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PREHISTORIC COPPER PRODUCTION IN THE INN VALLEY (AUSTRIA), AND THE EARLIEST COPPER IN CENTRAL EUROPE*

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In recent years archaeological finds and scientific analyses have provided increasing evidence for a very early beginning of copper production in the rich mining area of the Tyrolean Alps. The earliest findings derive from an excavation of a multi-phase settlement on the Mariahilfbergl in Brixlegg, which revealed evidence that a small amount of fahlores, probably of local provenance, was at least heated if not even smelted there in the Late Neolithic Münchshöfen culture (the second half of the fifth millennium BC*). However, most copper finds of this horizon consist of low-impurity copper that most probably derives from Majdanpek in Serbia. This long-distance relationship is corroborated by typological features that link some aspects of the Münchshöfen culture with the Carpathian basin. Thus it is not yet clear if, at Brixlegg, actual copper production took place or, rather, an experimental treatment of the local ores. The typical fahlore composition, with arsenic and antimony in the per cent and silver and bismuth in the per mille ranges, appears in quantity only in the Early Bronze Age. Many thousands of Ösenringe are known from many central European Early Bronze Age sites, with a chemical composition typical of fahlores. At Buchberg near Brixlegg, a fortified settlement with slags from fahlore smelting proves that the local ores were indeed exploited. The lead isotope ratios of Ösenringe from the Gammersham hoard in Bavaria, which consist of fahlore copper, confirm this and suggest that copper mining and production in the Inn Valley reached a first climax during that period. In the Late Bronze Age, copper was produced at an almost industrial level.*

KEYWORDS: TYROL, LATE NEOLITHIC, BRONZE AGE, FAHLORES, METAL PRODUCTION, COPPER OBJECTS, ÖSENRINGE, LEAD ISOTOPE ANALYSIS

INTRODUCTION

Thanks to recent research, evidence of metallurgy and the earliest use of metals in central Europe have emerged from considerably earlier periods than was hitherto commonly assumed. Accounts of the first metal objects dating to the late fifth millennium BC, in context of the horizon of the Late Neolithic Münchshöfen group, were published in the 1970s. These included an awl and a spiral ring from Schernau in Lower Franconia and a circular, slightly

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concave copper disc from Hornstaad-Hörnle on the shore of Lake Constance, dendro-dated to 3917 BC. The 'sintered bead' from nearby Gaienhofen probably does not consist of copper metal but of oxidized copper ore, as is suggested by the low copper and high iron contents (Table 1). Of particular interest in the context of metal production is the Mariahilfbergl site at Brixlegg, Tyrol, Austria, where evidence for the smelting of copper ores has become known with a radiocarbon age of 4500–3650 cal. BC (Bartelheim *et al*. 2002). Thus there emerges a horizon of metal usage that precedes the Mondsee, Altheim and Pfyn cultures of the first half of the fourth millennium BC, which have so far been considered as the earliest metal-using eras (Ottaway 1982). Note that this is still earlier than the famous Alpine Iceman, dated to around 3200 BC (Spindler 1994), who carried with him a copper axe. Such axes are well known in reasonable numbers from the north Italian Remedello culture. The axe itself has not been thoroughly investigated by scientific methods, but analyses of the teeth and bones of the mummy indicate that the man spent his entire life in the region (Müller *et al*. 2003), which suggests that the Alpine valleys of central Europe were permanently settled by the end of the fourth millennium BC.

Although the inventory of metal objects of this horizon is still small, they are more or less equally distributed (Fig. 1) and can no longer be ignored or their dates generally called into question. Naturally, the question arises of the provenance of this metal, since in southeastern Europe this is the period of a flourishing copper metallurgy, with copper mining attested to at Rudna Glava in Serbia and at Ai Bunar in Bulgaria. However, copper smelting has never been

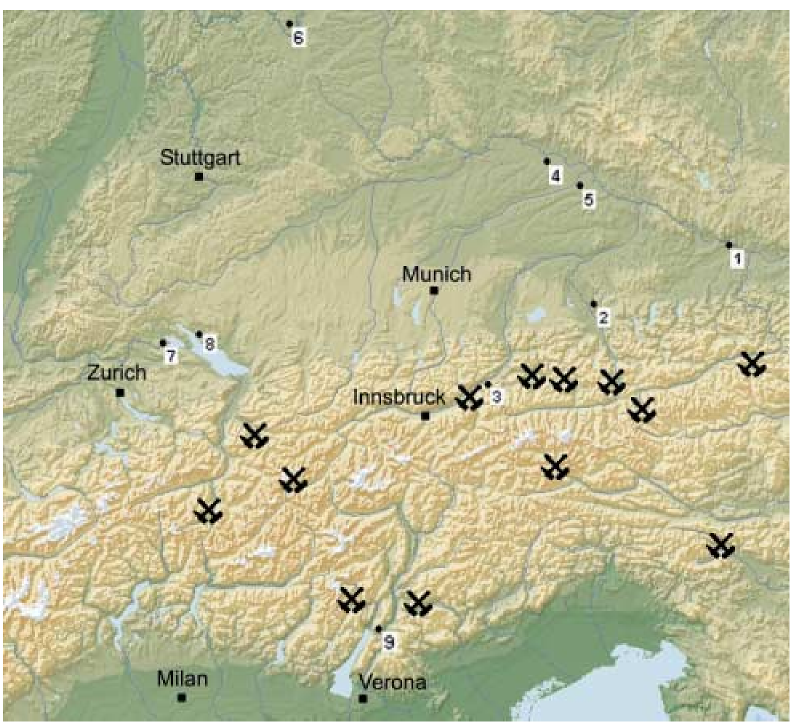

Figure 1 *The distribution of the metal finds of the Münchshöfen cultural horizon in central Europe and major prehistoric mining districts in the eastern Alps. 1, Linz, St Peter; 2, Salzburg, Maxglan; 3, Brixlegg, Mariahilfbergl; 4, Wallerfing, Bachling; 5, Straubing, Wasserwerk; 6, Schernau; 7, Gaienhofen, Hornstaad, Hörnle I; 8, Überlingen; 9, Torretta di Isera.*

Table 1 *Chemical compositions (in wt%) of copper objects from the Münchshöfen cultural horizon and from the Early Bronze Age hoard of Gammersham, Bavaria)*

Lab. no.	*Site*	*Object*	*Museum*	*Cu*	*Sn*	*Pb*	*As*	*Sb*	*Ag*	*Ni*	*Bi*	*Au*	*Zn*	*Co*	*Fe*
Late Neolithic															
BAR 95	Linz, St Peter	Hammer axe	Linz, OÖ LM A 4796	n.a.	n.d	n.a.	0	0	0	0.019	0.0025	0.002	0.031	0.0004	0.58
BAR 96	Linz, St Peter	Hammer axe	Linz, OÖ LM A 4795	n.a.	0	0.023	0	0.002	0.003	0.027	0.0019	0.0004	0.032	0.0006	0
SAM 11192	Linz, St Peter	Hammer axe	Linz, OÖ LM A 4795	n.a.	0	0	0	0	Tr	tr	0	0	0	0	0
SAM 11193	Linz, St Peter	Hammer axe	Linz, OÖ LM A 4795	n.a.	0	0	0	0	Tr	0	0	0	0	0	0
SAM 11194	Linz, St Peter	Flat axe	Linz, OÖ LM A 4796	n.a.	0	0	0	0	Tr	0	0	0	0	0	0
SAM 11195	Linz, St Peter	Flat axe	Linz, OÖ LM A 4796	n.a.	0	0	0	0	tr	0	tr	0	0	0	0
HDM 2784	Brixlegg	Bead		99	0.009	0.079	0.022	0.114	0.004	<0.01	0.007	<0.01	0.049	0.006	0.36
FG 990692	Brixlegg	Metal strip, unpolished		99	<0.005	0.03	0.021	0.107	0.013	<0.01	<0.005	<0.01	n.a.	<0.005	0.51
FG 990692	Brixlegg	Metal strip, polished		99	<0.005	0.01	0.01	0.032	0.008	0.011	<0.005	<0.01	n.a.	<0.005	<0.005
FMZM 405	Straubing	Ring	Straubing, without inv. no.	92	0.014	0.05	0.013	0.185	0.166	0.025	0.257	<0.01	0.10	<0.006	7
FMZM 387	Wallerfing	Awl	München 1967, 5077 a	100	<0.002	<0.01	0.0001	<0.00023	0.0027	0.0029	<0.005	0.0042	0.00043	<0.00012	<0.007
O. Werner	Schernau	Awl		n.a.	Tr	n.d.	0.03	0.04	0.03	0.01	0.008	0.0007	n.d.	n.a.	0.35
HDM 446	Hornstaad	Disc with three humps	PBO HO 85	97	<0.02	n.a.	0.043	0.039	1.22	<0.012	n.a.	0.00081	<0.009	<0.0001	<0.2
HDM 481	Gaienhofen	Bead, sintered	PBO	25	<0.015	n.a.	0.057	0.097	1.47	<0.0064	n.a.	0.046	<0.0045	<0.00015	18
HDM 499	Überlingen	Şiria axe type	Sberlingen	95	0.031	n.a.	0.0048	0.004	0.0071	0.0209	n.a.	0.000037	1.17	0.00017	0.043

Table 1 *Continued*

Lab. no.	*Site*	*Object*	*Museum*	*Cu*	*Sn*	*Pb*	*As*	*Sb*	*Ag*	*Ni*	*Bi*	*Au*	*Zn*	*Co*	*Fe*
Early Bronze Age															
FG-040649	Gammersham	Ösenring	München, 15592	96	<0.01	<0.01	2.06	1.47	0.82	<0.01	0.047	<0.01	<0.01	<0.01	<0.05
FG-040650	Gammersham	Ösenring	München, 15656	96	<0.01	<0.01	1.75	1.32	1.03	<0.01	0.052	<0.01	<0.01	<0.01	<0.05
FG-040651	Gammersham	Ösenring	München, 15589	95	<0.01	<0.01	2.38	1.51	0.85	<0.01	0.082	<0.01	<0.01	<0.01	0.13
FG-040652	Gammersham	Ösenring	München, 15576	95	<0.01	<0.01	2.28	1.41	0.81	<0.01	0.081	<0.01	<0.01	<0.01	<0.05
FG-040653	Gammersham	Ösenring	München, 15606	96	<0.01	0.01	2.09	1.45	0.74	0.01	0.069	<0.01	0.01	0.01	<0.05
FG-040654	Gammersham	Ösenring	München, 15641	96	<0.01	<0.01	1.98	1.41	1.05	<0.01	0.052	<0.01	<0.01	<0.01	<0.05
FG-040655	Gammersham	Ösenring	München, 15642	95	<0.01	0.01	2.13	1.52	0.91	0.01	0.055	<0.01	0.01	0.01	0.23
FG-040656	Gammersham	Ösenring	München, 15640	96	<0.01	<0.01	2.60	1.32	1.21	<0.01	0.073	<0.01	<0.01	<0.01	0.09
FG-040657	Gammersham	Ösenring	München, 15638	96	<0.01	<0.01	1.91	1.52	0.76	<0.01	0.044	<0.01	<0.01	<0.01	0.16
FG-040658	Gammersham	Ösenring	München, 15663	95	<0.01	<0.01	2.21	1.16	1.16	<0.01	0.100	<0.01	<0.01	<0.01	<0.05
FG-040664	Gammersham	Ösenring	München, 15608	96	<0.01	<0.01	1.77	1.35	0.73	<0.01	0.059	<0.01	<0.01	<0.01	<0.05
FG-040665	Gammersham	Ösenring	München, 15563	96	<0.01	<0.01	2.08	1.11	0.92	<0.01	0.065	<0.01	<0.01	<0.01	0.09
FG-040666	Gammersham	Ösenring	München, 15625	96	<0.01	<0.01	2.33	1.40	1.25	<0.01	0.083	<0.01	<0.01	<0.01	0.10
FG-040667	Gammersham	Ösenring	München, 15630	95	<0.01	<0.01	2.19	1.21	1.23	<0.01	0.112	<0.01	<0.01	<0.01	<0.05
FG-040668	Gammersham	Ösenring	München, 15662	96	<0.01	<0.01	1.66	1.61	1.14	<0.01	0.062	<0.01	<0.01	<0.01	0.09
FG-040669	Gammersham	Ösenring	München, 15660	96	<0.01	<0.01	1.73	1.17	1.06	<0.01	0.034	<0.01	<0.01	<0.01	0.07
FG-030872	Buchberg-Wiesing	Flanged axe		96	0.42	0.02	0.79	1.23	0.78	0.84	<0.005	0.03	0.1	0.009	<0.05

Abbreviations [analytical method in square brackets]

BAR, Ottaway (1982) [NAA and AAS for Fe, Ni, Pb and Bi].

FG, Institut für Archäometrie, TU Bergakademie Freiberg [EDXRF].

HDM, Max-Planck-Institut für Kernphysik, Heidelberg [NAA], with the exception of HDM 2784 (the copper bead from Brixlegg), which was analysed by EDXRF.

FMZM, Frühe Metallurgie im zentralen Mitteleuropa (Krause 2003) [EDXRF].

SAM, Württembergisches Landesmuseum Stuttgart, Studien zu den Anfängen der Metallurgie (Junghans et al. 1968, 1974) [AES]; the detection limit of the analytical method used was about 0.01%, and thus a zero figure should be read as '< 0.01%'; 'tr' was used for 'trace', suggesting that the concentration should be slightly above the detection limit.

O. Werner, Lüning (1973) [AES]; no detailed analytical information provided.

n.a., Not analysed; n.d., not detected.

unequivocally documented in the field, although copper production at Ai Bunar and Majdanpek, another large copper deposit in Serbia, has been indirectly proven in relation to copper artefacts (Pernicka *et al.* 1997). Therefore, we have analysed several of these Late Neolithic copper objects, in order to clarify whether copper was already being smelted from local ores in the Inn Valley at that early date.

A second motivation for a study of the copper deposits of this region was the fact that they form the largest mineralization of fahlore in the eastern Alps. It is well known that copper with high concentrations of arsenic, antimony and silver, often together with bismuth, is one of the major compositional types of copper from the Early Bronze Age in central Europe. It occurs predominantly in loop-ended, ring-shaped objects and in neck-rings made from them (the so-called Ösenringe), which are commonly considered to be copper ingots. They are mainly found in hoards that may consist of many hundreds of pieces, but also in graves distributed to the north and east of the eastern Alps. There are several thousands of them in total. If these rings were indeed ingots, then they would form an important component in the metallurgical sequence from the ore deposits to the finished products, similar to the Mediterranean oxhide ingots. This interpretation is now severely challenged, because copper of this composition mainly occurs in the form of Ösenringe and not in finished objects (Krause and Pernicka 1998). While one would expect a smaller chance of preservation for an intermediate technical product, one finds that two-thirds of all Bronze Age copper objects with this peculiar composition (about 3000 analysed) are Ösenringe. This makes it very unlikely that they indeed served as ingots. Whether they served religious purposes instead, or were some kind of premonetary means of payment and accumulation of wealth (Lenerz-De Wilde 1995) is now the subject of discussion. Nevertheless, due to their large numbers they play a key role in any attempt to understand the Early Bronze Age metal production and trade in central Europe.

The origin of the Ösenring copper has been variably sought in the Alps (see, e.g., Reinecke 1930; Bath-Bilková 1973; Butler 1978), in eastern Thuringia (Otto and Witter 1952) and in Slovakia (Pittioni 1957). The problem with all these associations is that they are either based on wrong assumptions—such as the statement by Otto and Witter (1952) that argentiferous fahlores with high arsenic and antimony occur only in eastern Thuringia—or on distribution maps. However, the greatest concentration of Ösenring metal is not in the piedmont of the eastern Alps but, rather, in eastern Austria and in Moravia, at about an equal distance from the three proposed source regions. Since the composition of fahlore metal is largely governed by the smelting process, at least as far as the concentrations of arsenic and antimony are concerned (Bourgarit and Mille 1999; Pernicka 1999), the chemical composition seems of little use for the identification of the source region. Therefore, lead isotope ratios in fahlore samples from the Inn Valley and in some Ösenringe from southern Bavaria were included in this study. However, this is an ongoing project, so only a preliminary report is presented here.

AN OUTLINE OF THE PREHISTORY OF THE INN VALLEY

Although the Inn Valley is one of the widest river valleys in the Alps, only a few sections were densely settled in prehistory. Only the areas around Landeck and Innsbruck, and between Wörgl and Kufstein, show concentrations of settlement activity (von Uslar 1991). There, the valley is wider than usual and in addition some moderately inclined terraces above the river bed provide good conditions for settlement and agriculture. The side valleys were scarcely populated. Archaeological finds are known mainly from the Sill Valley, south of Innsbruck, which was the principal access to the Brenner Pass and formed part of one of the most important routes across the Alps. Although the knowledge on the Mesolithic, especially at high altitudes, has increased due to intensified research during recent years after the find of the Iceman, very little evidence exists for the Palaeolithic. Only stray finds are known from the Neolithic (*c*. 5500–2200 BC), with the exception of the Mariahilfbergl in Brixlegg.

Apart from its function as a transit route, the Inn Valley provided several other economic resources. Among them are rock salt deposits at Hall in the Tyrol and, above all, the large copper deposits in the Schwaz–Brixlegg area (Gstrein 1979). These contained predominantly argentiferous tetrahedrite, which formed the basis of enormous wealth in the 14th and 15th centuries AD, when the Inn Valley was one of the leading mining districts in Europe, producing about 3000 metric tons of silver and about 250 000 metric tons of copper (Hanneberg and Schuster 1994). The identification of prehistoric mining came relatively late but is now ascertained from at least the late second millennium BC onwards (Gstrein 1981; Goldenberg 1998; Rieser and Schrattenthaler 1998–9, fig. 2).

The excavation on the Mariahilfbergl not only revealed the remains of the earliest hilltop settlement in the northern Tyrol, dating to the Late Neolithic Münchshöfen culture (4500–3900 BC) (Huijsmans 1996) but also the first indications for the smelting of copper ores, as mentioned above. Its botanical record also yielded the earliest evidence for farming in the area. The finds show a similar gradual adaptation of agriculture to Alpine environmental conditions that can also be observed in other parts of the northern Alps in this period.

During the Early and the Middle Bronze Age, the population density in the Inn Valley increased steadily and settlement concentrations can be observed in the above-mentioned sections of the valley. Among them, the Buchberg fortified hilltop settlement, with finds of copper ore, slag and raw metal, a tuyère and crucible fragments, probably from metal casting, figures as one of the best known sites (Martinek 1995; Sydow 1995; Martinek and Sydow 2004). Although well-dated archaeological evidence is scarce, it seems that in that period the copper ore deposits were already being mined regularly. The prehistoric population density reached its climax during the Late Bronze Age Urnfield culture. At this time, there is also extensive evidence for copper mining and smelting in the area. The Late Bronze Age cemetery of Volders seems to belong to a new population that had migrated from the north, possibly in search of copper ores (Sperber 1999, 2003). Although the graves show a certain level of wealth, they do not compare with the rich graves further to the north of the Alps; for example, in the Danube Valley (Clausing 1999). Thus the economic emphasis of the Bronze Age population was probably on agriculture and trans-Alpine trade rather than copper mining, because the major settlement concentration is located around Innsbruck and not within the mining areas.

LATE NEOLITHIC METAL PRODUCTION AT BRIXLEGG

The excavation of the settlement on the Mariahilfbergl in Brixlegg by M. Huijsmans and R. Krauss yielded finds from the Late Neolithic Münchshöfen up to the Urnfield cultures (from the second half of the fifth to the late second millennium BC). The site is located on a hilltop above the middle Inn Valley in the Tyrolean Alps, approximately 50 km to the east of Innsbruck (Fig. 1). Copper slags and a few copper objects were found in and around a fireplace (area Qu. 4 of the excavation), which was stratigraphically dated to the Late Neolithic (Bartelheim *et al*. 2002). The majority of the ceramic material in the associated SE 6 settlement layer belonged typologically to the Münchshöfen culture, which is mainly known from southeastern Bavaria; Brixlegg represents its first appearance in the Alps. Two radiocarbon dates of animal bone samples from this layer—one even from the fireplace—yielded data

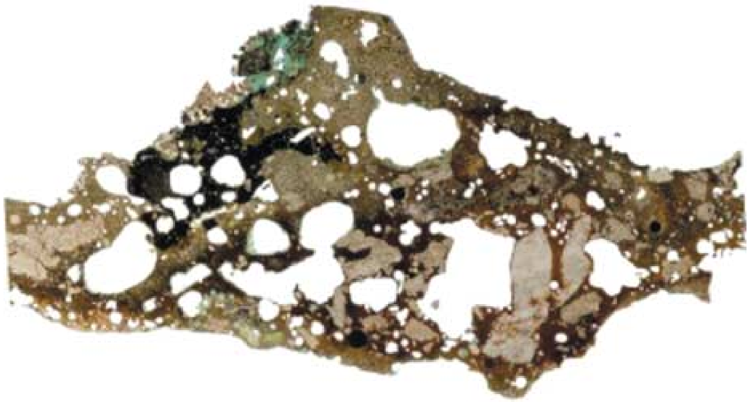

Figure 2 *A section through slag sample BRX 1, showing the typical appearance of early copper slags. Besides many vesicles, relict quartz and copper droplets are visible. The matrix between the inclusions clearly solidified from the liquid state, so that it is permissible to describe this find as metallurgical slag. The width of the section is 35 mm.*

(GrN-22167 BP 5480 ± 60, cal. BC 4460−4160 [2σ] and GrN-213641 BP 5570 ± 50, cal. BC 4500−4330 [2σ]) that match other published results from Bavaria (Matuschik 1992) quite well.

Without doubt, the most remarkable finds within the Münchshöfen inventory were pieces of copper slag found close to the fireplace. They were discovered in a very limited area within the Neolithic SE 6 settlement layer and represent the earliest indication of copper metallurgy in the Tyrol. The fireplace is made up of several layers of reddish burnt clay and was initially interpreted as a smelting place for copper ores. In summer 1999, this specific structure was excavated and studied by a team from the Freiberg Institute of Archaeometry. No further slags could be detected, but close to the fireplace and within layer SE 6, a copper bead and a copper band were found. Two clay nozzles that are also derived from layer SE 6, but that are not linked to any structure, are possible hints concerning some kind of pyrotechnical process. Their precise function remains unclear. The amount of slag is rather small, so it cannot be decided with certainty whether true copper production actually took place. However, the slag contained copper prills of a composition that suggests that the locally abundant tetrahedrite fahlores (see below and Fig. 2) were used. The archaeological association with the Late Neolithic is confirmed by a radiocarbon date of charcoal from pieces of baked clay, partly mixed with green copper minerals (BP 5000 ± 80, cal. BC 3960–3650 [2σ]; Bronk Ramsey *et al.* 1999).

Although the three radiocarbon dates from layer SE 6 cover a relatively large time interval between 4500 and 3640 BC, a date within the second half of the fifth millennium BC appears more likely, because all datable material in this layer belongs to the Münchshöfen horizon. Absolute dates for this period from all sites studied also fall into the second half of the fifth millennium (Matuschik 1992; de Marinis and Pedrotti 1997) while finds of the somewhat later 'cultural facies' Wallerfing (Uenze 1989) and the following period of the Mondsee, Altheim and Pfyn cultures are missing. If one considers the upper end of the time span for layer SE 6 as the more likely one, then the copper objects from Brixlegg belong to the earliest north Alpine metal-using horizon, of which until now only very few objects are known (Table 1).

The main objective of the analysis of copper objects and slag specimens from Mariahilfbergl was to identify the process from which they derive. In addition, it was intended to determine the role that the fireplace played in this process and whether local raw materials were used.

Most of the slags seem to have been broken intentionally into small pieces of a size between 0.5 and 2 cm. Their total weight is about 250 g. On the brownish surfaces green spots are visible, which provide a first hint about the presence of copper. Polished thin sections were examined by optical microscopy and analysed using the EDX system of a scanning electron microscope.

Almost all of the slags analysed (six samples) contain a high proportion of pores, which vary substantially in size. Inclusions of unsmelted minerals are also visible. A first look at the sectioned surface reveals the typical appearance of early smelting slags: large gas bubbles, numerous partially decomposed constituents and metal prills (Fig. 2). A much more detailed report of the slag analyses is published in Bartelheim *et al*. (2002).

EARLY BRONZE AGE METAL PRODUCTION AT BUCHBERG

Buchberg is a small limestone hill near Jenbach, in the middle of the flat bottom of the Inn Valley, with an Early Bronze Age fortification on top. Former finds of pottery with slag temper and scattered pieces of nut-sized copper ore suggested an association with the local copper ores and their exploitation (Sydow 1984). In 1994, a new excavation delivered the complete inventory of a copper-smelting workshop, from ore to raw metal (Martinek 1995; Sydow 1995; Martinek and Sydow 2004). A charcoal sample from the site yielded a calibrated ^{14}C date [2σ] of 2030–1820 BC (HD-17868 BP 3586 ± 26). Two important Early Bronze Age stray finds from the Buchberg, a flanged axe (Martinek 1993) and a pin (Schrattenthaler and Rieser 1994), were considered as possible products of the local copper industry.

The mineralizations in the Schwaz–Brixlegg area occur in three geological complexes (Fig. 3). In the Palaeozoic mylonitized gneisses of the Kellerjoch, south-east of Schwaz, discordant veins of siderite occur, with chalcopyrite, galena and fahlore. Economically, by far the most important deposits are located within the Schwaz dolomite, which is of lower Devonian age.

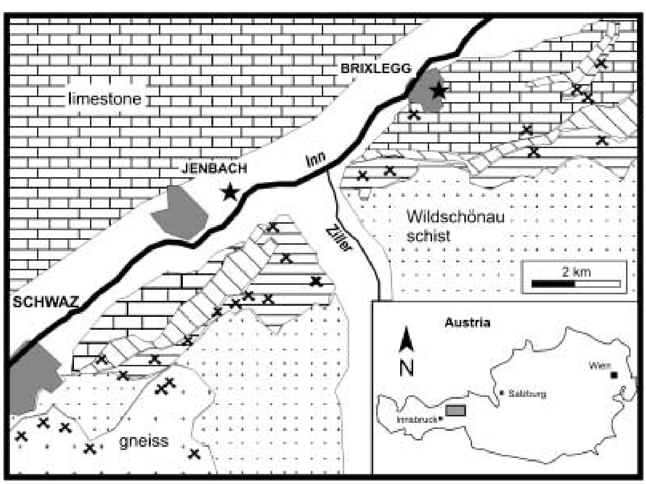

Figure 3 *Major geological units in the Inn Valley between Schwaz and Brixlegg with medieval copper–silver mines, some of which may have been exploited already in the Bronze Age. The most fertile host rock is the 'Schwazer Dolomit' (horizontal hatching) of Devonian age, which is bordered by barren Permian red sandstone to the north. Mariahilfbergl is on the southeastern rim of the town of Brixlegg and Buchberg is just north of the Inn River, between Brixlegg and Jenbach. Both sites are indicated by stars.*

The original carbonate platform was broken into several pieces during the tectonic uplifting of the Alps. This explains the presence of several mining districts with similar ore compositions. In the area of Brixlegg, the Triassic limestones are partly mineralized with copper, lead and zinc ores, with minor cobalt and silver minerals. While the fahlore composition in the gneiss and the Schwazer dolomite is predominantly arsenical tetrahedrite, it is mainly tennantite in the Triassic limestone. The schist of the lower Palaeozoic and the Permian red sandstone are not mineralized (Arlt and Martinek 1994).

The primary ore of the deposits between Schwaz and Brixlegg is almost exclusively arsenical tetrahedrite. REM analyses with EDX have revealed Cu, S, Sb and As as major components, with significant concentrations of Zn, Hg, Fe and Ag, as well as traces of Bi. In decomposed fahlores, Ag and Hg are enriched and Co and Ni are often present. This mineral paragenesis is characteristic of the local fahlore mineralizations in the Devonian dolomite of the so-called Grauwackenzone of the northern Alps. Secondary copper minerals occur as impregnations of the host rock as well as in massive form, and consist predominantly of theisite $Cu_5Zn_5[(OH)_2|(As,Sb)O_4]_2$ and malachite $Cu_2[(OH)_2|CO_3]$, with minor azurite $Cu_3[OH|CO_3]$, tirolite $Ca_2Cu_9[(OH)_{10}|(AsO_4)_4]\cdot 10H_2O$ and cupro-adamine $(Zn,Cu)_2[OH|AsO_4]$. Note that the smelting of a mixture of these secondary minerals would result in a copper that was rich in arsenic and antimony.

For the first investigation (Martinek 1995), a total of about 600 g of slag pieces from the archaeological site on Buchberg were available. They were in the size range of up to 5 cm in diameter, with many bubbles and green stains (Fig. 4 (a)). In cross-sections they appear rather inhomogeneous, with numerous inclusions of unsmelted materials and copper prills. The slags are fully crystallized and consist mainly of calcium–iron silicates and oxides (clinopyroxenes, spinels and melilithe; Fig. 4 (b)). They also contain generally high concentrations of arsenic and antimony, in the range between 0.3% and 1%. The almost complete absence of fayalite, the most common slag mineral, is obviously due to the calcium-rich host rock of the ore. The identified slag phases are thermodynamically stable at high partial pressures of oxygen and melt above 1200°C. On remelting in a crucible, the slags turned into a low-viscosity liquid in the range between 1250°C and 1300°C. However, judging from the large number of copper inclusions, it can be assumed that the slag was never fully molten. These would probably have been collected by breaking and grinding of the slags. The resulting slag sand could be used as temper for pottery. Such slag-tempered shards have indeed also been found on Buchberg. Most slags and copper prills from Buchberg have the typical fahlore composition to be expected when local ores have been smelted (Martinek 1995; Schubert and Pernicka in preparation). In addition, among the loose copper prills, one consisted of fahlore copper containing 4.5% nickel and also cobalt in measurable concentrations. Due to the comparatively low contents of arsenic, antimony and sulphur, it was assumed that this metal is a product of the smelting of a mixture of fahlore with secondary copper minerals that contain nickel. The flanged axe mentioned above contains nickel in the order of 1%. It was thus concluded that the copper of these artefacts likewise derives from an ore mixture (Martinek 1997).

INVESTIGATIONS RELATING TO THE PROVENANCE OF THE ORES

Late Neolithic

Even though the slags from Brixlegg–Mariahilfbergl contain unmelted portions, the abundant multiphase inclusions of metal sulphide clearly show that massive transformations from ore to

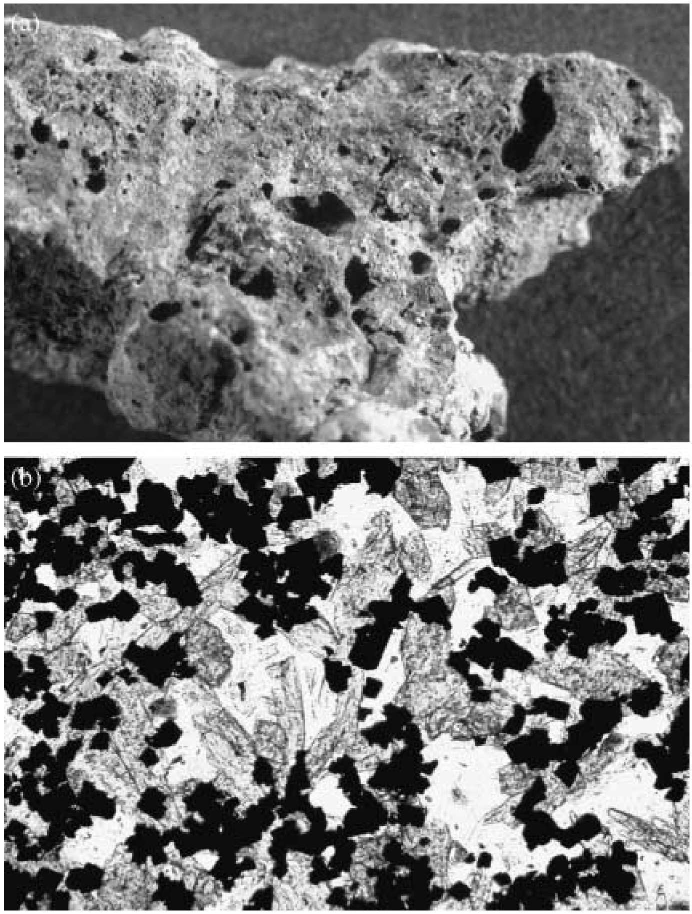

Figure 4 *(a) The typical appearance of Early Bronze Age copper slags from Buchberg (width 30 mm). (b) Fully crystallized slag with ferrospinel (black) tightly intergrown with clinopyroxene and melilithe (grey). White areas are gas bubbles. Optical microscope; thin section (width 0.7 mm).*

metal had taken place. It is therefore likely that an essentially sulphidic ore was smelted to obtain metal. Such an ore is the local tetrahedrite fahlore, which occurs within dolomitic host rocks at many places around Brixlegg. Embedded in the slags are abundant copper prills with low contents of antimony and arsenic, formed by direct reduction from a siliceous smelt. Larger prills generally exhibit high concentrations of arsenic and/or antimony in the copper, confirming the assumption that local fahlores were smelted. It is frequently stated in the archaeological literature that fahlores are difficult to smelt, but this refers only to the modern smelting technology in a shaft furnace, under strongly reducing conditions. In these circumstances, speiss is formed, which takes up copper and noble metals, resulting in intolerable losses for modern smelters. Prehistoric smelting took place at much higher partial pressures of oxygen, so that most of the arsenic and antimony were probably volatilized as oxides. Actually, Richard Pittioni, who most explicitly rejected the idea that fahlores were smelted for copper in prehistory, himself mentioned that on the Philippine islands copper could be smelted in a primitive bowl furnace from enargite ore (copper–arsenic sulphide) in the 19th century AD

(Pittioni *et al*. 1970). Similar fahlores were also smelted in the third millennium BC in the region of Cabrières in southern France (Ambert 1990/1991, 1995, Bourgarit *et al*. 2003). Smelting experiments with initial roasting of the ore yielded copper with about 2% Sb, similar to the Ösenring copper of the central European Early Bronze Age (Pernicka 1999).

The metal samples from Brixlegg were analysed for major and some trace elements by EDXRF, using the procedure of Lutz and Pernicka (1996). The results are given in Table 1. Lead isotope ratios in both slag and metal samples were determined by multi-collector ICP–MS (for details of the analytical method, see Niederschlag *et al*. 2003). Basically, an appropriate amount of sample was dissolved in half-concentrated HNO_3 (Merck Suprapur) and the solution diluted with high-purity deionized water to contain a lead concentration of 200 ng ml^{-1} in 2% HNO_3. All measured solutions were doped with 50 ppb thallium for correction of the internal fractionation within the spectrometer. Any possible mercury interference was corrected by measuring the ^{202}Hg peak. For accuracy checks, the standard material SRM-981 was prepared in a similar manner and measured together with the samples. Long-term observation of such check measurements results in a relative standard deviation (2σ) of 0.09% for the $^{206}Pb/^{204}Pb$ ratio, of 0.04% for the $^{208}Pb/^{206}Pb$ ratio and of 0.02% for the $^{207}Pb/^{206}Pb$ ratio, with maximal deviations from published TIMS values for SRM-981 (Todt *et al*. 1996; Galer and Abouchami 1998) of about 0.05% for the lead isotope ratios reported. The results of the lead isotope measurements of the Late Neolithic samples are summarized in Table 2.

Most Late Neolithic copper objects consist of low-impurity copper, even including the two copper pieces from the Mariahilfbergl (Table 1). Although the bead could only be analysed in the uncleaned state, the two analyses of the metal strip with and without corrosion that are more or less comparable show that this statement is also valid for the bead (Table 1). It is not impossible that low-impurity copper ores occurred in the Brixlegg area, especially in the

Table 2 *Lead isotope ratios in Late Neolithic metal from central Europe and in slag samples from Mariahilfbergl, Brixlegg*

Sample	*Lab. no.*	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{204}Pb$
Neolithic copper				
Linz, St Peter, hammer-axe	SAM 11192	2.0776	0.84303	18.503
Linz, St Peter, hammer axe	SAM 11193	2.0774	0.84296	18.502
Linz, St Peter, flat axe	SAM 11194	2.0774	0.84261	18.539
Linz, St Peter, flat axe	SAM 11195	2.0771	0.84255	18.535
Wallerfing, awl	FMZM 387	2.0762	0.84273	18.512
Brixlegg, metal strip	FG-990692	2.0783	0.84290	18.527
Hornstaad, disc	HDM 446	2.0899	0.84649	18.520
Hornstaad, disc, patina	HDM 446	2.0925	0.84924	18.449
Überlingen, Şiria axe type	HDM 499	2.0832	0.84465	18.510
Neolithic slags				
BRX 1	1423	2.0733	0.84014	18.657
BRX 3	1422	2.0920	0.85035	18.426
BRX 4	1421	2.0831	0.84675	18.497
BRX 4	1425	2.0785	0.84404	18.572
BRX 5	1424	2.0889	0.85071	18.391
BRX 6	1420	2.0968	0.85266	18.374
BRX 7	1426	2.0691	0.83849	18.698

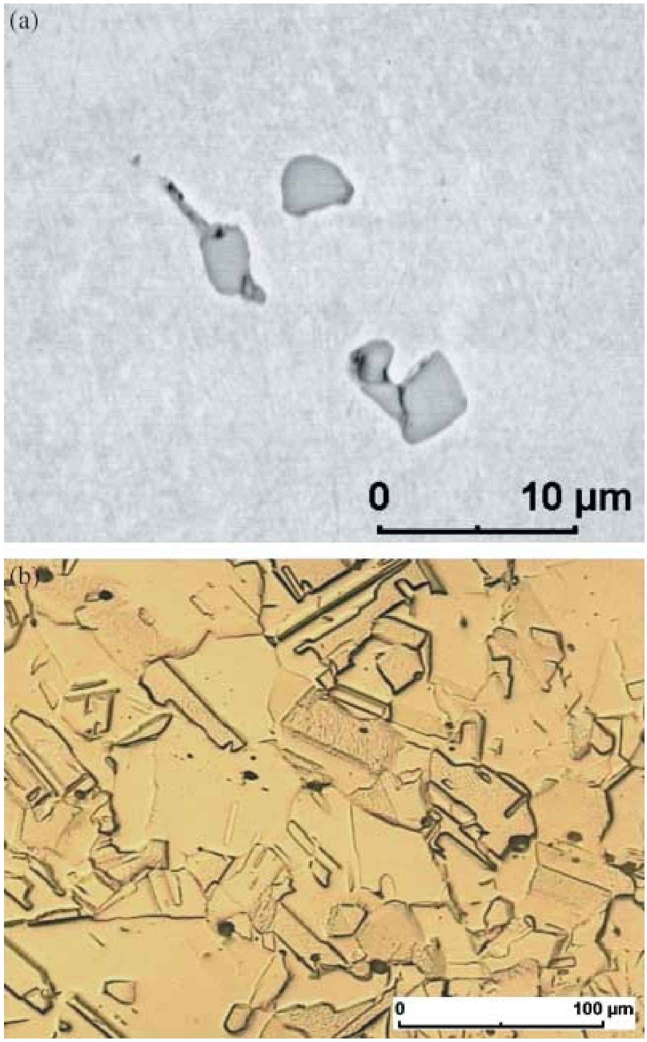

Figure 5 *(a) Cuprite inclusions in the copper strip from Mariahilfbergl, Brixlegg: a SEM back-scattered electron image of a polished section, not etched. (b) Recrystallized copper with twinning and cuprite inclusions. Optical microscope; reflected light; polished section etched with alcoholic* $FeCl_3$.

oxidized zone, but it is nevertheless surprising that the compositions of the two copper objects found in context do not resemble that of the prills in the slags. Thus, the association of the copper objects with local ores is certainly not as obvious as initially thought. The microstructure of the copper strip from Mariahilfbergl (FG-990692) shows abundant inclusions of cuprite Cu_2O, a clear indication that the metal has solidified from a melt (Fig. 5). No sulphide inclusions were observed. The strip was ground, as can be deduced from the deep parallel streaks on the surface. It was annealed at least once and the annealing twins in some of the recrystallized copper grains are not deformed, so the strip was left in the annealed state and was not further deformed after cooling.

Table 3 *Lead isotope ratios in fahlore samples from the Inn Valley. The host rock is Devonian dolomite (Schwazer Dolomit) unless indicated otherwise. The numbers of the samples from Falkenstein are the same as used by Neuninger* et al. *(1960, table 8). All samples with 'FG' numbers were analysed by EDXRF to ascertain their composition with high concentrations of copper, arsenic and antimony. The remaining samples were analysed in Vienna by semi-quantitative AES*

Sample designation		*Locality*	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{204}Pb$
Schwaz region					
FG-041611	0/4	Falkenstein, Schwabboden	2.0742	0.84065	18.663
FG-041508	1/23	Falkenstein, Eiblschrofen	2.0149	0.81607	19.273
FG-041508	1/23	Falkenstein, Eiblschrofen	2.0113	0.81478	19.281
FG-041508	1/23	Falkenstein, Eiblschrofen	2.0280	0.82140	19.128
FG-041509	1/24	Falkenstein, Eiblschrofen	2.0227	0.81918	19.207
FG-041481	2/20	Falkenstein, Eiblschrofen	2.0679	0.83845	18.718
FG-041392	3/3	Falkenstein, Eiblschrofen	2.0674	0.83719	18.744
FG-041535	4/26	Falkenstein, Eiblschrofen	2.0671	0.83697	18.746
FG-041464	5/4	Falkenstein, Eiblschrofen	2.0640	0.83851	18.704
FG-041450	6/2	Falkenstein, Eiblschrofen	1.9972	0.80252	19.614
FG-041454	6/6	Falkenstein, Eiblschrofen	2.0392	0.82490	19.072
FG-041590	7/31	Falkenstein, Eiblschrofen	2.0452	0.82855	18.960
FG-041415	8/4	Falkenstein, Eiblschrofen	1.9981	0.80871	19.474
FG-041415	8/4	Falkenstein, Eiblschrofen	1.9939	0.80707	19.482
FG-041415	8/4	Falkenstein, Eiblschrofen	1.9956	0.80851	19.455
FG-041400	8/10	Falkenstein, Eiblschrofen	2.0574	0.83279	18.862
FG-041551	11/14	Falkenstein, Eiblschrofen	2.0331	0.82328	19.110
FG-041554	11/17	Falkenstein, Eiblschrofen	1.9983	0.81002	19.415
FG-041554	11/17	Falkenstein, Eiblschrofen	1.9924	0.80648	19.503
FG-041554	11/17	Falkenstein, Eiblschrofen	2.0043	0.81115	19.381
FG-041444	12/6	Falkenstein, Sigismund-Erbstollen	2.0381	0.82486	19.045
FG-011207	PP047	Falkenstein, Erbstollen	2.0565	0.83345	18.852
FG-011172	PP012	Danielböden, Mehrerkopf	1.9863	0.80574	19.551
FG-011196	PP036	Roggland	2.0227	0.81486	19.294
Brixlegg region					
FG-011165	PP005	Silberberg, Friedlingstollen (Triassic limestone)	2.0964	0.85297	18.358
FG-011177	PP017	Maukenötz, Kramstollen (Triassic limestone)	2.0969	0.85386	18.336
FG-011192	PP032	Mockleiten, Mauken-Stadel-Stollen	2.0734	0.84024	18.660
FG-011193	PP033	Mockleiten, Kreuzstollen	2.0704	0.84058	18.653
FG-011194	PP034	Ramsberg	1.9434	0.79346	19.804
FG-011198	PP038	Großkogel	2.0657	0.83667	18.759
Innsbruck region					
FG-011184	PP024	Navis near Matrei/Brenner (Palaeozoic phyllite)	2.0650	0.83251	18.897
FG-011190	PP030	Innsbruck, Hötting, Höttinger Bild (Triassic limestone)	2.0941	0.85164	18.379

The lead isotope ratios (Table 3) of the ore deposits of Schwaz–Brixlegg show a wide spread in the usual three-isotope plot of $^{208}Pb/^{206}Pb$ versus $^{208}Pb/^{206}Pb$ (Fig. 6 (a)). Even single hand specimens are isotopically inhomogeneous, as demonstrated with samples 1/23, 8/4 and 11/17 (Table 3), of which three replicate samples each were measured. Fahlore minerals are not rare, but they usually occur only as accessory minerals in copper deposits. However, there are at least two regions in central Europe where fahlore minerals predominate locally, namely

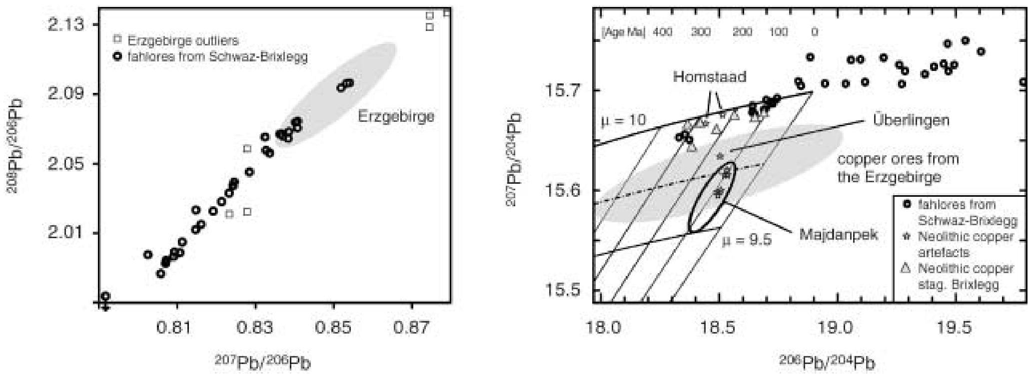

Figure 6 *(a) Lead isotope ratios in ore samples from the Inn Valley compared with those of copper ores from the Erzgebirge (Niederschlag* et al. *2003) in the most often used diagram. The experimental uncertainty is much smaller than the size of the symbols. The ores from both regions are highly variable, most likely due to high and variable U/Pb ratios. The Erzgebirge field comprises 71 samples. (b) Lead isotope ratios in Neolithic copper artefacts and slags from Brixlegg, in Ösenringe with a fahlore composition and in ores from the Inn Valley, represented in the conventional geological diagram. Also given is the field of ores from the Erzgebirge and evolutionary curves for different μ-values ($^{238}U/^{204}Pb$), as well as a few isochrons. The dashed line in the middle is the evolutionary curve according to the model of Stacey and Kramers (1975), which is an approximation of the average isotope composition of lead in the continental crust. The majority of the Neolithic copper samples are isotopically similar to ores from the large copper deposit of Majdanpek and to a group of 90 contemporary copper artefacts from southeastern Europe (Pernicka* et al. *1997).*

the Slovakian Ore Mountains and the Erzgebirge. Accordingly, both regions have been suggested in the literature as possible sources for the Early Bronze Age fahlore copper. Otto and Witter (1952) maintained that the Erzgebirge and the adjacent Vogtland was the source of fahlore copper, while Pittioni (1957) favoured the Slovakian Ore Mountains and even termed this type of copper 'Ostkupfer'. There are no lead isotope analyses available for fahlores from Slovakia, but a large data set has recently been published for mixed copper ores from the Erzgebirge and adjacent regions (Niederschlag *et al*. 2003).

Although the lead isotope ratios of ores from the Inn Valley and the Erzgebirge overlap in Figure 5 (a) they can be distinguished in a plot of $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ (Fig. 6 (b)). The ores from the Inn Valley generally have geologically younger uranogenic model ages and have higher μ-values ($^{238}U/^{204}Pb$) between 9.5 and 10.0 than the ores from the Erzgebirge, with μ-values between 9.0 and 9.5. In fact, most ore samples from the Inn Valley exhibit negative apparent ages, which is most likely due to variable high μ-values ($^{238}U/^{204}Pb$) in the ore deposits. Three samples (FG-11165, FG-11177 and FG-11190) yielded reasonably consistent geological ages according to the model of Stacey and Kramers (1975), of 319, 300 and 292 Ma, respectively, which are nevertheless too young for the Devonian dolomite that hosts most of the mineralizations in the Inn Valley. These ore-genetic aspects will be discussed in more detail elsewhere.

For the provenance question, the large spread within the deposits makes it difficult to discuss a possible relationship of the ores when only a few finds are available. However, with the exception of the copper disc from Hornstaad, all Neolithic copper samples plot within or close to a narrow region, which suggests that they may not be isotopically consistent with the copper ores from the Inn Valley (Fig. 6). Chemically, they are completely different anyway.

If one searches the database of published lead isotope ratios of archaeometallurgical relevance (this database was originally assembled by F. Begemann and S. Schmitt-Strecker, from

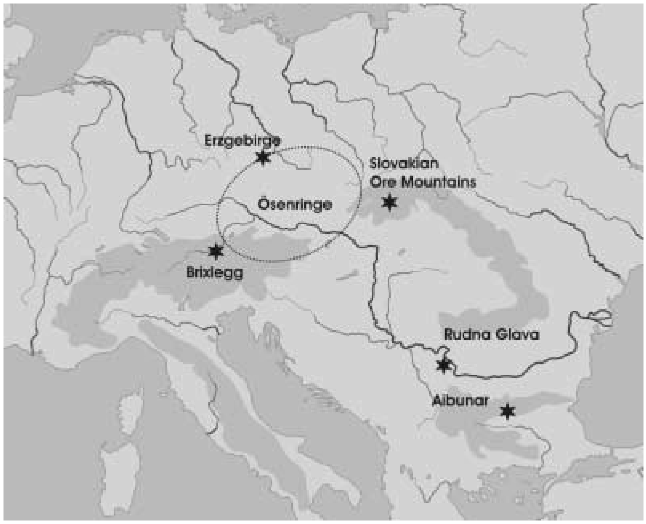

Figure 7 *The locations of the sites mentioned in the text. Rudna Glava and Aibunar are the earliest copper mines in Europe (Jovanovic 1976; Chernykh 1978) and have been shown to have supplied copper over large distances in southeastern Europe in the late fifth millennium* BC *(Pernicka* et al. *1993, 1997). Also shown are the three mining regions that have been discussed for the supply of the Early Bronze Age fahlore copper represented especially by the Ösenringe, whose approximate distribution area is indicated by the ellipse.*

Mainz, and is continually updated at Freiberg) then the best matching samples for the Neolithic copper artefacts are to be found in Serbia and Bulgaria. They consist mainly of chalcolithic copper samples (dating roughly from the late fifth to the early fourth millennium BC) and copper ores from the large copper deposit of Majdanpek in Serbia (Fig. 7). This coincidence has been taken to demonstrate that this deposit was already being exploited by the fifth millennium BC, although all remnants of the ancient mining have been destroyed by the modern open pit mine (Pernicka *et al*. 1993, 1997).

Indeed, altogether 90 copper artefacts of this period have lead isotope ratios that are similar to those of this deposit. Moreover, the majority of these artefacts have similar trace element patterns (Fig. 8). Again, with the exception of the copper disc from Hornstaad, all isotopically analysed Neolithic samples for which there are trace element data available (zero in the SAM data is equivalent to $< 0.01\%$) also conform to this pattern, so that there is a good case for suggesting that they indeed derive from the Majdanpek deposit, or at least from this metallogenic region. While this large copper deposit is rather homogeneous as far as the lead isotope ratios are concerned, the chemical composition of its ores is not. Since it is difficult today to obtain ore samples from Majdanpek, which would have been accessible to prehistoric miners, two samples from the oxidation zone, consisting of malachite/azurite and cuprite, respectively, from the collection of the Mining Museum in Bor, were taken as representative of the ore that could have been available in the late Neolithic (analyses taken from Pernicka *et al*. 1993). It is obvious from Figure 8 that these two ore types would produce rather pure copper, with a trace element pattern similar to that of the Chalcolithic artefacts. The two ore specimens were small, almost monomineralic. In nature, these would be intermixed, and if one were to assume that the Chalcolithic smelters did not care to separate the cuprite from the malachite, then the agreement with the trace element pattern of the artefacts would even be better.

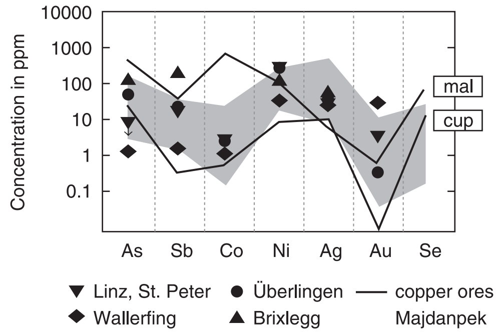

Figure 8 *The shaded area encompasses the trace element concentrations of samples in chemical cluster #2 identified in Eneolithic copper artefacts from southeastern Europe (Pernicka* et al. *1997). This pattern is often found together with lead isotope grouplet #1, which is the geochemical signature of the Majdanpek copper deposit in Serbia. The two solid lines show the trace element concentrations in two ore samples from the oxidation zone of this deposit (sample HDM 1474, 'mal', consists mainly of malachite and azurite, while sample HDM 1473, 'cup', consists predominantly of cuprite; Pernicka* et al. *1993). The symbols indicate the concentrations in four Neolithic copper artefacts from central Europe (Table 1).*

The copper disc from Hornstaad is chemically and isotopically different. It is even inhomogeneous, as the patina has significantly different lead isotope ratios compared to the interior. The reason for this result is unclear. It could be due to contamination during restoration or it could result from deposition of lead from the water of Lake Constance, where the disc was found at the site of a lake dwelling. The largely reducing conditions in the lake sediments would facilitate reduction of lead from the water on the surface of the metal. Since the lead concentration in the metal of the disc was less than 100 $\mu g\ g^{-1}$, even a small lead contribution from the environment could alter the lead isotope ratios in the patina. Concerning the possible provenance of the metal, it plots together with the copper ores from the Inn Valley. However, its chemical composition is rather different from the fahlore composition to be expected from the ores of the Schwaz–Brixlegg area, because the typical fahlore copper has an As:Sb:Ag ratio of about 2:2:1. We have found 21 chemically and chronologically matching artefacts in our database of roughly 40 000 analyses of prehistoric metal objects (Krause and Pernicka 1996). Seven of those are from the Lake Constance region, mostly from lake dwellings. It is thus likely that this copper derives from a different deposit in the Alpine region—possibly further west, where prehistoric mining has also been attested to (Schaer 2003; Krause *et al*. 2004).

Regarding lead isotope ratios, the axe from Überlingen matches the ores and associated Chalcolithic copper objects from Aibunar in Bulgaria best (Pernicka *et al*. 1997), but this copper is characterized by substantially higher concentrations of arsenic and antimony, of about 0.1% and 0.05%, respectively. On the other hand, the trace element pattern conforms well with the copper that is attributed to Majdanpek (Fig. 8). Therefore, the question of where this copper might come from must remain open at present, but the Şiria axe type is most abundant in present-day Romania, so the ore source may be sought there.

Early Bronze Age

While in the Late Neolithic the archaeological occurrence of fahlore copper is so far attested to only in the tiny prills within the slags from Mariahilfbergl, Brixlegg, it comprises a substantial part of the copper-based metal inventory in the Early Bronze Age of central Europe. Its typical composition (As:Sb:Ag about 2:2:1 in the low-percentage range, usually also with about 0.1% Bi and low Ni) has always been recognized as indicating the smelting of fahlores or copper ores containing fahlores as major components. However, the compositional range of the artefacts is rather small, which may indicate that it is not only governed by the ore composition but also by the smelting process (Bourgarit and Mille 1999; Pernicka 1999).

Here, we are mainly concerned with the provenance of this copper type. As an example, we have selected Ösenringe from the Gammersham hoard, located some 50 km east of Munich, which resemble the composition of the slags on Buchberg and the local ores from the Inn Valley (Table 1). Moreover, their lead isotope ratios (Table 4) seem to corroborate the assumption that this copper derives from the area between Schwaz and Brixlegg. The range of lead isotope

Table 4 *Lead isotope ratios in Early Bronze Age metal and slag samples from Buchberg-Wiesing and in Ösenringe from the Gammersham hoard*

Sample	*Lab. no.*	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{204}Pb$
Gammersham				
Ösenring	FG-040649	2.0847	0.84478	18.575
Ösenring	FG-040650	2.0738	0.84063	18.646
Ösenring	FG-040651	2.0838	0.84418	18.586
Ösenring	FG-040652	2.0842	0.84426	18.587
Ösenring	FG-040653	2.0839	0.84407	18.591
Ösenring	FG-040654	2.0574	0.83320	18.852
Ösenring	FG-040666	2.0722	0.84295	18.585
Ösenring	FG-040667	2.0786	0.84534	18.535
Ösenring	FG-040668	2.0727	0.83955	18.684
Ösenring	FG-040669	2.0777	0.84478	18.634
Ösenring	FG-040655	2.0747	0.84264	18.592
Ösenring	FG-040656	2.0688	0.83809	18.715
Ösenring	FG-040657	2.0755	0.84290	18.584
Ösenring	FG-040658	2.0613	0.83612	18.781
Ösenring	FG-040659	2.0669	0.82378	19.040
Ösenring	FG-040660	2.0681	0.82853	18.954
Ösenring	FG-040661	2.0594	0.82643	18.993
Ösenring	FG-040662	2.0627	0.83008	18.904
Ösenring	FG-040663	2.0599	0.82920	18.915
Ösenring	FG-040664	2.0838	0.84418	18.582
Ösenring	FG-040665	2.0844	0.84620	18.518
Buchberg-Wiesing				
Flanged axe	FG-030872	2.0933	0.85113	18.411
Slag	FG-040627	2.0713	0.84071	18.639
Slag	FG-040628	2.0719	0.84004	18.676
Slag	FG-040629	2.07	0.84074	18.669
Slag	FG-040630	2.0612	0.83576	18.767
Slag	FG-040631	2.0534	0.83185	18.872
Slag	FG-040632	2.0703	0.84004	18.664
Slag	FG-040633	2.0759	0.84297	18.593
Slag	FG-040634	2.0698	0.83972	18.679
Slag	FG-040635	2.0717	0.84082	18.644
Slag	FG-040636	2.0696	0.83977	18.670

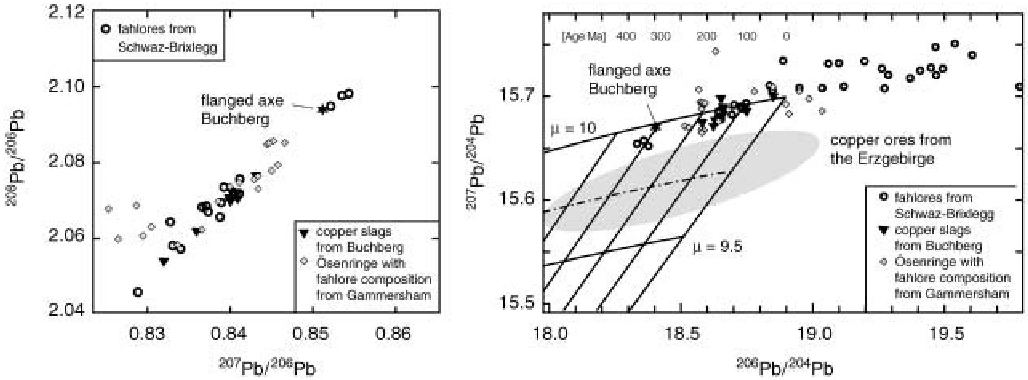

Figure 9 *Lead isotope ratios in all of the metal artefacts analysed. The Ösenringe from the Gammersham hoard show a pattern of variation that is distinctly different from that of the Neolithic copper artefacts, but consistent with the fahlore deposits of Schwaz–Brixlegg.*

ratios in the Ösenringe is much smaller than is found in the ores from the whole region (only ore samples with $^{206}Pb/^{204}Pb < 18.9$ would overlap with the Ösenringe in Fig. 6). If only this section is considered (Fig. 9 (a)), then most of the ore samples from the Falkenstein (Schwaz) area, which was mined extensively in the 15th–17th centuries AD, can be excluded as possible raw material for Early Bronze Age copper smelting because of their radiogenic lead. Only ores from the top of the deposit (Schwabboden and Eiblschrofen) match the lead in the Ösenringe. Especially at the Eiblschrofen locality, many ancient mines are known, but have only been recognized as probably prehistoric in recent times (Goldenberg 1998). Unfortunately, most of these mines are now lost or inaccessible, due to a gigantic rockslide a few years ago. It is likely that the abundant ancient mines weakened the whole mountain and thus contributed significantly to this rockslide. Also, five of the six ore samples so far analysed from the Brixlegg area would fit the lead from the Ösenringe just as well as one sample from a small mineralization in Innsbruck. This suggests that in prehistoric times this area was at least as important as the Falkenstein. Indeed, at least at one location, the Moosschrofen, a huge mine is still accessible that shows the characteristic rounded walls that result from fire-setting and working with stone mauls. Now, with the geochemical congruence of fahlores and Ösenringe, we have the first clear indication that fahlore copper was already being produced in the Early Bronze Age at a considerable scale that far surpassed the local needs. Köppel (1997) published lead isotope ratios of eight fahlore samples from Brixlegg and two from Schwaz, which generally agree with the above conclusions. They have not been plotted in Figure 9, because their exact location is not known. Although the variability of lead isotope ratios in the Ösenringe is smaller than in the ores, it is not yet clear whether they all belong together, since five samples seem to form a subgroup in Figure 9. However, such a conclusion requires a larger database. The slags from Buchberg cover the same range as the Ösenringe, supporting the interpretation that only the uppermost parts of the Falkenstein deposits and the deposits around Brixlegg were exploited in the Early Bronze Age.

The flanged axe that was found within the settlement and working area on Buchberg also fits the ores and slags from Buchberg in both lead isotope diagrams. However, it is chemically different, as it contains more nickel than is usually found in fahlore copper, although some slags do contain nickel besides arsenic, antimony and silver. However, if a relationship between the ores and the metal is sought, the low tin concentration is a matter of concern. Such low concentrations would not alter the mechanical or casting properties significantly, considering the other elements that are present. Therefore, it is unlikely that this amount of tin was added intentionally to the (impure) copper. Rather, it may indicate the re-use of different pieces of scrap metal, so that the final composition of the metal could not be controlled.

DISCUSSION

The Münchshöfen culture marks the beginning of the Late Neolithic in southern Germany. It is usually subdivided into three phases, early, middle and late Münchshöfen (^{14}C dated from *c*. 4500 to *c*. 4000 BC; Matuschik 1992; Nadler and Zeeb 1994). The inventory of finds exhibits hardly any association with the preceding cultures of the Middle Neolithic, so that it seems that, rather, it represents a discontinuity in the cultural development. The closest typological parallels are found in the Carpathian basin, especially in the cultures that are contemporary with and related with the Lengyel complex. Particularly close are formal relationships with the groups with painted pottery in Moravia and Lower Austria (the 'mährisch bemalte Keramik' and 'Bemaltkeramik' in eastern Austria). This is exemplified by vessel types such as the pedestalled bowls with solid stems and profiled bowls with knobs (Podborský 1970; Süß 1976; Pavúk 1981), and in the decoration with plaited bands and metope patterns. These cultures are followed by the Balaton–Lasinja I group in the south-east Alpine region and the western part of the Carpathian basin. Typological relationships with the Münchshöfen culture are documented by mushroom-shaped bottles, bowls and pots with retracting lower parts. In the late phase of the Münchshöfen culture, jars of Balaton–Lasinja type are common (Maier 1972, fig. 2; Kalicz 1991, figs 3–5; Nadler and Zeeb 1994, fig. 28,4).

In this context, it may not be so surprising that the copper came from southeastern Europe, where—similar to agriculture—it appears a little earlier than in central Europe. It is somewhat surprising that the copper strip from Brixlegg is also an import, although it was found in a context in which fahlores were obviously heated to an extent that slag and copper metal formed, even though no real metallurgical installations have been found. A possible scenario could be an experimental smelting of local ores by people who knew of and possessed copper. Either the yield of copper metal was so low that these ores were considered to be useless, or the output was so small that we do not find it in our admittedly very small inventory of metal finds from this period.

Although the metal strip and the small copper bead of rolled sheet are typologically not really significant, the strip at least seems to corroborate typologically the relationship with contemporary cultures that also are in close contact with the Carpathian basin. In Figure 10,

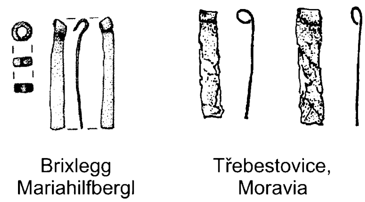

Figure 10 *A comparison of the copper objects from Brixlegg, Mariahilfbergl, with contemporary artefacts made of copper strips from Třebestovice, Bohemia, belonging to the Late Neolithic Jordanów culture (after Rulf 1994, figs 1, 6, 7, 9 and 13).*

two copper strips from Třebestovice with very similar shapes to the one from Brixlegg are shown as examples. One could also imagine that the strip was intended to be made into a simple or a spiral bead formed from curled copper sheet. Such types are also typical of the metal inventory of the Lengyel culture.

Even though it is likely that at Brixlegg copper was produced from local ores, it remains unclear whether this is an isolated finding or whether this technology was more widespread in the north Alpine region in the Münchshöfen horizon. Up to now, this is the earliest evidence for pyrotechnological metal production in central Europe. This is a considerable shift in time, because hitherto it was assumed that smelting of copper ore began only in the Early Bronze Age.

There can now be no doubt that fahlores were regularly smelted in the Early Bronze Age in the Inn Valley. At Buchberg, all stages of the metallurgical chain are represented: ores, slags, metal prills and finished objects. However, it is not clear whether the single artefact analysed in this study, a flanged axe, was actually made at Buchberg. Rather, its composition suggests re-use of scrap metal. If this conclusion were to be substantiated by future analyses, then inferences on the possible provenance of the metal would have to be regarded with caution.

CONCLUSIONS

Mariahilfbergl in Brixlegg has yielded the earliest evidence for copper smelting in the eastern Alps and thus remains as an important site in documenting the earliest stages of metallurgy. The previous chronological gap between copper production in southeastern and central Europe has decreased from more than two millennia to a few centuries. In a previous publication (Bartelheim *et al*. 2002) we assumed that the copper metal found at Brixlegg could be of local origin, although the chemical composition did not fit the local ores or even the metal prills in the slags. Now, with additional information from lead isotope analysis, it is clear that at least the metal strip from Brixlegg and several other Late Neolithic metal finds from central Europe cannot have been produced from the local ores. Rather, they are compatible with ores from the large copper deposit of Majdanpek in Serbia, and with contemporary or slightly earlier metal artefacts from southeastern Europe (Pernicka *et al*. 1997). The most plausible scenario is an influx of metallurgical knowledge from the east. Since the Münchshöfen culture has a number of typological parallels in the Carpathian basin, it is not unreasonable to suggest that the bearers of this culture either had strong links with this region or even originated from that location. Similar suggestions have already been made for a Neolithic axe from southern Scandinavia (Klassen and Pernicka 1988) and for the copper find from Schernau (Gleser and Schmitz 2001).

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