Provenance of the gold of the Early Bronze Age Nebra Sky Disk, Central Germany: geochemical characterization of natural gold from Cornwall

Article *in* European Journal of Mineralogy · December 2011

DOI: 10.1127/0935-1221/2011/0023-2140

3 authors, including:

Gregor Borg
Martin Luther University Halle-Wittenberg

Ernst Pernicka
Curt Engelhorn Zentrum Archäometrie and University of Heidelberg

Eur. J. Mineral.
2011, **23**, 895–910
Published online August 2011

Provenance of the gold of the Early Bronze Age Nebra Sky Disk, central Germany: geochemical characterization of natural gold from Cornwall

ANJA EHSER[1,*], GREGOR BORG[1] and ERNST PERNICKA[2]

[1] Institute of Geosciences, Martin-Luther-University Halle-Wittenberg, Von-Seckendorff-Platz 3, 06120 Halle (Saale), Germany
*Corresponding author, e-mail: anja.ehser@geo.uni-halle.de
[2] Curt-Engelhorn-Zentrum Archäometrie, D6, 3, 68159 Mannheim, Germany

Abstract: The Early Bronze Age Nebra Sky Disk, central Germany, comprises different types of gold inlays which have been plated and punched onto a bronze disk in three phases. The present study aims at provenancing the gold, used for the first phase, which includes gold sheets in the shape of a sun or full moon, a crescent-shaped moon, and 32 stars. The geochemical composition, determined by LA-ICP-MS, of one fragment of the sun sheet is compared with 66 native gold particles from six placer deposits and one lode gold deposit in Cornwall. The focus on Cornish gold deposits is based on results of previous provenance and tin isotope studies. The geochemical survey is performed using distinctive geochemical tracers (*e.g.,* Co, Ni, Cu, Ru, Pd, Ag, Sn, Sb, Ir, and Pt) which are characterized by high stability during geological and metallurgical processes. For Cornwall, the Carnon gold placers at the localities Devoran and Feock show different variations in Co, Ni, Pd, Ag, Sn, and Sb which correlate with the variation found in the gold from the sun sheet when mixed. This mixture would have been easily possible as both localities are located about three km apart from each other. Similar geochemical comparisons with natural gold from central and southeastern Europe, carried out in a previous provenance study, showed no similarity with the sun sheet. Differences in Cu and Pt contents between the Carnon gold placers and the sun sheet, which have also been detected for the previously studied gold deposits, question the relevance of mineral (micro) inclusions and accretions or unintended contamination with heavy minerals during processing. The results on the gold further led to the comparison of 18 Cornish copper ores with the bronze of the Nebra hoard using lead isotope ratios, which showed no correlation, excluding Cornwall as copper source. With the gold of the first phase of the Nebra Sky Disk being likely to originate from Cornwall, substantial metal trade from the British Isles towards central Germany during the Early Bronze Age must be assumed.

Key-words: LA-ICP-MS, provenance, gold, Nebra Sky Disk, Cornwall, copper, geochemical tracer.

1. Introduction

The Early Bronze Age Nebra hoard, which comprises the Nebra Sky Disk, two bronze swords decorated with gold cuffs, two flanged bronze axes, two bronze arm spirals and one bronze chisel, was discovered during an illegal excavation in 1999 AD on the Mittelberg in southern Sachsen-Anhalt, central Germany. Scientific investigations of the hoard and particularly of the Sky Disk initially concentrated on the authentication by mineralogical, trace element and lead isotope analyses of the bronze, the mineralogical and chemical composition of the corrosion layer and soil adhesions, as well as the technology of manufacture (Pernicka & Wunderlich, 2002; Pernicka *et al.*, 2008; Pernicka, 2010). More detailed investigations on the manufacturing technique were published by Berger *et al.* (2010) including the study of the 0.1–0.4 mm thin gold sheets that had been plated and punched onto the bronze disk, which measures about 32 cm in diameter. The gold inlays have been interpreted as a sun or full moon, a crescent-shaped moon, and 32 stars. Two of the stars were removed and the position of a third was changed when two horizon arches were later attached to the disk, followed by the final attachment of an arcuate boat or barge (Meller, 2003; Fig. 1). The constellation of the gold inlays suggests that the disk initially may have been used for calendrical purposes (Schlosser, 2003), making the Nebra Sky Disk the earliest astronomical representation of the night sky.

The archaeological context of the Sky Disk can be deduced from the accompanying finds in the hoard, which can all be dated to the Early Bronze Age in central Europe around 1600 BC, the classical Únětice Culture. This date of burial of the hoard was confirmed by ^{14}C analyses of a small piece of birch bark found in the handle of one sword. However, the date of manufacture of the Nebra Sky Disk remains unknown due to the lack of a suitable age dating method for metal objects. Because of

0935-1221/11/0023-2140 $ 7.20
DOI: 10.1127/0935-1221/2011/0023-2140

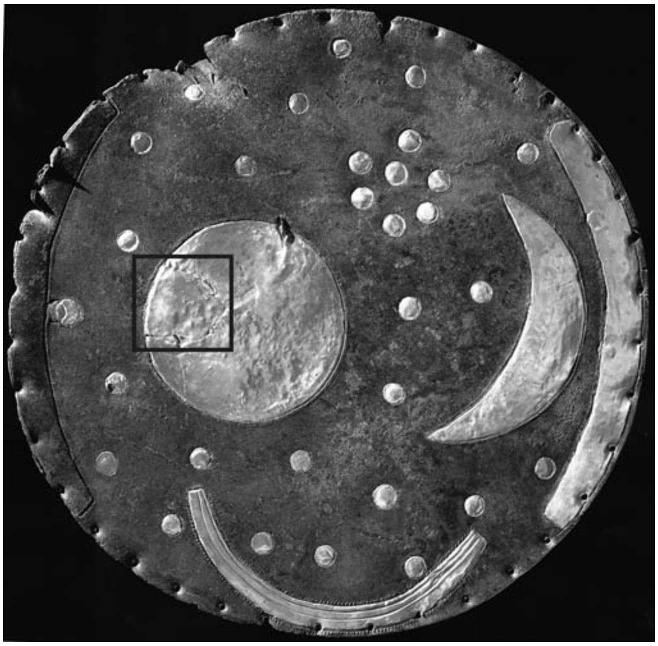

Fig. 1. Photograph of the Nebra Sky Disk, which measures about 32 cm in diameter (Photograph: Landesamt für Denkmalpflege und Archäologie Sachsen-Anhalt). The square indicates the fragment of the sun sheet that was analysed by LA-ICP-MS.

the uniqueness of the object, the geochemical analyses of all gold inlays were performed by non-destructive particle-induced X-ray emission (PIXE) and synchrotron radiation-induced X-ray fluorescence (SyXRF). The SyXRF analyses revealed that there are three types of gold on the Sky Disk, which suggests that the gold sheets were plated and punched to the disk in three phases, being distinguishable from each other by their Ag and Sn concentrations (Pernicka *et al.*, 2003; Gumprich, 2004). The gold inlays of the sun, the moon, and the original stars were attached in the first phase of manufacture, followed by the replacement of one star and the attachment of two horizon arches in the second phase and the attachment of the arcuate boat or barge during the third phase. These results corroborated visual and X-ray radiographic differences in the degree of perfection of work of the individual metallurgists (goldsmiths), the aesthetic concept of the design and the distinctly visible displacement of three stars (Berger *et al.*, 2010).

The present study aims to define the provenance of the gold, used for the first phase, following the results of previous provenance studies of the gold of the Nebra Sky Disk. Against this background, our new analytical data from seven Cornish gold deposits, determined by LA-ICP-MS, is presented and compared with the gold of the Nebra Sky Disk, using distinctive geochemical tracers. The results are evaluated with respect to archaeological evidence for Early Bronze Age mining in Cornwall, as well as Early Bronze Age trade and cultural exchange between western and central Europe. Additional correlations of Cornish copper ores with the bronze of the Nebra hoard, using Pb isotope ratios, question the relevance of Cornwall as source for the copper.

2. Previous provenance studies

During initial investigations on the provenance of the gold of the Nebra Sky Disk, the composition of the gold inlays was compared with gold artifacts and natural gold from various European regions. For the comparison with artifact gold, data from the systematic analytical investigations by Hartmann (1970, 1982) were used which includes analyses of more than 4000 European gold artifacts from the Chalcolithic to the Iron Age, using atom emission spectroscopy (AES). Hartmann used mainly the concentrations of Au, Ag, Cu, and Sn to define groups of gold artifacts with similar composition. The concentrations of Ni, Pt, Hg, Pb, and Bi could only be determined occasionally. The distribution of these material groups in space and time allowed him to discuss trade routes and make assumptions on the potential sources of the gold. Initial comparisons of the artifact gold of the Nebra Sky Disk with the data base of Hartmann (1970, 1982) showed the best geochemical correlation with his material group A3, excluding the arcuate boat or barge that correlates best with material groups L and Q respectively (Gumprich, 2004). The material group A3 is characterized by Ag concentrations of more than 20 wt% as well as a relative abundance at 0.3 wt% Cu and 0.012 wt% Sn. This type of gold is mainly found in southeastern Europe and subordinately in northern central Europe, suggesting that the gold deposits of the "Golden Quadrangle" in Romania could have been the source of the gold (Pernicka *et al.*, 2003). Looking at the data of the material group A3 in more detail, Borg (2010) subdivided this group further into A3 and A3D. The gold artifacts of the subgroup A3D occur particularly in northern central Europe ($n = 30$) and Cornwall ($n = 1$) and show a composition rather similar to the gold of the Sky Disk. The remaining artifacts of the initial group A3 ($n = 128$) occur mainly in southeastern Europe, in the region of the river Danube.

Since the studies by Hartmann (1970, 1982), more sensitive analytical methods have become available, notably inductively coupled plasma mass spectrometry combined with laser ablation (LA-ICP-MS) as the most suitable technique for the trace element analyses of gold. However, in the course of processing (sintering, melting) natural gold, changes can occur in the major, minor, and trace element composition as shown by Hauptmann *et al.* (1995) and Schmiderer (2009). Many prehistoric gold artifacts contain tin in concentrations of 0.01–0.1 wt% (Hartmann, 1970, 1982). Because of the generally rather different geochemical properties of tin and gold in natural geological environments, it was initially assumed that tin was either introduced through the addition of bronze or by melting alluvial gold containing cassiterite (SnO_2). The first assumption was apparently supported by the relatively high copper concentrations of most prehistoric gold objects (often more than 0.1 wt% Cu) compared with natural gold (less than 0.1 wt% Cu in general; Schmiderer, 2009). However, there is no significant positive correlation of tin and copper in Bronze Age artifacts so that elevated tin contents are more likely an indicator for gold originating from an alluvial environment (Hartmann, 1970). In placer deposits, native gold and tin in the form of cassiterite form a paragenetic association in the heavy mineral fraction, provided that both minerals are present in the catchment area of the stream or river. The behavior of gold and cassiterite during sintering and melting under changing conditions was studied by Eluère & Raub (1991) and Raub (1995), using alluvial as well as modern industrial gold (999.5 and 999.9 fineness) and cassiterite. The experiments show that impurities are not removed during sintering and that cassiterite is slagged under oxidizing conditions, while being efficiently converted to metallic tin under reducing conditions. Gumprich (2004) described similar results from melting experiments with industrial gold and cassiterite at a mass ratio of 100. Whether the elevated copper content of most gold artifacts can be considered to result from unintended alloying of natural gold with copper minerals and/or (micro) inclusions during processing still needs to be investigated. However, unintended alloying would explain relatively low concentrations of copper in prehistoric gold artifacts, which have hardly any recognizable influence on the specific characteristics of the gold (*e.g.,* color or hardness).

For the comparison of the gold of the Nebra Sky Disk with natural gold, a large number of potential prehistoric lode and placer gold deposits from western, central and southeastern Europe had to be characterized for their chemical composition. It was attempted to analyze as many elements as possible in order to identify distinctive geochemical tracers. While geochemical differences between the natural gold from certain gold deposits and the gold from the Nebra Sky Disk results in the exclusion of the deposit as potential metal source (*i.e.,* negative evidence), geochemical similarities are much more difficult to use as positive evidence for a particular metal source. However, supporting evidence can be achieved by further exclusion of other gold deposits as metal source and, additionally, by independent evidence from *e.g.* isotope studies or archaeological findings. A comprehensive study of natural gold from about 150 central and southeastern European placer and lode gold deposits by Schmiderer (2009) has shown that none of the investigated gold deposits showed a significant geochemical similarity with the artifact gold of the Nebra Sky Disk. These deposits also comprise regions in relatively close proximity to the region where the Nebra Sky Disk was buried *e.g.* the Thüringer Schiefergebirge in central Germany, as well as highly productive gold mineralized regions such as the Austrian Alps (Schmiderer, 2009). Based on these previous results, the present study expands the investigations of natural gold deposits to Western Europe with focus on Cornwall (see also Ehser *et al.*, 2010). This regional focus is based on a recent study of tin isotopes in both the bronze of the Nebra Sky Disk and European ore deposits by Haustein *et al.* (2010), which suggests that the tin in the bronze of the Nebra Sky Disk may originate from Cornwall.

3. Geological setting of Cornwall

The Cornubian ore field in southwest England is spatially associated with the roof zone of an elongated Variscan granite batholith (Dunham *et al.*, 1978; Willis-Richards & Jackson, 1989), of which five major cupolas are exposed (Fig. 2). The granite is hosted by folded and faulted Lower Devonian to Upper Carboniferous slates and sandstones that are intercalated by subordinate volcanic rocks (Willis-Richards & Jackson, 1989; Duff & Smith, 1992) and flanked to the south by the metamorphic and igneous complexes of Stuart Point and Lizard. Both the granite and the country rocks are cross-cut by felsic dykes and sills (''elvans''). The Cornubian ore field has been formed in three stages with respect to the emplacement of the batholith (Willis-Richards & Jackson, 1989). Following the subordinate pre-batholith stage, the syn-batholith or main stage of hydrothermal mineralization along the roof zone and margins of the major plutons took place between 295 and 270 Ma (Willis-Richards & Jackson, 1989). This stage developed the vast majority of metalliferous mineralization. Most of the metal production has been obtained from large and steeply-dipping fissure veins called ''lodes'' (Jackson *et al.*, 1989) that are commonly developed along fractures and originate as faults parallel to the longitudinal axes of the batholith. Some of the geologically earliest lodes also show a pegmatitic affinity. Replacement deposits in the form of pipes (''carbonas'') and sheets (''floors'') generally occur both in granite and hornfels envelopes in close proximity to the granite contact (Jackson *et al.*, 1989). Alteration commonly consists of kaolinization and tourmalinization within the hornfels envelopes. Both lode and replacement deposits contain cassiterite and Cu, As, Fe, and Zn sulphides (Jackson *et al.*, 1989) with quartz and minor feldspar, mica, tourmaline, chlorite, and hematite as major gangue minerals. Disseminated mineralization (sheeted vein systems, stockworks) occurs where extensive fracturing caused the mineralizing fluids to penetrate through country rock above the granite or the granite cupola. Fluorine-rich hydrothermal fluids at the margins of the lodes caused greisenization. These sheeted greisen-bordered vein swarms are characterized by wolframite and cassiterite with minor Sn, Cu, Fe, As, and Zn sulphides (Jackson *et al.*, 1989). Metasomatic deposits in the form of stanniferous lodes in altered greenstones do occur but are less common (Leveridge *et al.*, 1990). The source of the metals in the syn-batholith stage can be described as a mixture of direct magmatic derivation and assimilation or leaching from altered metal-rich Paleozoic (country) rock. The mineralizing fluids are of mixed magmatic, metamorphic and meteoric origin (Jackson *et al.*, 1989; Leveridge *et al.*, 1990).

The post-batholith stage of epithermal mineralization occurred in several phases between 220 and 210 Ma, 170 and 160 Ma, and at about 75 Ma (Jackson *et al.*, 1982) as a result of tectonic processes and/or erosion of the roof rocks

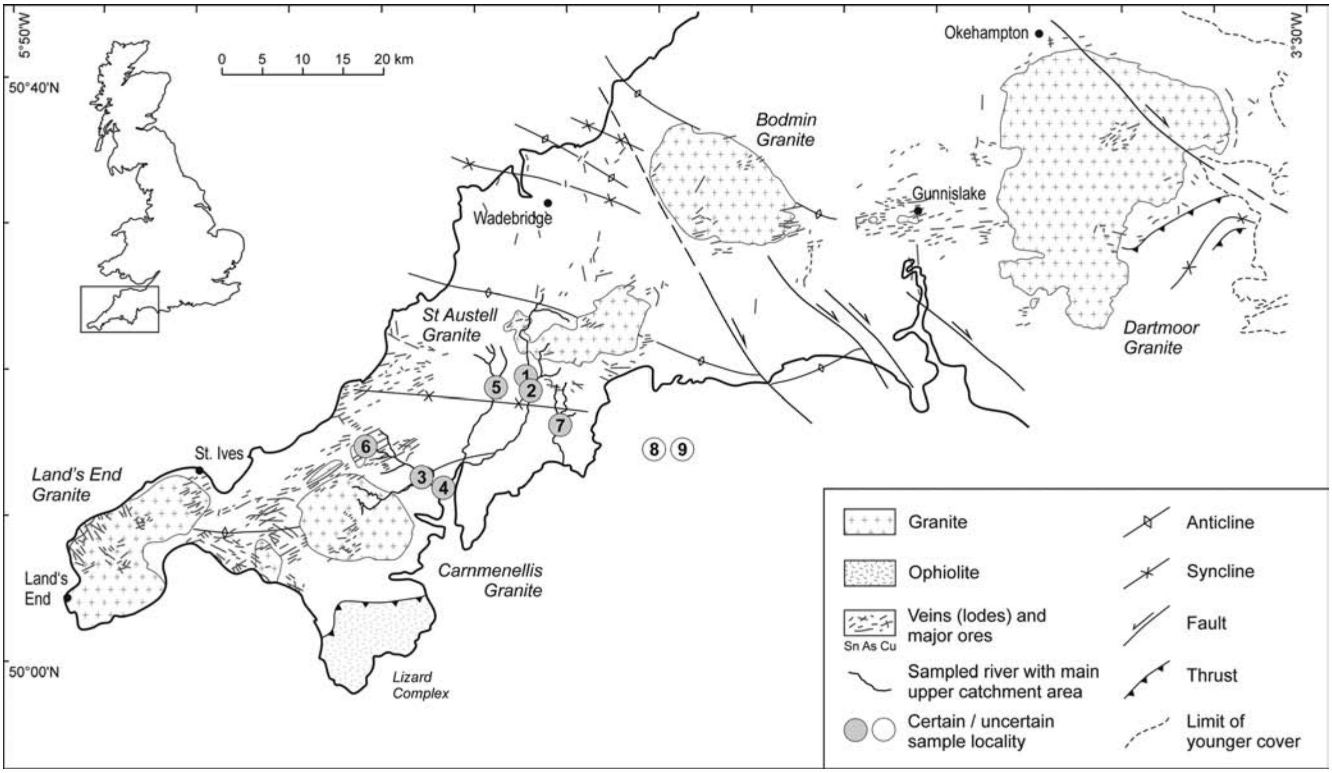

Fig. 2. Geological sketch map of Cornwall, modified after Dunham *et al.* (1978), showing the natural gold occurrences included in this study: (1,2) river Fal, Crow Hill; (3) river Carnon, Devoran; (4) river Carnon, Feock; (5) river Tresillian, Ladock; (6) St Day United Mines, Gorland; (7) river Luney, Polmassick; (8) undifferentiated placer, Cornwall 1; (9) undifferentiated placer, Cornwall 2.

(Jackson *et al.*, 1989; Duff & Smith, 1992). The high heat production of the batholith ensured a high heat flow during the Mesozoic and Cenozoic and promoted thermal convection of meteoric ground water (Jackson *et al.*, 1989). Vein mineralization generally occurs in north and north-west trending steeply-dipping faults called ''crosscourses'' that often cut and displace the lodes and have an influence on their mineral concentration as some lodes were formed through episodic injection of mineralizing fluids. The veins generally occur outside the main granite outcrops vertically above granite contacts and host most of the Pb, Ag, Sb, Ba, Zn, Fe, U, Co, Ni, and Au mineralizations (Jackson *et al.*, 1989). Quartz, chalcedony, carbonate, jasper, hematite, and clay are the main components of the veins. The gold is associated with Pb-Sb-(Au) and Au-Se-Pb-Ag-Hg mineralizations (Jackson *et al.*, 1989). Supergene enrichment of these zones formed auriferous gossans that are thought to be the main source of the alluvial gold (Duff & Smith, 1992) which can be found in considerable quantities in stream sediments, commonly together with cassiterite. The primary granite-hosted kaolinite (china clay) deposits of southwest England originate from hypogene and supergene processes which result from hydrothermal and epithermal activity, as well as deep tropical weathering during the Mesozoic and early Cenozoic (Jackson *et al.*, 1989). Records of production estimate a total output of 97 Mt of china clay compared with the major metals of tin with 2.5 Mt, copper with 2 Mt, iron with 2 Mt, lead with 0.25 Mt, arsenic with 0.25 Mt, and tungsten with 5600 t (Dunham *et al.*, 1978).

4. Methods

4.1. Experimental procedure

Full details of the laser ablation analysis of gold samples at the Curt-Engelhorn-Zentrum Archäometrie (CEZA) in Mannheim are given in Kovacs *et al.* (2009) and Schlosser *et al.* (2009). The analyses were carried out under ''wet conditions'' using a solid-state Nd:YAG laser operating at 213 nm (Microprobe II Laser Ablation System with later integrated LUV213 Laser, New Wave Research, USA) coupled to an XSeriesII quadrupole ICP-MS (Thermo Electron Corporation) with Collision Cell Technology (CCT). Details on the operating conditions for the ICP-MS and laser ablation systems are summarized in Table 1. Depending on the thickness of the gold sample, either a spot or a line ablation was performed (see Table 2) as gold of less than 150–200 μm thickness yields a very short signal if sampled in the drilling (spot) mode with the laser. A very short pre-ablation time (less than 3 s) was applied to the gold to prevent the influence of surface impurities on the measurements, since polished sections were available only for several natural gold samples. Au and Ag which were considered as major elements in the

Table 1. Operating conditions for the ICP-MS and laser ablation systems at the Curt-Engelhorn-Zentrum Archäometrie (CEZA), Mannheim.

ICP-MS		Laser ablation	
Instrument	Thermo XSeriesII	Laser ablation system	Microprobe II with LUV213, 213 nm
Nebulizer gas flow	0.8–0.9 L min^{-1} Ar	Pulse length	4 ns
Auxiliary gas flow	0.7 L min^{-1} Ar	Ablation frequency	4 Hz
Plasma/cool gas flow	13.0 L min^{-1} Ar	Spot size	50 m
Collision gas	6.0 mL min^{-1} Ar H_2-He mixture (8 % H_2, rest He)	Laser fluence or pulse energy	24–30 J cm^{-2}
RF power	1200 W		
Lens setting	L1 -1200; L2 -85.5; L3 -79.2; D1 -51.8; D2 -140; DA -65.1 V		
Biases	Slight KED (kinetic energy discrimination): Pole bias -12.9, Hexapole bias -13.0		
Detector mode	Dual		
Dwell time	10 ms		
Scan mode	Peak jump		
Carrier gas flow	0.8 L min^{-1} He		

Table 2. Laser operating conditions for the line and spot ablation modes used at the CEZA.

	Pre-ablation		Ablation	
	Line	Spot	Line	Spot
Duration (s)	20–40	<3	100–200	50
Length (μm)	300–600	–	300–600	–
Diameter (μm)	75	75	50	50
Energy (%)	30	40	45	100

gold samples were measured in high resolution mode to reduce the high signal intensity and diminish the influence of interferences. ^{63}Cu was used as internal standard in the liquid standard solutions. External drift correction and multiple calibration blocks using the Plasmalab software (Thermo) of the instrument were used for calculations. For ^{111}Cd, ^{115}In, and ^{125}Te, a correction factor had to be used due to interferences. The obtained results were normalized to 100 %. Accuracy and precision were controlled by repeat analyses of two commercial reference materials (NA1 and NA2) and found to be better than 8 and 5 %, respectively, for most of the determined elements (see Kovacs *et al.*, 2009). Two commercial jewelry gold alloys of different fineness (750 and 585) were also routinely analyzed for further quality control.

The lead isotope analyses of the sulphidic copper ores were also carried out at the CEZA using a double-focusing magnetic sector based multiple collector ICP-MS (Axiom, VG Elemental). The solid samples were decomposed by mineral acids and the sample solutions were cleaned by ion exchange chromatography to obtain a pure lead solution which avoids spectral interferences. The lead fraction was than diluted to a concentration of 200 ng ml^{-1} Pb in 2 % HNO_3 and doped with 50 ng ml^{-1} Tl for mass bias correction. ^{204}Pb was corrected for the isobaric interference with ^{204}Hg by measuring ^{202}Hg. SRM 981 was analyzed with the samples to monitor accuracy.

4.2. Artifact gold

Due to the size of the ablation cell and the uniqueness of the object, analyses were only carried out on one gold fragment of the sun sheet (see square in Fig. 1), representing the first type (phase) of gold that was plated and punched to the disk. To obtain an average composition, a total of 11 spot analyses on the obverse and reverse, as well as in one hole (center) of the fragment were carried out by Schmiderer (2009). For all elements determined, the median value and the interquartile range (IQR) were used in this study as both represent robust estimators when the data has no normal (Gaussian) distribution.

4.3. Natural gold

To characterize the commonly heterogeneous composition of each individual deposit as well as its gold particles (micro-nuggets), a minimum of ten particles per deposit as well as three spots or one line per particle were measured. The emphasis of the measurements was on the analyses of the trace element concentrations of the gold. Analytical results from locally identified natural mineral inclusions within the gold were recorded separately (for Pt and Pd see Fig. 3). To compare the natural gold with artifacts, this study aimed at selecting specific elements that are characterized by a high stability during geological (*e.g.,* fluvial transport) and metallurgical (*e.g.,* smelting) processes. The metals Co, Ni, Cu, Ru, Pd, Ag, Sn, Sb, Ir, and Pt seem to be best suited based on experimental and

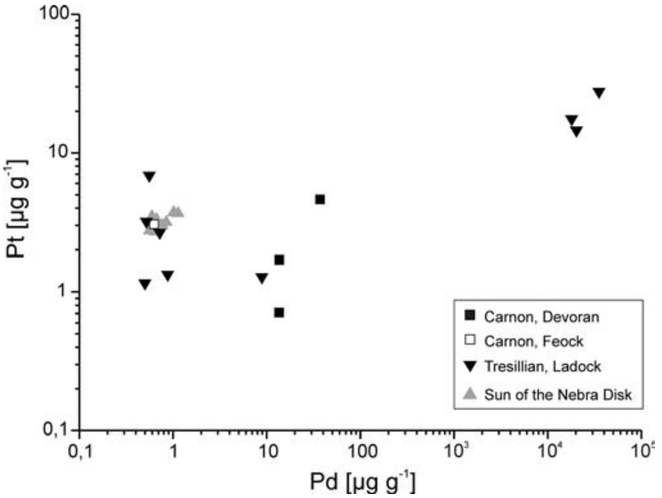

Fig. 3. Pt and Pd concentrations of the Cornish gold occurrences in comparison with the concentrations of the gold from the sun sheet of the Nebra Sky Disk (grey triangle).

analytical results of other studies (*e.g.,* Eluère & Raub, 1991; Raub, 1995; Hauptmann *et al.*, 1995; Guerra *et al.*, 1999; Bendall, 2003; Gumprich, 2004; Schmiderer, 2009). To assess the variation within a gold deposit, a large number of individual localities, as well as gold particles of, preferably, different size and morphology were analyzed. Schmiderer (2009) has shown that the spread of trace element concentrations between the leached rim and the center of a single natural gold particle, as well as within a deposit is usually less than between different gold deposits, which is essential for provenance studies of prehistoric and ancient gold. Another difficulty is the fact that artifacts can contain Cu as an alloy. Since Cu is commonly associated with Co, Ni, As, Se, Ag, and Sb, these elements cannot be used for comparison with natural gold in such cases. For the Chalcolithic and the Early Bronze Age, however, intentional alloying with copper can most likely be excluded. Whether Early Bronze Age artifacts were manufactured from one specific gold deposit without mixing and recycling of other natural or artifact gold is unknown. In view of the mostly large variations, the median of the analyses from each locality of one gold deposit is used for the comparison with artifacts. The use of the median value also reduces the influence of inclusions with aberrant values on the overall chemical composition of the mostly very pure natural gold.

The investigation on the source of the gold used for the Nebra Sky Disk required the establishment of a data base of the largest and historically most important European gold deposits. The study area was chosen according to the archaeological context and chemical comparisons with artifacts. The selection of gold deposits incorporated archaeological evidence or at least reasoning for prehistoric or ancient gold production through workings or corresponding settlements, as well as the recent gold potential of the deposit. Including the study by Schmiderer (2009), more than 200 lode and placer gold deposits were sampled by collecting natural gold in the field as well as from well-documented public and private mineralogical collections. The main geological domains where sampling has been carried out include (1) the Harz, Rheinisches Schiefergebirge, Thüringer Schiefergebirge, Erzgebirge, Bohemian Massive, Upper Rhine Valley, Eastern Alps, and Western Carpathians in central Europe, (2) the Eastern Carpathians (Baia Mare district), Apuseni Mountains, and Southern Carpathians (Banat districts) in southeastern Europe, and 3) Cornwall, the Scottish Northwest Highlands and the western Iberian Massive in Western Europe. For Cornwall, sampling mainly focused on the most important gold placers already described by Calvert (1853) and Lehrberger (1995). In total, 66 grains of native gold from six placer deposits, including two placer deposits of unknown Cornish origin but with a mineral assemblage of tin and gold, as well as two grains from one macro sample of a lode gold deposit (Fig. 2) were collected from the mineralogical collection of the Royal Cornwall Museum (RCM) in Truro.

5. Results and discussion

5.1. Gold of the Nebra Sky Disk

Of the 59 elements measured in the sun sheet of the Nebra Sky Disk by Schmiderer (2009), 33 show median concentrations of at least 0.1 µg g^{-1} (Table 3). These include elements, such as Ti, V, Cr, Mn, and Co, which tend to partition into the slag during melting and show concentrations of less than 1.0 µg g^{-1} (V, Cr, Co) and 5.0 µg g^{-1} (Ti, Mn) in the sun sheet. Similarly low concentrations of less than 1.5 µg g^{-1} can be observed for the highly volatile elements As, Se, and Te. In contrast, the median Hg concentration is 820 µg g^{-1}. However, Hg can only be used as an indicator for a possible mineral assemblage of gold and mercury in the associated deposit due to the bad reproducibility of Hg in LA-ICP-MS measurements (see Sarah, 2008). From the Platinum Group Elements (PGE), only Ru, Pd, and Pt show concentrations of at least 0.1 µg g^{-1} with Pt being most enriched in the sun sheet. From the minor and trace elements that have also been determined in the studies of Hartmann (1970, 1982), Cu and Ag are found in concentrations of 5200 µg g^{-1} (Cu) and 25 wt% (Ag) in the sun sheet. The relatively high Sn concentration (300 µg g^{-1}) suggests that the gold may have been produced from alluvial gold by sintering or melting under reducing conditions (Gumprich, 2004). As similar median Sn contents have also been determined by SyXRF in the gold of phases two (510 µg g^{-1}) and three (350 µg g^{-1}) of the Nebra Sky Disk, this can be assumed for all gold inlays of the Sky Disk. Differences in the distribution of the concentrations between the obverse and reverse, as well as the center of the fragment can be detected for Cu and Sn that show median contents of 4400 µg g^{-1} (Cu) and 160 µg g^{-1} (Sn) on the obverse

Table 3. Major, minor, and trace element concentrations (median and interquartile range (IQR)) of the gold from the sun sheet of the Nebra Sky Disk after Schmiderer (2009). Values (in μg g^{-1}) are averaged from 11 spot analyses.

Element	Median	IQR	Element	Median	IQR	Element	Median	IQR
Ti	2.7	2.2–8.6	As	1.4	0.6–1.6	Sb	6.6	3.8–7.0
V	0.5	0.4–0.6	Se	1	0.4–1.3	Te	0.7	0.7–0.8
Cr	0.2	0.2–0.6	Rb	0.4	0.4–0.6	I	22	21–30
Mn	4.3	3.8–5.0	Sr	0.4	0.2–0.4	Ba	0.4	0.3–0.6
Fe	58	52–74	Mo	0.2	0.2–0.3	Sm	0.2	–
Co	0.5	0.4–0.5	Ru	0.1	–	W	0.1	0.0–0.3
Ni	8.3	7.5–9.2	Pd	0.7	0.6–0.8	Pt	3	2.8–3.4
Cu	5200	4800–5400	Ag	25 wt%	24–25 wt%	Au	74 wt%	74–75 wt%
Zn	23	13–28	Cd	0.3	0.0–1.2	Hg	820	650–1400
Ga	0.5	0.4–0.5	In	0.4	0.4–0.6	Pb	2.2	1.4–2.9
Ge	1.3	1.3–1.6	Sn	300	210–340	Bi	0.6	0.3–0.7

compared with 5500 μg g^{-1} (Cu) and 250 μg g^{-1} (Sn) on the reverse and 5200 μg g^{-1} (Cu) and 350 μg g^{-1} (Sn) in the center. In addition, the median concentrations of Zn, Sb, Hg, and Pb are about twice as high in the center (28 μg g^{-1} for Zn, 7.2 μg g^{-1} for Sb, 1500 μg g^{-1} for Hg, and 2.6 μg g^{-1} for Pb) compared with both sides. As described by Gumprich (2004), these differences could be the result of electrochemical reactions between gold and bronze (Pernicka & Wunderlich, 2002) or, more likely, of selective corrosion since the time of the disk's burial where base metals such as Cu in the form Cu^{2+} are removed by aqueous solution from the surface of the gold inlays (Kaesche, 1990).

To illustrate the total variation in composition of gold from the first phase, as well as the geochemical differences to the subsequent phases of the Nebra Sky Disk, the SyXRF results by Pernicka *et al.* (2003) have to be used. Analyses of the first phase include three from the sun or full moon, two from the crescent-shaped moon, and 30 from the remaining initial 29 stars. For the major and main elements Au and Ag, the median concentrations are 79 wt% (Au) and 21 wt% (Ag) with a total range for both of 1 wt%. The Sn and Cu concentrations of 0.016 wt% for Sn and 0.31 wt% for Cu exhibit a total range of 0.021 wt% (Sn) and 0.32 wt% (Cu), which is relatively high compared to Au and Ag. Geochemical differences to the gold of the second phase can only be found in the Sn content, which is in the median 0.051 wt% with a total range of 0.057 wt%. The second phase is represented by one replaced star, which also shows a lower degree of perfection of work compared to the initial stars (Berger *et al.*, 2010), and one of the initial two horizon arches. Gold of the third phase, which comprises the arcuate boat placed unusually close to the surrounding stars, shows Sn concentrations of 0.035 wt% which ranges in between the concentrations found in the earlier phases. However, the gold of the third phase can be discriminated from the earlier phases by its low Ag (13 wt%) and high Au (86 wt%) contents, suggesting a different source of gold to be used.

5.2. Characteristics of Cornish natural gold

As described earlier, the focus on Cornish gold deposits is based on the results of a recent provenance study by Haustein *et al.* (2010), without excluding the importance of additional geochemical investigations on other prehistorically important gold deposits in western, as well as the remaining parts of central and southeastern Europe. Looking at the chemical composition of Cornish natural gold, of the 10 elements selected as geochemical tracers for provenance definition, the PGE generally show concentrations below the detection limit, namely 0.1 μg g^{-1} for Ir, 0.2 μg g^{-1} for Ru, and 1.0 μg g^{-1} for Pd and Pt. However, alluvial gold from the river Carnon yields detectable Pd and subordinate Pt concentrations in two gold particles from the locality Devoran (Fig. 3). The remaining gold particles from this locality carry Pd concentrations of up to 37.0 μg g^{-1}, except for one detected mineral inclusion, which contains up to 117.0 μg g^{-1} Pd in association with elevated Pb, As, Bi, and Sb contents. In contrast, natural gold from the locality Feock contains only minor Pd and Pt concentrations. The largest variation in Pd and Pt concentrations can be found in gold placers from the river Tresillian (Fig. 3), which is further characterized by two gold particles containing Pd-(Pt) inclusions with 1.8–3.5 wt% Pd.

Apart from the PGE, Cornish natural gold shows large variations in Ag with concentrations of more than 30 wt% found in both lode and placer gold deposits (Table 4). Placer gold containing Ag in concentrations around and below 5 wt% is also most enriched in Sn, ranging between 290 and 460 μg g^{-1}. The Sb content in all analyzed gold occurrences is generally less than 10 μg g^{-1} whereas median Co and Ni concentrations are generally less than 1.0 μg g^{-1} (Co) and 2.0 μg g^{-1} (Ni). The only analyzed lode gold deposit (St Day United Mines, Gorland) can be best discriminated from the placer gold deposits by its high median Pb content of 1500 μg g^{-1}. Together with the relatively high Ag concentration (31 wt%), this suggests

Table 4. Selected major, minor, and trace element concentrations (median and interquartile range (IQR)) of the Cornish gold occurrences. All samples are from the Royal Cornwall Museum (RCM), Truro.

Locality	Deposit	RCM Inv. no.	No. of grains	No. of analyses	Co $\mu g\ g^{-1}$	Ni $\mu g\ g^{-1}$	Cu $\mu g\ g^{-1}$	Pd $\mu g\ g^{-1}$	Ag wt%	Sn $\mu g\ g^{-1}$	Sb $\mu g\ g^{-1}$	Pt $\mu g\ g^{-1}$	Au wt%	Pb $\mu g\ g^{-1}$
Fal 1 (Crow Hill)	Placer	600.15 a	8	24										
Median					0.2	1.5	190	0.3*	12	21	4.5	0.3*	87	6.5
IQR					0.2–0.4	0.8–3.4	99–650	–	2.7–19	7.8–36	1.8–21	–	81–97	4.2–50
Fal 2 (Crow Hill)	Placer	600.15 b	9	26										
Median					0.4	1.4	220	0.3*	8.8	10	5.1	0.3*	90	140
IQR					0.3–3.6	1.1–49	140–340	–	5.9–15	5.2–23	2.4–11	–	84–94	81–290
Carnon (Devoran)	Placer	801.853	7	19										
Median					6.1	77	1100	5.9	5.3	350	5.2	0.3*	91	990
IQR					2.7–27	9.4–140	1000–1600	2.0–14	3.8–7.6	110–580	2.7–9.3	–	87–94	300–1700
Carnon (Feock)	Placer	801.854	14	42										
Median					0.2	1.3	22	0.3*	33	40	0.9	0.3*	67	1.3
IQR					0.1–0.3	0.6–2.0	15–98	–	19–36	11–83	0.6–2.7	–	64–81	0.5–3.6
Tresillian (Ladock)	Placer	801.6251	15	39										
Median					0.0**	1.1	92	0.3*	20	7.8	2.5	0.3*	80	3.9
IQR					–	0.5–2.8	7.3–310	0,3*–1.0	4,0–27	2.0–47	0.3–8.3	0.3*–2.0	73–96	1.1–23
Luney (Polmassick)	Placer	1985.2.1	9	26										
Median					0.0**	0.9	180	0.3*	9	8.3	2.3	0.3*	91	16
IQR					0.0**–0.5	0.3–4.4	120–350	0.3*–1.4	7.4–10	3.6–23	0.3–22	–	90–93	1.7–42
St Day United Mines (Gorland)	Lode	1977.17.1	2	2										
Median					2.4	15	770	0.3*	31	20	28	0.3*	68	1500
IQR					2.3–2.5	14–15	700–830	–	30–31	18–22	24–31	–	67–68	1400–1600
Cornwall 1	Placer	801.625	16	39										
Median					0.3	1.2	390	0.3*	3.8	460	2	0.3*	95	1.4
IQR					0.2–1.3	0.7–7.8	280–560	–	3.1–5.5	130–820	1.0–3.2	–	94–97	0.6–16
Cornwall 2	Placer	1903.1.82	17	48										
Median					0.3	1.7	340	0.3*	5.3	290	2.9	0.3*	95	2.1
IQR					0.2–0.6	1.2–7.8	270–490	–	4.0–7.3	130–670	1.6–4.6	–	92–96	0.7–11

Notes: *value represents ¼ of the detection limit as the majority of the analyses were below the detection limit of 1.0 $\mu g\ g^{-1}$
**value represents ¼ of the detection limit as the majority of the analyses were below the detection limit of 0.1 $\mu g\ g^{-1}$

that the gold most likely originated from an Au-Se-Pb-Ag-Hg mineralization rather than a Pb-Sb-(Au) mineralization. The mineral assemblage of the fibrous lode gold aggregates, however, comprises hematite, with quartz and minor carbonate as gangue. Similarly high Pb (990 μg g^{-1}) but lower Ag (5.3 wt%) contents were detected in gold from the river Carnon gold placer at the locality Devoran. The natural gold from this locality also has the highest total level of trace elements of all analyzed Cornish gold occurrences. The Cu concentrations of the Cornish gold occurrences are generally less than 0.1 wt% with only single spot analyses reaching up to 3200 μg g^{-1} (Cornwall 1).

5.3. Provenance of the artifact gold

In the course of the investigations on the source of the gold used for the Early Bronze Age Nebra Sky Disk, the trace element patterns of approximately 150 gold deposits from central and southeastern Europe were statistically grouped in two cluster analyses, using the logarithmic data, and compared with the gold from the sun sheet by Schmiderer (2009). The variables used for the two cluster analyses by Schmiderer (2009) were Cr, Mn, Ni, Zn, Ag, Sb, Te, and Bi as well as the PGE (Rh, Pd, Os, Ir, and Pt) which differ from the geochemical tracers used in this study where the focus has been put on the geological and metallurgical stability of the elements. In the study by Schmiderer (2009), no convincing similarity between gold deposits from both groups and the sun sheet of the Nebra Sky Disk was observed. The deposits that provided the best match in his comparison include two lode gold deposits from the ''Golden Quadrangle'' in the Romanian Apuseni Mountains, Roşia Montană and Topliţa-Măgura. From the placer gold deposits, the river Schwarza in the Thüringer Schiefergebirge and the upper river Rhine at the locality Rosenau showed the best match with the gold from the sun sheet. To validate the results from Schmiderer (2009), the four gold deposits were again compared with the sun sheet of the Nebra Sky Disk using the element suite proposed in this study (Co, Ni, Ru, Pd, Ag, Sn, Sb, Ir, and Pt). In our comparison, differences for the two placer gold deposits can be observed in the median Sn and/or Ag contents (Fig. 4). These reach up to 15 wt% Ag and 230 μg g^{-1} Sn for the upper Rhine and up to 15 wt% Ag and 11 μg g^{-1} Sn for the Schwarza alluvial gold, compared with 25 wt% Ag and 300 μg g^{-1} Sn for the gold from the sun sheet. The relatively high Sn content of alluvial gold from the upper Rhine at the locality Rosenau is confirmed by the additional identification of cassiterite accretions (Schmiderer, 2009). The low Ag content, however, can also be found in alluvial gold from other localities of the Upper Rhine Valley. These include Istein (up to 13 wt% Ag) or Kleinkems (8.3 wt% Ag) that are located opposite and 5 km downstream from the locality Rosenau respectively. Mixing of alluvial gold from the Upper Rhine Valley to form the gold from the sun sheet can, therefore, be excluded. The two lode gold deposits from the ''Golden Quadrangle'' show significant geochemical differences in

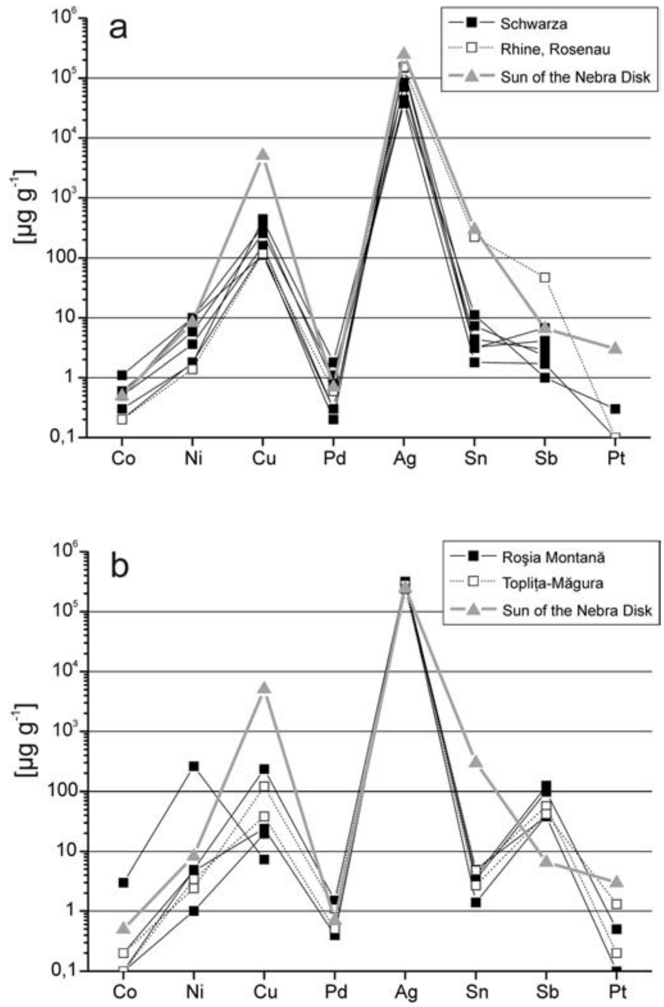

Fig. 4. Minor and trace element concentrations (median) of the gold occurrences in central (a) and southeastern (b) Europe that result from cluster analysis by Schmiderer (2009), in comparison with the composition of the gold from the sun sheet of the Nebra Sky Disk (grey triangle).

their Sn and Sb contents compared with the gold from the sun sheet (Fig. 4b). The median of the Ag concentrations in both deposits, however, is similarly high, namely 24 wt% (Topliţa-Măgura) and 32 wt% (Roşia Montană). Overall, the initial assumption that the ''Golden Quadrangle'' may have been the source for the gold of the Nebra Sky Disk is not supported by the present investigations.

For Cornwall, the comparison of natural gold with gold from the sun sheet (Fig. 5) shows similar Co and Ni concentrations, as found in the gold deposits discussed for central and southeastern Europe. Because of the detection limit for Pd of 1.0 μg g^{-1}, Pd concentrations of 0.7 μg g^{-1}, found in the sun sheet, were only detected by single spot analysis in Cornish natural gold. However, Pd could be detected in all placer gold deposits in the range of 0.5 μg g^{-1}–3.5 % (Tresillian). The median Sb concentrations of Cornish gold placers are between 1.4 and 5.7 μg g^{-1} below the concentrations found in the sun sheet, which is comparable with the differences found in the river Schwarza gold

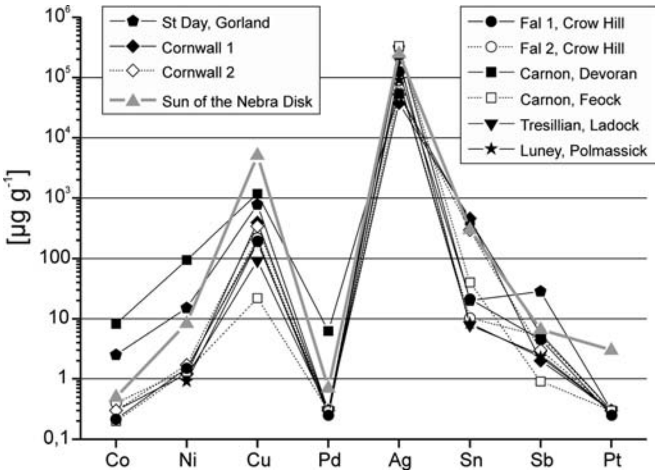

Fig. 5. Minor and trace element concentrations (median) of the Cornish gold occurrences in comparison with the composition of the gold from the sun sheet of the Nebra Sky Disk (grey triangle).

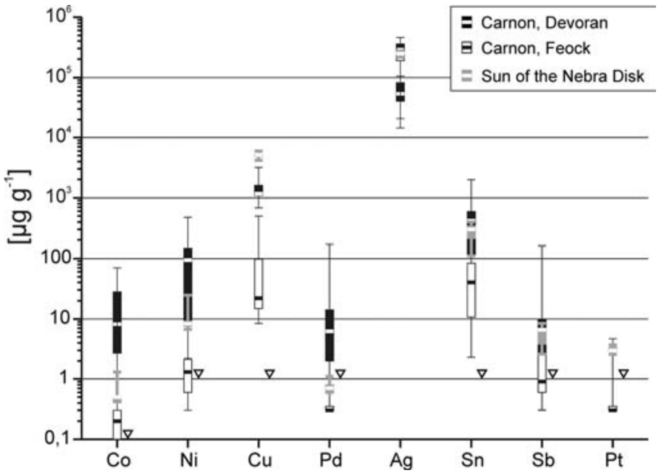

Fig. 6. Minor and trace element variations (maximum value, upper quartile, median, lower quartile, minimum value) of the river Carnon gold samples in comparison with the variation of the gold from the sun sheet of the Nebra Sky Disk (grey). Triangles indicate detection limits of the natural gold analyses. Detection limits of the artifact gold analyses are given in Schmiderer (2009).

placers. Similar to the alluvial gold from the upper river Rhine, three Cornish gold placers show Sn concentrations between 290 and 460 µg g^{-1}, the range found in the gold from the sun sheet. These three placer gold deposits also contain the lowest Ag concentrations, ranging between 3.8 and 5.3 wt%. However, when looking at each of the six placer gold deposits, the river Carnon comprises a population of high Sn (350 µg g^{-1}) and low Ag (5.4 wt%) content found at the locality Devoran, as well as relatively low Sn (40 µg g^{-1}) and high Ag (33 wt%) content found at the locality Feock. As both alluvial gold placers are located about three km apart from each other, mixing is easily possible.

The overall variation of element concentrations in alluvial gold from the river Carnon is illustrated in Fig. 6, where the range between the minimum and maximum value of the natural gold is up to three orders of magnitude compared with one order of magnitude for the interquartile range. The geochemical variation of the sun sheet ranges in between the variations of the two gold placers, partly also overlapping with the alluvial gold. A mixture of both localities results in a close correlation of the Carnon gold placers with the sun sheet. Only Cu and Pt are found in lower concentrations in the alluvial gold compared with the artifact gold, although some spot analyses reach up to 2200 µg g^{-1} for Cu and 4.6 µg g^{-1} for Pt in gold from the river Carnon at the locality Devoran. Similarly low median values of Cu and Pt in comparison with the gold of the Nebra Sky Disk have been detected for gold deposits in central and southeastern Europe (see Schmiderer, 2009). This observation again brings up the question concerning the relevance of mineral (micro) inclusions and accretions or unintended contamination with heavy minerals during processing. Nevertheless, with regard to the investigations already conducted, natural gold from the river Carnon provides a much better fit with the gold from the first phase of the Nebra Sky Disk compared with the previously studied natural gold from central and southeastern Europe. This result might seem to be in conflict with the geographical distribution of the gold artifacts of material group A3 (of Hartmann, 1970, 1982) or the new subgroup A3D (of Borg, 2010). However, these considerations were based on – at the time – existing artifact analyses, prior to the study of natural gold deposits. In the material group A3 or the new subgroup A3D, only one Cornish gold artifact can be identified: the Rillaton gold cup from Rillaton near Minios or more precisely one part of the Rillaton gold cup, the handle (no. Au3114 in Hartmann, 1982). The different compositions of the handle and the cup suggested the handle to have been applied later (Hartmann, 1982). The composition of the cup (Table 5) correlates with the material group Q2, which is characterized by a relative

Table 5. Major, minor, and trace element concentrations (in wt%) of the Rillaton cup and handle from Rillaton near Minios, Cornwall, after Hartmann (1982).

No.	Locality	Object	Ag	Cu	Sn	Ni	Sb
Au3113	Rillaton near Minios, Cornwall	Cup	*ca.* 10	0.7	0.2	0.02	tr
Au3114	Rillaton near Minios, Cornwall	Handle of the cup	*ca.* 25	0.38	0.082	tr	–

abundance at 0.8 wt% Cu and is found more abundant in Germany compared with the British Isles.

Cultural relationships between northwestern and central Europe during the Bronze Age were originally pointed out by Billig (1957) and were subsequently emphasized by Cowie (2004) who also drew attention to the stylistic similarities of the gold cuffs from the swords of the Nebra hoard with objects from the British Isles (Metzner-Nebelsick, personal communication). Other parallels can be found with Early Bronze Age disks from the British Isles that show close decorative similarities with some Únětice raquet-headed pins suggesting that they carry some of the central European traits arising with later Beaker types (Clarke, 1970; Taylor, 1980; Eluère, 1983). Contacts between northwestern and central Europe are further documented by stray finds from the less gold-rich regions of the Netherlands, Germany (*i.e.,* lunulae from Schulenburg and Butzbach), Denmark and Poland (basket-earrings). The distribution pattern of these gold objects along the periphery of the Únětice Culture, as well as the ''Blechkreis'', supports the existence of relationships between both regions. For the area around Devoran and Feock, Crawford (1921) and Shell (1978) pointed out Early Bronze Age ''tin trade'' routes from Ireland and the British Isles to Brittany and continental Europe, which are, in the east, from Harlyn Bay to the present channel south of St. Austell (Crawford, 1921) and, in the west, from St. Ives Bay to Marazion (Shell, 1978).

5.4. Carnon tin stream works

In the Falmouth district, the main types of mineralization (primarily Sn, Cu, Pb, As, Zn, W, and Au) are lodes, replacement ore bodies, disseminated mineralizations, greisen-bordered bodies, veins of pegmatitic affinity and minor metasomatic deposits (Leveridge *et al.*, 1990). The zone of mineralization occurs north of the Carnmenellis granite and includes the Carn Brea and Carn Marth granites as well as numerous elvans. The tin lodes that are associated with these granites are some of the most important of the peninsula (Pearce, 1983) and are extensively cut by

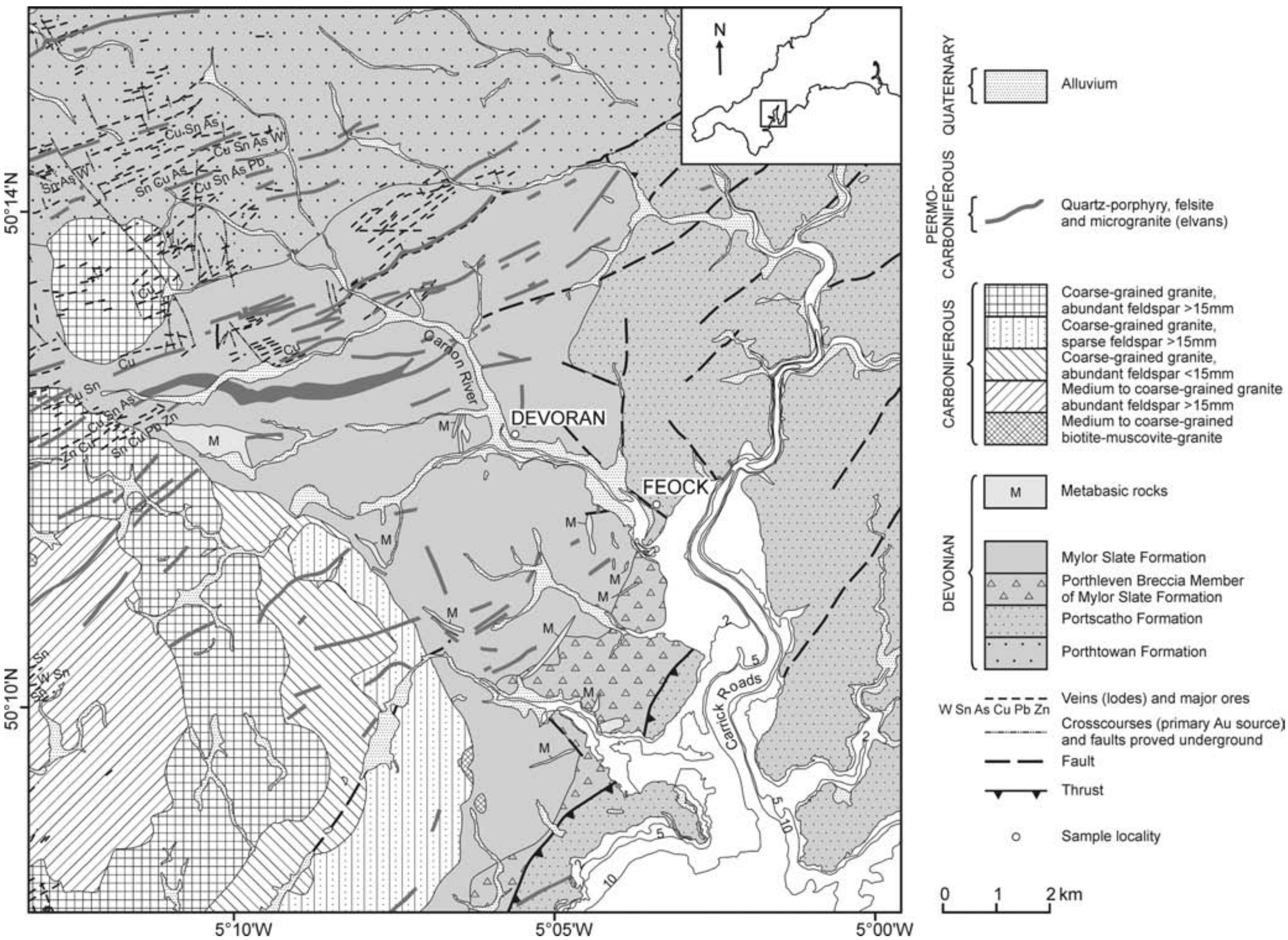

Fig. 7. Geologic map of the catchment area of the river Carnon including the Carn Marth granite and parts of the Carnmenellis granite, modified after the British Geological Survey (1990, Geology of the country around Falmouth). The Carrick Roads estuary is shown with its -2 m, -5 m, and -10 m depth contours, modified after the United Kingdom Hydrographic Office (2003, Admiralty charts of the River Fal: Falmouth to Truro).

crosscourses, contributing to the wide-spread alluvial deposits in this region (Fig. 7).

The river Carnon is thus one of the best known alluvial tin deposits in Cornwall (Penhallurick, 1986) and carries significant amounts of gold compared with other Cornish tin stream works (Pearce, 1983; Lehrberger, 1995). As a consequence, the alluvial gold in the Carnon may have acted as a stimulus to alluvial tin miners in prehistoric times (Penhallurick, 1986) who concentrated their attention on the lower valleys. The gold and tin was most enriched in the ''tin ground'', which typically rests on top of the solid rock of the valley floor (Penhallurick, 1986) and can reach up to 3.5 m thickness at the Carnon (Murray, 1859). Evidence for workings from the Early Bronze Age is given by one flat axe and two antler picks found on the ''tin ground'' of the Carnon riverbed (Penhallurick, 1986). However, the amount of recovered gold is unknown, whereas the total amount of gold in all Cornish tin streams has been estimated at 1.25 t by Penhallurick (1986). In the lower valleys, the Bronze Age tin miners were also confronted by a ''tin ground'' buried at considerable depth by variably thick layers of fluviatile and, near the sea, marine sediments (Penhallurick, 1986). At the Carnon, this cover measures between 12 and 15 m (Penhallurick, 1986). However, based on an estimated Late Holocene relative land subsidence/sea level rise of 1.12 mm yr^{-1} for Cornwall (Shennan & Horton, 2002), the Early Bronze Age shore line has been about 4.5–4 m lower compared with the present sea level. Other studies by Waller & Long (2003) have estimated the mean sea level in Cornwall to have been –4 m ODN (Ordnance Datum Newlyn) at about 3100 BC, having slowed down in the rate of rise to about –3 to –2 m ODN during the Early Bronze Age. With a sea level decrease of at least 2–4 m, the present fluviatile drainage system of the rivers Carnon, Tresillian, and Fal into the Carrick Roads estuary would have been largely exposed as flat marshes or flood plains with a narrowly incised river course in the Early Bronze Age (Fig. 7). As a result, this drastically different topography had a far greater potential for extractable alluvial gold from the prospective riverbeds and alluvial terraces compared with the present-day situation.

The investigated gold particles from the Carnon gold placers show a maximum diameter between 2.5 and 6.5 mm at the locality Devoran and between 0.5 and 1.5 mm three km downstream at the locality Feock. The average thickness of the gold particles ranges at 2.1 mm (Devoran) and 0.35 mm (Feock). Using the morphological characteristics by Townley *et al.* (2003), the alluvial gold from the locality Devoran shows a rectangular shape and abundant cavities with an irregular outline and a rugged surface. There is clear evidence for primary crystal imprints and associated gangue minerals comprise quartz and minor iron oxides. In contrast, alluvial gold from the locality Feock is characterized by oval to elongated rather than rectangular shapes, as well as a regular to minor irregular outline. The surfaces are generally smooth but dominated by small impacts and minor cavities. There is some evidence of folding, welding and minor hammering of the

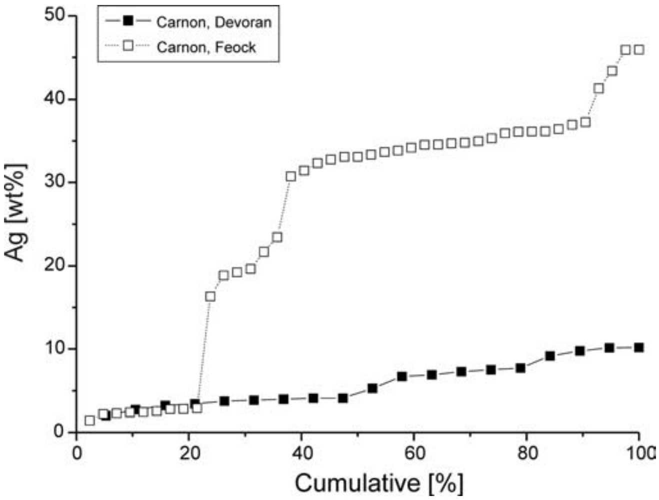

Fig. 8. Comparison of Ag contents of populations of placer gold particles from the river Carnon. One gold particle generally comprises three spot analyses.

gold particles. Primary imprints are diffuse but mostly absent and the only associated gangue mineral is quartz, where present. These observations imply the alluvial gold from the locality Devoran to be located in the direct vicinity of its primary source whereas the alluvial gold from the locality Feock has most likely been transported for some distance, at least for 300–1000 m using the criteria by Townley *et al.* (2003).

The Ag content of the population of placer gold from the Carnon is between 2.0 and 10 wt% at the locality Devoran and between 1.4 and 46 wt% at the locality Feock (Fig. 8). The low Ag contents and compositional range of placer gold from the locality Devoran, together with the uniform morphology of the gold particles, suggest the gold to originate from a single source. At the locality Feock, the analyzed placer gold has a wide range of Ag contents, as well as a number of plateaus in the corresponding cumulative curve. About 20 % of the population (particles 2, 5, and 8 in Table 6) show Ag contents between 1.4 and 2.9 wt% with corresponding Cu contents in the range of 74–500 μg g^{-1}, possibly representing the population found at the locality Devoran. The gold particles found at the locality Feock are characterized by relatively large maximum diameters of about 1.5 mm with rectangular shapes but regular outlines. The remaining 80 % of the population at this locality show Ag contents between 16 and 46 wt% with each plateau in the cumulative curve to be distinguishable further by individual gold particles. These include particles 9 and 10 for the range from 16 to 23 wt% Ag and particles 1, 3, 4, 6, 7, 11, 12, 13, and 14 for the range from 31 to 46 wt% Ag. As the morphological characteristics are similar for all particles, including a maximum diameter between 0.5 and 1.5 mm with oval to elongated shapes and regular to minor irregular outlines, differential leaching of silver from the gold particles can be suggested. This could possibly result from second-cycle liberation of gold from Tertiary regolith (terraces), which has been described for cassiterite placers in the same

Table 6. Selected major, minor, and trace element concentrations of alluvial gold from the river Carnon gold placer.

Locality	Sample no.	Co $\mu g\ g^{-1}$	Ni $\mu g\ g^{-1}$	Cu $\mu g\ g^{-1}$	Pd $\mu g\ g^{-1}$	Ag wt%	Sn $\mu g\ g^{-1}$	Sb $\mu g\ g^{-1}$	Pt $\mu g\ g^{-1}$	Au wt%	Pb $\mu g\ g^{-1}$
Devoran	01a	43	240	1130	16	7.5	440	5.2	<1	85	1300
	01b	43	130	1030	14	7.7	140	12	<1	85	4800
	01c	3.3	2.2	1160	<1	6.9	61	14	<1	91	7200
	02a	20	230	1410	12	4.1	410	5.4	<1	92	590
	02b	1.1	2.3	1600	<1	3.2	135	3.4	<1	96	92
	03b	46	160	1100	5.1	2	36	3.4	<1	95	160
	03c	5.6	110	1250	2.4	2.7	48	2.4	<1	95	230
	04a	3.1	18.5	1130	6.2	10	600	6.2	<1	88	1500
	04b	2.3	5.7	810	1.1	10	300	2.3	<1	89	380
	04c	65	340	630	5.9	9.8	1900	24	<1	83	2000
	05a	1.3	5.2	1600	1.3	4.1	780	3.9	<1	95	1060
	05b	6.1	77	2200	120	3.4	350	110	<1	65	280000
	05c	33	450	2200	14	4	650	19	0.7	90	2900
	06a	18	130	960	10	9.2	400	5.4	<1	87	990
	06b	1.7	20	1110	1.7	6.7	38	0.9	<1	93	120
	06c	8	93	1050	2.3	7.3	270	6.8	<1	90	1200
	09a	12	65	1600	14	3.9	560	1.7	1.7	94	510
	09b	5.4	13	2100	37	5.3	850	3.1	4.6	93	790
	09c	<0.1	5.3	1050	5.3	3.7	94	<1	<1	96	54
Feock	01a	0.1	0.9	110	<1	34	139	1.1	<1	66	0.6
	01b	0.5	1.4	17	<1	36	67	3.2	<1	64	1.2
	01c	0.2	1.4	20	<1	35	130	2.2	<1	65	3.4
	02a	0.1	12.3	440	<1	2.4	73	<1	<1	98	0.5
	02b	0.1	<1	500	<1	2.2	44	0.5	<1	98	7.1
	02c	0.1	<1	380	<1	2.5	6.8	<1	<1	97	<1
	03a	0.1	0.6	15	<1	31	75	5.3	0.8	69	0.9
	03b	0.2	1.7	17	<1	31	62	5.7	<1	69	2.8
	03c	0.2	1.7	16	<1	32	14	5.5	<1	68	0.9
	04a	0.3	2.1	32	<1	34	120	0.8	<1	66	2.2
	04b	0.1	0.6	23	<1	35	2.6	<1	<1	65	2.1
	04c	0.1	<1	14	<1	35	60	1.2	<1	65	1
	05a	0.1	0.6	420	<1	2.4	16	0.6	<1	98	0.6
	05b	4	7.8	390	<1	1.4	300	2.9	2.4	97	20
	05c	0.1	<1	390	<1	2.3	8.8	<1	<1	98	<1
	06a	0.1	<1	16	<1	37	36	1.2	<1	63	0.6
	06b	0.2	1.8	240	<1	41	10	0.8	<1	59	1.2
	06c	0.1	2.3	21	<1	36	24	0.9	<1	64	0.6
	07a	0.2	1.3	12	<1	46	290	4.5	<1	54	1.7
	07b	0.2	0.7	11	<1	46	160	5.1	<1	54	34
	07c	0.8	0.5	8.4	<1	43	180	4.9	<1	57	1.3
	08a	0.8	4.8	110	<1	2.8	31	1	<1	97	9.3
	08b	0.1	0.6	90	<1	2.8	50	0.8	<1	97	6.2
	08c	0.5	4.9	74	<1	2.9	330	0.7	<1	97	18
	09a	0.1	0.8	62	<1	20	47	<1	<1	80	6.5
	09b	0.2	2	39	<1	23	71	<1	<1	77	2.1
	09c	0.1	1.6	19	<1	22	61	<1	<1	78	<1
	10a	0.3	1.3	82	<1	19	5.7	0.9	<1	81	2
	10b	0.1	0.8	140	<1	19	9.7	0.6	<1	81	1.7
	10c	2	29.1	100	<1	16	12	0.8	<1	84	51
	11a	0.1	<1	21	<1	35	290	0.8	<1	65	2.2
	11b	20.7	65	200	0.6	36	380	8.3	3.1	63	27.8
	11c	0.1	0.7	28	<1	36	86	7.2	<1	64	<1
	12a	0.1	0.3	16	<1	33	16	0.8	<1	67	<1
	12b	0.1	0.6	15	<1	35	14	1.9	<1	65	<1
	12c	0.2	1.7	15	<1	34	25	<1	<1	66	0.6
	13a	0.1	2	14	<1	35	8.7	1.7	<1	65	3.6
	13b	0.2	3.5	38	<1	37	5.1	1.4	<1	63	<1
	13c	1.3	8.5	28	<1	36	8	3.5	<1	63	6.6
	14a	0.2	2.1	13	<1	33	13	1.2	<1	67	<1
	14b	0.4	1.6	15	<1	33	2.3	<1	<1	67	<1
	14c	0.1	<1	15	<1	33	5.8	<1	<1	67	<1

region by Camm & Groot (1994). However, since the locality Feock is located at the confluence of the river Carnon into the present Carrick Roads estuary (Fig. 7), gold at this locality could also derive from the rivers Fal and Tresillian, which have their catchment area to the north. Further sampling and more detailed studies on the mineral (micro) inclusion assemblage would be necessary to further characterize and differentiate between the different populations of placer gold found at the Carnon. Similar studies have been carried out by Leake *et al.* (1998), Chapman *et al.* (2000), and Chapman *et al.* (2006) on natural gold from other British localities.

5.5. Cornish copper

The results on the gold of the Nebra Sky Disk bring up the question whether Cornish copper could also have been the source for the copper of the bronze of the disk. This question is supported by a recent provenance study by Haustein *et al.* (2010), which suggests that the tin in the bronze of the Nebra Sky Disk may originate from Cornwall. Apart from tin, copper represents the second most important metal of the Cornubian ore field based on the total estimated output of 2 Mt, which reached its peak of half the world output in the 1860s (Dunham *et al.*, 1978). In our study, a total of 18 copper ores from 11 localities in Cornwall was sampled and analyzed for both trace element and lead isotope composition. These copper ores comprise 15 chalcopyrite and two chalcocite samples, as well as one covellite sample. The source area of 10 of the samples is the Camborne-Redruth-St Day mining district north of the Carnmenellis granite, whereas the remaining copper ores originate from the St Just, Callington and St Agnes mining districts. In addition to the lead isotope data from this study, published data (Rohl & Needham, 1998) were used for comparison with the bronze of the Nebra hoard (Fig. 9). The variation

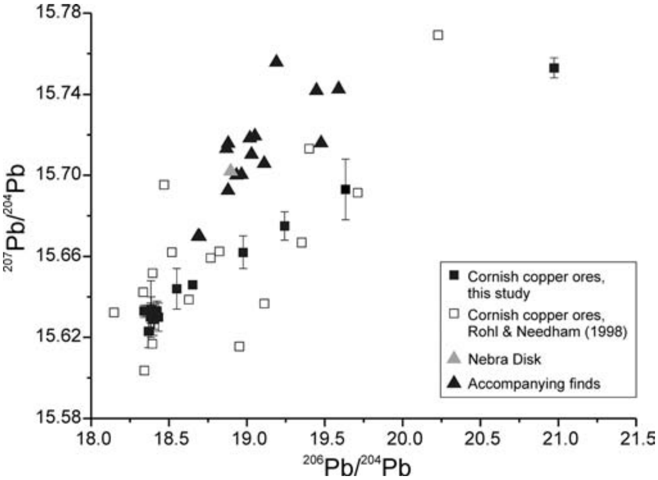

Fig. 9. Lead isotope diagram of Cornish copper ores from this study and the study by Rohl & Needham (1998) in comparison with the bronze of the Nebra hoard (grey triangle = Nebra Sky Disk, black triangles = accompanying finds). Additional information on the copper ores from this study are given in the text.

in $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ ratios of Cornish copper ores from this study is comparable with the variation from the studies by Rohl & Needham (1998) and can result from both episodic mineralizations over a period of about 200 Ma and a mineral assemblage of copper with uranium. The lead isotope composition of the Cornish copper, however, shows no correlation with the bronze of the Nebra hoard (Fig. 9), thus excluding Cornwall clearly as copper source. This negative evidence further supports the Mitterberg mining district in the eastern Alps to be the source for the copper of the bronze of the Nebra Sky Disk, which has been shown by Lutz *et al.* (2009) and subsequently emphasized by Pernicka (2010).

6. Conclusions

The chemical comparison of artifact gold from the sun sheet of the Early Bronze Age Nebra Sky Disk with natural gold from Cornwall shows a close correlation with gold from the prehistorically important alluvial tin and (minor) gold deposit of the river Carnon. From the elements used as distinctive geochemical tracers, Co, Ni, Pd, Ag, Sn, and Sb show a variation in the Carnon gold placers that is similar to the variation found in the gold from the sun sheet of the Nebra Sky Disk. The only differences in composition can be observed for Cu and Pt, which show lower concentrations in the natural gold compared with the artifact gold. As this observation has also been detected for other gold deposits in a previous provenance study, the relevance of mineral (micro) inclusions and accretions or unintended contamination with heavy minerals on the chemical composition of the artifact gold has to be questioned. Previous results on the geochemical comparison of gold deposits of central and southeastern Europe, which showed no similarity with the gold of the sun sheet, could be validated in this study using the element suite proposed. The results of this study would emphasize the close cultural relationships between the British Isles and central Germany during the Early Bronze Age, as substantial metal trade of gold (and tin) can be assumed.

Acknowledgements: We thank Sara Chambers from the Royal Cornwall Museum for providing the gold samples and Jane Marley for her comments on an earlier version of our manuscript. Simon Camm is thanked for his support during and after field work in Cornwall. His knowledge of Cornish gold deposits and the prehistoric landscape have been a valuable source of information. We are grateful to Nicole Lockhoff from the Curt-Engelhorn-Zentrum Archäometrie for her support during the entire process of the study and thank Ian Lerche for his help during the preparation of the manuscript. We must also thank the guest editors of this volume, Isabella Turbanti Memmi and Corina Ionescu, for giving us the opportunity to publish our results within this context. The manuscript was much improved by the valuable comments of two anonymous referees and the editorial work of Isabella Turbanti

Memmi and Ulrich Schuessler. The research was carried out in the framework of the Forschergruppe 550, funded by the Deutsche Forschungsgemeinschaft (DFG).

References

Bendall, C. (2003): The application of trace element and isotopic analyses to the study of Celtic gold coins and their metal sources. PhD thesis, Johann-Wolfgang-Goethe University, Frankfurt (Main), 282 p.

Berger, D., Schwab, R., Wunderlich, C.-H. (2010): Technologische Untersuchungen zu bronzezeitlichen Metallziertechniken nördlich der Alpen vor dem Hintergrund des Hortfundes von Nebra. *in* ''Der Griff nach den Sternen. Wie Europas Eliten zu Macht und Reichtum kamen'', F. Bertemes & H. Meller, eds., Internationales Symposium, Tagungen des Landesmuseums für Vorgeschichte Halle (Saale), Band 5/II, 751–778.

Billig, G. (1957): Das Prunkbeil von Schwechta. Ein Beitrag zur Herstellungstechnik und zum Verwendungszweck frühbronzezeitlicher Randleistenbeile in Mitteldeutschland. *Arbeits-u. Forschber. Sächs. Bodendenkmalpflege*, **6**, 285–316.

Borg, G. (2010): Warum in die Ferne schweifen? Geochemische Fakten und geologische Forschungsansätze zu Europas Goldvorkommen und zur Herkunft des Nebra-Goldes. *in* ''Der Griff nach den Sternen. Wie Europas Eliten zu Macht und Reichtum kamen,'' F. Bertemes & H. Meller, eds., Internationales Symposium, Tagungen des Landesmuseums für Vorgeschichte Halle (Saale), Band 5/II, 735–750.

Calvert, J. (1853): The gold rocks of Great Britain and Ireland: and a general outline of the gold regions of the world, with a treatise on the geology of gold. Chapman and Hall, London, 324 p.

Camm, G.S. & Groot, D.G. (1994): Quaternary placer cassiterite deposits in Cornwall: the role of periglacial processes in their development. Note of poster display, Annual Conference of the Usher Society, 328–330.

Chapman, R.J., Leake, R.C., Moles, N.R., Earls, G., Cooper, C., Harrington, K., Berzins, R. (2000): The application of microchemical analysis of alluvial gold grains to the understanding of complex local and regional gold mineralisation: a case study in the Irish and Scottish Caledonides. *Econ. Geol*., **95**, 1753–1773.

Chapman, R.J., Leake, R.C., Warner, R.A., Cahill, M.C., Moles, N.R., Shell, C.A., Taylor, J.J. (2006): Microchemical characterisation of natural gold and artefact gold as a tool for provenancing prehistoric gold artefacts. *Appl. Geochem*., **21**, 904–918.

Clarke, D.L. (1970): Beaker pottery of Great Britain and Ireland. Cambridge University Press, Cambridge, 576 p.

Cowie, T. (2004): Prunkvolle Dolche aus Schottland. *in* ''Der geschmiedete Himmel. Die weite Welt im Herzen Europas vor 3600 Jahren'', H. Meller, ed., Konrad Theiss Verlag, Stuttgart, 176–177.

Crawford, O.G.S. (1921): The ancient settlements at Harlyn Bay. *Antiq. J*., **1**, 283–299.

Duff, P.McL.D. & Smith, A.J. (1992): Geology of England and Wales. Geological Society, London, 651 p.

Dunham, K., Beer, K.E., Ellis, R.A., Gallagher, M.J., Nutt, M.J.C., Webb, B.C. (1978): United Kingdom. *in* ''Mineral Deposits of Europe Volume 1: Northwest Europe'', S.H.U. Bowie, A. Kvalheim, H.W. Haslam, eds., The Institution of Mining and Metallurgy, The Mineralogical Society, London, 263–317.

Ehser, A., Borg, G., Pernicka, E. (2010): Fingerprinting of Cornish gold for provenancing prehistoric gold artefacts from Central Europe. *in* ''IMA 2010: Bonds and Bridges'', E. Pal-Molnar, ed., 20th General Meeting of the International Mineralogical Association, Budapest, *Acta Mineral.-Petrogr*., **6**, 106.

Eluère, C. (1983): Prehistoric goldwork in Western Europe. *Gold Bull*., **16**, 82–91.

Eluère, C. & Raub, C.J. (1991): New investigation on early gold foil manufacture. Archaeometry 90, Birkhäuser Verlag Basel, 45–54.

Guerra, M.F., Sarthre, C.-O., Gondonneau, A., Barrandon, J.-N. (1999): Precious metals and provenance enquiries using LA-ICP-MS. *J. Archaeol. Sci*., **26**, 1101–1110.

Gumprich, A. (2004): Archäometrische Untersuchungen an den Goldteilen aus dem Hortfund von Nebra. Diploma thesis, TU Bergakademie Freiberg, 126 p.

Hartmann, A. (1970): Prähistorische Goldfunde aus Europa. Studien zu den Anfängen der Metallurgie (SAM), Band 3, Gebr. Mann Verlag, Berlin, 129 p.

Hartmann, A. (1982): Prähistorische Goldfunde aus Europa II. Studien zu den Anfängen der Metallurgie (SAM), Band 5, Gebr. Mann Verlag, Berlin, 155 p.

Hauptmann, A., Rehren, T., Pernicka, E. (1995): The composition of gold from the ancient mining district of Verespatak/Roşia Montana, Romania. *in* ''Prehistoric Gold in Europe'', G. Morteani & J.P. Northover, eds., Kluwer Academic Publishers, Amsterdam, 369–381.

Haustein, M., Gillis, C., Pernicka, E. (2010): Tin isotopy – a new method for solving old questions. *Archaeometry*, **52**, 816–832.

Jackson, N.J., Halliday, A.N., Sheppard, S.M.F., Mitchell, J.G. (1982): Hydrothermal activity in the St. Just mining district, Cornwall, England. *in* ''Metallization Associated with Acid Magmatism'', A.M. Evans, ed., Chichester, Wiley, 137–179.

Jackson, N.J., Willis-Richards, J., Manning, D.A.C., Sams, M.S. (1989): Evolution of the cornubian ore field, Southwest England: Part II. Mineral deposits and ore-forming processes. *Econ. Geol*., **84**, 1101–1133.

Kaesche, H. (1990): Die Korrosion der Metalle. Physikalisch-chemische Prinzipien und aktuelle Probleme. Springer-Verlag, 185 p.

Kovacs, R., Schlosser, S., Samuel, P.S., Schmiderer, A., Pernicka, E., Günther, D. (2009): Characterisation of calibration materials for trace element analysis and fingerprint studies of gold using LA-ICP-MS, *J. Anal. At. Spectrom*., **24**, 476–483.

Leake, R.C., Chapman, R.J., Bland, D.J., Stone, P., Cameron, D.G., Styles, M.T. (1998): The origin of alluvial gold in the Leadhills area of Scotland: evidence from interpretation of internal chemical characteristics. *J. Geochem. Explor*., **63**, 7–36.

Lehrberger, G. (1995): The gold deposits of Europe. An overview of the possible metal sources for prehistoric gold objects. *in* ''Prehistoric Gold in Europe'', G. Morteani & J.P. Northover, eds., Kluwer, Netherlands, 115–144.

Leveridge, B.E., Holder, M.T., Goode, A.J.J. (1990): Geology of the country around Falmouth. British Geological Survey, London, 71 p.

Lutz, J., Pernicka, E., Pils, R., Tomedi, G., Vavtar, F. (2009): Geochemical characteristics of copper ores from the Greywacke Zone in the Austrian Alps and their relevance as a source of copper in prehistoric times. *in* ''Die Geschichte des Bergbaus in Tirol und seinen angrenzenden Gebieten'', K. Oeggl & M. Prast, eds., Proceedings of the 3rd Milestone-Meeting of the SFB HiMAT, Innsbruck, 175–181.

Meller, H. (2003): Die Himmelsscheibe von Nebra. Fundgeschichte und archäologische Bewertung. *Sterne und Weltraum*, **12**, 28–33.

Murray, J. (1859): Handbook for devon and cornwall. John Murray, London.

Pearce, S. (1983): The Bronze Age Metalwork of South Western Britain. BAR British Series, 120(i), Oxford, 350 p.

Penhallurick, R.D. (1986): Prehistoric finds from Cornish tin streams. *in* ''Tin in Antiquity'', R.D. Penhallurick, ed., Maney, London, 173–224.

Pernicka, E, & Wunderlich, C.-H. (2002): Naturwissenschaftliche Untersuchungen an den Funden von Nebra. *Archäologie in Sachsen-Anhalt*, **1**, 17–22.

Pernicka, E., Radtke, M., Riesemeier, C.-H., Wunderlich, C.-H. (2003): European Network in Competence at 1600 BC. *BESSY, Highlights* **2003,** 8–9.

Pernicka, E., Wunderlich, C.-H., Reichenberger, A., Meller, H., Borg, G. (2008): Zur Echtheit der Himmelsscheibe von Nebra – eine kurze Zusammenfassung der durchgeführten Untersuchungen. *Archäologisches Korrespondenzblatt*, **38**, 331–352.

Pernicka, E. (2010): Archäometallurgische Untersuchungen am und zum Hortfund von Nebra. *in* ''Der Griff nach den Sternen. Wie Europas Eliten zu Macht und Reichtum kamen'', F. Bertemes & H. Meller, eds., Internationales Symposium, Tagungen des Landesmuseums für Vorgeschichte Halle (Saale), Band 5/II, 719–734.

Raub, C. (1995): The metallurgy of gold and silver in prehistoric times. *in* ''Prehistoric Gold in Europe'', G. Morteani & J.P. Northover, eds., Kluwer, Netherlands, 115–144.

Rohl, B. & Needham, S. (1998): The circulation of metal in the British Bronze Age: application of lead isotope analysis. *British Museum Occasional Paper*, **102**, 195 p.

Sarah, G. (2008): Caractérisation de la composition et de la structure des alliages argent-cuivre par ICP-MS avec prélèvement par ablation laser. Application au monnayage carolingien. PhD thesis, University of Orléans, France, 461 p.

Schlosser, W. (2003): Astronomische Deutung der Himmelsscheibe von Nebra. *Sterne und Weltraum*, **12**, 34–38.

Schlosser, S., Kovacs, R., Pernicka, E., Günther, D., Tellenbach, M. (2009): Fingerprints in Gold. *in* ''New Technologies for Archaeology. Multidisciplinary Investigations in Palpa and Nasca, Peru'', M. Reindel & G.A. Wagner, eds., Springer, Berlin, 409–436.

Schmiderer, A. (2009): Geochemische Charakterisierung von Goldvorkommen in Europa. PhD thesis, Martin-Luther-University Halle-Wittenberg, Halle (Saale), 140 p.

Shell, C.A. (1978): The early exploitation of tin deposits in South West England. *in* ''The Origins of Metallurgy in Atlantic Europe'', M. Ryan, ed., Proceedings of the 5th Atlantic Colloqium, Dublin, 251–263.

Shennan, I. & Horton, B. (2002): Holocene land- and sea-level changes in Great Britain. *J. Quaternary Sci*., **17**, 511–526.

Taylor, J.J. (1980): Bronze age goldwork of the British Isles. Cambridge University Press, Cambridge.

Townley, B.K., Hérail, G., Maksaev, V., Palacios, C., Parseval, P., Sepulveda, F., Orellana, R., Rivas, P., Ulloa, C. (2003): Gold grain morphology and composition as an exploration tool: application to gold exploration in covered areas. *Geochem. Explor. Env. A*., **3**, 29–38.

Waller, M.P. & Long, A.J. (2003): Holocene coastal evolution and sea-level change on the southern coast of England: a review. *J. Quat. Sci*., **18**, 351–359.

Willis-Richards, J. & Jackson, N.J. (1989): Evolution of the cornubian ore field, Southwest England: Part I. Batholith modeling and ore distribution. *Econ. Geol*., **84**, 1078–1100.

Received 21 February 2011
Modified version received 29 April 2011
Accepted 25 July 2011