (LEWIN, HAUPTMANN 1984; MOESTA, SCHNAU 1982; MOESTA, SCHNAU 1983; MOESTA, SCHLICK 1989). Another option could be similar to a copper smelting process practiced in Nepal, which was described by Blanford in the second half of the 19th century (in PERCY 1861, 388-391) and was carried out in an almost identical fashion up until quite recently (ANFINSET 2011, 42-61). One problem, however, is that the historical furnaces vary sometimes greatly from the Bronze Age

Fig. 2: Reconstruction of clay tuyere attached to a goat skin "bag" bellow.

archaeological remains, and thus the technology cannot be directly transferred to the prehistoric metallurgical process.

Experimental reconstructions

Several experimental reconstructions of the Bronze Age Alpine smelting technology have also been done over the years, and are too many to be gone into detail here. Again these practical experiments have also led to different and sometimes contrasting results (ex. Böhne 1968; Gelhoit 2003; Herdits 1997; Happ 2001; Modl 2011). This is in part due to varying reconstructions of the metallurgical installations and operational sequence, which were not preserved in the archaeological record. Moreover, the success or failure of a smelt can be the result of several interdependent variables including the composition of the furnace charge (ore, flux, fuel), temperature and the oxidation-reduction environment in the furnace; many of these variables are very hard or impossible to keep constant in non-laboratory conditions, especially in an outdoor furnace driven by hand-operated bellows.

In light of the archaeological evidence, ethnographic examples, as well as previous theoretical and practical reconstructions of the Alpine smelting process, a new series of experimental reconstructions are being carried out as part of the author's PhD thesis. The goal of these experiments was not only the successful smelting of copper sulfide ore, but were also designed to test the viability of previous theories, as well as different variants of reconstructed variables that were not preserved in the archaeological record – such as the construction of the furnace frontal wall, position and number of tuyeres, ore:flux:fuel ratios – as well as the general operational sequence.

Over the course of two years, a series of smelting experiments were carried out in three reconstructed furnaces. The inner dimensions of the furnaces were calculated by taking an average of known archaeological examples. These remained roughly the same for all three furnaces with slight variations due to the use of natural stone for the walls: the width was fixed at ca. 45 cm, the full length of the side walls was ca. 60 cm which left an inner dimension of 45x45 cm when the front wall was in place. The front wall only abutted the side walls, allowing to it be easily torn down and rebuilt after each smelt, and an opening was left in the lower part of the front wall in which to insert the tuyeres. The height was set at 100 cm, though this remains theoretical since no prehistoric furnace has been preserved to its full height. In all three furnaces, the inner surface of the furnace walls were lined with clay and the bottom of the furnace was formed into a slight bowl-shaped depression, with the lowest point ranging from 10-15 cm below the level of the tuyeres, depending on the experiment. The tuyeres were reconstructed from archaeological finds (see above) and attached to simple goat

Fig. 3: First furnace, built near the mine "Arthurstöllen", Mitterberg Mining District, St. Johann in Pongau, Austria. Preheating the furnace with wood, without the use of bellows.

Fig. 4: Second furnace, with two bellows attached, built on the banks of stream near the "Hochkeilhaus", Mitterberg, Mühlbach am Hochkönig, Austria.

skin bag bellows, reconstructed from ethnographic examples (*Fig. 2*).

The first two furnaces were constructed in the Bronze Age mining district of Mitterberg (*Fig. 3, 4*), from stone and clay that would have also been available to the prehistoric smelters. In order to continue

Fig. 5: Third furnace, built on the ground of the LWL-Industrie Museum Henrichshütte, Hattingen, Germany. Here two sets of tuyeres were used: one was attached to the bellows and was loosely set into a second tuyere that was entered into the furnace. This was done to keep the backdraft from the furnace from burning the inside of the bellows. The small clay pipe in the middle was used to measure the temperature. The area above the tuyeres was kept closed with clay and stone during the smelt.

the work, a third furnace (*Fig. 5*) was constructed on the grounds of a former iron foundry near Bochum, at the LWL-Industriemuseum Henrichshütte, Hattingen, Germany. Due to the flatness of the experimental area in Hattingen, roughly 6 m³ of earth was then piled underneath and on three sides of the furnace to simulate the hill, which in turn stabilized and insulated the furnace walls. Although not as "authentic" as the first two furnaces, the third location had several advantages: the experiments were closer to the workplace of the author and could be spaced out over the course of the whole summer and not just during a relatively short window during the campaigns at Mitterberg; the smelting remains could be taken directly to the laboratory for analysis; there was a larger pool of volunteers from the university and museum who took part on these very time intensive and physically demanding experiments.

Ore

Due to the relatively small amount of copper sulfide ore available from Alpine deposits, which is usually in the form of low grade ore gleaned from old mining dumps, a mineralogically comparable copper ore from Mexico was used for the experiments, which consisted mainly of Chalcopyrite with smaller amounts of Pyrite (FeS_2), Sphalerite (ZnS) Galena (PbS) and Bournonite ($CuPbSbS_3$). In addition, the pieces of ore contained moderate amounts of gangue and host rock, in the form of Quartz (SiO_2) and Calcite ($CaCO_3$).

Roasting of the ore

For most of the experiments, the ore was first preroasted. It was first broken into 3-5 cm pieces, layered with brush and wood and roasted in an open clay lined roasting bed. Wood was piled on at need. The wood burned down after 4-6 hours with temperatures ranging between 500-900° C. At the end of the roast, the ore showed varying degrees of oxidation (reddend outer surfaces, from the formation of iron oxides, etc.), although many pieces still retained some of the gold color in their core, pointing to an only partial oxidation of the ore. All attempts to completely desulfurize (dead roast) the ore failed, most likely owing to the relatively short period of roasting and relatively large diameter of the pieces of ore.

1st series

The first series of 5 smelting and 2 roasting experiments (Hanning, Pils 2011; Hanning, in press) were carried out in June 2010, using charcoal as the main fuel. The furnace (*Fig. 3*) was preheated with wood, without the use of the bellows. The bellows was then placed in the lower opening and the rest of the opening filled with a damp earth and stone. Charcoal was added and the bellows continually worked for the rest of the smelt. The roasted ore was crushed to a size of no more than 2 centimeters and was charged in small portions into the top of the furnace and covered by a fresh layer of charcoal. The process was repeated until the complete charge, ranging from 4 to 6 kilos was put into the furnace. A single smelt lasted between ca. 7,5 and 8,5 hours and consumed between 24-33 kg of charcoal, plus an additional 15-25 kg of wood to preheat the furnace.

The first series (Hanning, Pils 2011; Hanning, in press) led to mixed results: the back and corners of the furnace tended to stay relatively cool, while the charcoal layer nearest the tuyeres at the front of the furnace burned away rapidly giving temperatures of up to 1450° C. As a result, the ore in the rear of the furnace remained unreacted, while the ore in front of the tuyeres tended to form a mass of matte (an intermediary product composed of copper iron sulfides, i.e. Kupferstein) and slag which blocked the tuyere tip and led to a premature end of the smelt and an imperfect separation of the slag and matte. Placing the tuyeres farther into the furnace in order to increase the heat at the back only led to a quicker slagging and blockage of the openings. Part of the matte did separate from the slag, however, and copper hairs and cones could be seen growing in the cracks and pores of the matte. Preliminary chemical analysis show a large amount of iron in the matte, pointing to an insufficient oxidation and slagging of the iron. A longer roasting period, as well as additional quartz could lead to a better slagging of the iron content.

2nd series

The second furnace reconstruction (*Fig. 4*) and series of 6 smelting and 2 roasting experiments were carried during September and October 2010 (HANNING, in press). The main difference in this series was the choice of fuel: only wood was used throughout the smelting process instead of switching to charcoal after preheating the furnace. The fuel consisted mainly of softwoods such as larch and fir: such species were also predominantly found in the botanical remains of the prehistoric furnaces (NELLE, KLEMM 2010; SCHWARZ, OEGGL 2011). The ore was mixed with slag from previous experiments, with the addition of ground quartz to facilitate the slagging of the iron. The furnace was preheated without the use of a forced draft for about 2 hours, until a bed of coals ca. 30 cm thick had built up in the bottom of the furnace. The bellows were put in place and the lower furnace opening closed around the tuyeres with clay and stone. Alternating layers of ore and wood were charged into the furnace, being careful to always lay enough wood into the furnace to keep a 30-40 cm thick layer of glowing coals at the bottom of the furnace. The bellows were then worked for 6 to 8 hours, using between 106 and 178 kilos of fresh wood (*Tab. 1*). With the use of two hand operated bellows, temperatures above 1300° C were reached. The charge was able to smelt evenly, settle to the bottom of the furnace and separate into layers of slag and matte. The tuyeres were also less prone to clogging and could be reused for several smelts. Additionally the furnace walls became slagged, with partial vitrification of the clay lining, which also reflects the archaeological remains. Metallic copper could be seen on the surface of the matte in the form of small hairs or cones, as well as small prills embedded in the slag.
A roasting and second smelting of the matte led again to another layer of sulfide underneath a mass of slag on the bottom of the furnace. Although the product from the second smelting was more enriched in copper and depleted in iron and sulfur, most of the copper remained in sulfide form and there was a larger amount of metal and sulfides prills entrapped in the slag. Possible reasons for this could be an insufficient desulfurization from too short of a roasting period and the addition of too much quartz, leading to a highly viscous slag. Moreover, a greater amount of small slag pieces with sulfide inclusions were found dispersed in the ash and coals of the furnace; most likely the amount of material to be smelted was too small for the volume of the furnace, spreading out the charge over too large of an area and inhibiting the formation of a well-consolidated mass at the bottom.

3rd series

In order to build on the experience gained from the first two series, a third furnace

	Exp.	Duration (Hours)	Charcoal Kg (Wood Equilvalent)	Wood Kg	Wood Total
1st series	2	7:30	24.4 (122)	10.0	(132.0)
	3	9:00	26.2 (131)	25.5	(156.5)
	4	8:30	35.3 (176,5)	18.5	(195.0)
	5	7:30	33.9 (169,5)	8.9	(178.4)
2nd series	1	9:00	0	163.7	163.7
	2	6:00	0	129.1	129.1
	3	5:40	0	106.2	106.2
	4	7:45	0	177.7	177.7
	5	6:00	0	133.0	133.0
	6	6:30	0	147.8	147.8
3rd series	1	6:10	0	198.0	198.0
	2	5:30	0	210.2	210.2
	3	6:40	0	211.3	211.3
	4	6:40	0	292.3	292.3
	5	8:10	0	306.2	306.2
	6	5:10	0	219.6	219.6

Tab. 1: Duration and fuel use of the smelting experiments. The theoretical weight of the charcoal as wood is given in parentheses (), using a charcoal yield of 20% by weight.

Fig. 6: Consolidated mass of slag and matte at the bottom of the furnace.

was built (*Fig. 5*) and series of 6 smelting and 4 roasting experiments were carried during spring, summer and fall of 2011. The results of the third series are very promising: on average, 8 kg of preroasted ore were mixed with 4 kg of slag and 2 kg of ground quartz. Coniferous wood was again used as the fuel and two bellows with two tuyeres provided the blast. After two hours of preheating, the bellows were set into action and the furnace was kept constantly filled ¾ full of wood. The layers of wood were packed more closely together in an effort to retain more of the heat around the hottest zone near the tuyere openings and to create a more reducing environment. This did lead,

Fig. 7: Section through the mass of slag, where the matte can be seen at its bottom (outlined in green). The upper part of the slag is characterized by being very porous with inclusions of charcoal, and pieces of quartz, which is also typical of the prehistoric slag cakes.

however, to a much higher amount of wood being used, ranging from 198-306 kg of wood for a 6-8 hour smelt (*Tab. 1*). In one experiment, the furnace was also packed too tightly, which blocked the furnace and detrimentally affected the smelt.

The result of the successful smelts was a consolidated mass of slag with a thick and well-separated layer of matte at the bottom (*Fig. 6, 7*), very little matte was distributed in the slag. Again metallic copper was present on the surface of the matte in the form of copper cones and hairs. It was possible to successfully replicate the process 4 times, which led to the collection of roughly 14 kg of concentrated matte from the smelting of 32 kg of ore. A second roasting and smelting of the matte with the addition of 2 kg of quartz and 2 kg of slag again led to a more concentrated copper sulfide, which this time settled to the bottom of the furnace in a distinct, well-consolidated layer, on the underside of the slag. Due to the onset of winter, further refining of the matte was not possible, but further experiments are planned for 2012.

Wood vs. Charcoal

Although the temperatures were lower when using wood (≤1350°C instead of ≤1450°C when using charcoal), they still proved sufficient to smelt the copper ore. Un-charred wood was also easily stackable in the rectangular shape of the furnace, and the channels created between the individual pieces of firewood facilitated the flow of air from the tuyeres to the back of the chamber, providing a more even heat throughout the furnace. It must be noted that an optimal diameter for the woods pieces proved to be ca. 10 cm – too large of pieces tended not to burn quickly enough and blocked the furnace, leading to a drop in temperature.

When using wood, the fuel consumption seems to be much higher than when running the furnace with charcoal.

However, when the amount of charcoal used in the experiments is converted back to the weight of the original wood (the weight of the charcoal will theoretically be about 20% of the weight of the original wood, depending on the wood type, moisture content and charring process; PERCY 1861, 129-133), then the first experiments burned a very comparable amount of fuel (*Tab. 1*). The higher amount of fuel used in the third set of experiments was partly due to overcharging the furnace with wood, which did not always lead to a better smelt or hotter conditions within the furnace.

Wood, instead of charcoal, has been documented for traditional iron smelting in Norway (NØRBACH 1997, 59), and has even been used in early modern copper smelting operations (PETERS 1911, 379-405). Uncharred wood was also successfully used in copper smelting experiments carried out in a furnace reconstructed from finds from Agia Varvara – Almyras on Cypress (FASNACHT 2010, 124), as well as experimental iron smelting reconstructions (Nørbach 1997). The use of wood for both roasting and smelting would eliminate the need for such massive charcoal production, effectively cutting out a time and labor-intensive step from the metallurgical operational sequence; the only prerequisite is an abundant supply of wood. This could explain the lack of Bronze Age charcoal production sites in the alpine region; recent dating of large charcoal kilns located on or near prehistoric smelting sites have turned out to be a reuse of the podiums for Medieval or more recent charcoal production sites (KLEMM 2003, 18, 36-39, 191; KLEMM ET Al 2005). This is difficult to definitively prove, however, since simple low-volume charcoal production pits, such as those used by the Nepalese smelters (ANFINSET 2011, 43-44) leave little trace in the landscape and would be difficult to differentiate from pits used for cooking or other fire-based activities.

The question remains, however, where is the copper?

The reconstructed Alpine furnaces turned out to be quite efficient in concentrating the ore into a copper-iron sulfide matte, with the creation of a mass of slag closely resembling prehistoric slag cakes (Schlackenkuchen). The matte could be easily separated from the bottom of the slag cake, while entrapped copper prills and sulfide droplets could be extracted from the slag by crushing it with stone hammers, creating crushed slag, which is also common in the archaeological finds. The furnaces, however, were not as efficient in converting the matte into copper metal, even when large amount of re-roasted matte from several smelts were charged into the furnace at once. The failure to obtain large amounts of metal could simply be a matter of not enough repetition – that the roast-reduction sequence must be repeated more times before copper is obtained. Another option is that the matte was transformed into copper metal in a separate pit furnace or hearth with air blown from above, with or without the use of a crucible: this option has also been used by most other experimental archaeologists working with these Alpine furnaces (BÖHNE 1968; GELHOIT 2003; HERDITS 1997; MODL 2011). A third option would be the reuse of the furnace as a refining hearth by leaving the front wall open, or closing it only with a low sill create a small pit-like hearth. A similar setup was used by Modl (2011, 149) to melt and cast a plano-convex copper ingot. Since the concentrated matte has a much smaller volume as the original ore, there is also not the need of a high front wall to contain a large amount of material and fuel. The more open form of a pit-like hearth would also facilitate the desulfurization of the matte. At the moment, this last reconstruction is only a theory, which still needs to be tested.

The experiment series has also shown how an experimental archaeological reconstruction has evolved over time, and how many small factors play a role in the success or failure of such reconstructions attempts. The results of the current experiments make it clear that not only the choice of ore, flux and fuel play a large part to the success or failure of the smelt, but also the way the ore and fuel is charged, the rhythm of the bellows, and overall experience of the people running the furnace. It must be stressed that particularly for relatively complicated pyrometallurgical processes, a single experiment is not enough, and such experimental archaeological projects must be laid out with sufficient time and repetitions in order to gain experience and to systematically test as many factors as possible.

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Fig. 1: Zschocke, Preuschen 1932, Taf. III, V

Fig. 2: Photo U. Töchterle

Fig. 3-7: E. Hanning

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