Geological Quarterly, 2024, 68, 35
DOI: http://dx.doi.org/10.7306/gq.1763

The Skora River: an anthropogenically modified gold-bearing fluvial deposit (North Sudetic Trough, SW Poland)

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Kania, M., Muszer, A., 2004. The Skora River: an anthropogenically modified gold-bearing fluvial deposit (North Sudetic Trough, SW Poland). Geological Quarterly, 68, 35; https://doi.org/10.7306/gq.1763

Associate Editor: Stanisław Mikulski

We describe detrital gold grains obtained from sediments from the Skora River bed in the North Sudetic Trough, focussing on identification of microinclusions of ore minerals, combined with analyses of grain morphology and their chemical composition, to constrain the origin of the detrital gold. A population of gold grains of natural origin was identified, represented mostly by phases of native gold. A few microinclusions of Pd selenides and tellurides were identified, suggesting that local outcrops of the Rotliegend-Zechstein boundary zone are the probable source areas for the gold grains. In addition, a large population of amalgams of probable anthropogenic origin was identified. Their identification is of potential importance in the study of environmental mercury contamination, while distinguishing between the two grain populations is crucial to studying the origin of modern placer gold deposits.

Key words: gold, Hg-amalgams, inclusions, placer deposits, North Sudetic Trough.

INTRODUCTION

The Skora River is one of the best-known occurrences of the detrital gold in Lower Silesia, much appreciated by local prospectors (Maciejak, 2011; Jakubowski, 2023) because of the relatively high content of gold in local channel-fill sediments. Although the major gold-bearing deposits located in the Fore-Sudetic areas of Lwówek Śląski-Bolesławiec, Złotoryja, Mikołajowice-Legnickie Pole-Wądroże Wielkie and Sudetic areas of Wleń-Jelenia Góra have already been investigated for their mineralogical and chemical composition (Grodzicki, 1998, 2011, and the references therein; Łuszczkiewicz and Muszer, 1999; Urbański, 2010; Muszer, 2011; Mikulski and Wierchowiec, 2013; Wierchowiec et al., 2018, 2021; Kania, 2018, 2023), few publications have considered detrital gold from the Skora River Basin (Muszer et al., 2016; Wierchowiec and Zieliński, 2017).

This work continues previous studies on the search for and identification of ore mineral micro-inclusions in Holocene alluvial deposits of the Polish part of the Sudetes and the Sudetes Foothills. Studies of microinclusions, combined with analyses of grain morphology and chemical composition, have so far been used in the prospecting of primary gold deposits in Africa, south-east Asia and the Western Hemisphere (Leake et al., 1995; Styles, 1995; Kelley et al., 2003; Chapman et al., 2023). The results we describe herein extend this research methodology to Polish detrital gold-bearing sediments and to contribute to research on their genesis.

However, in contrast to the previously published results of analyses of detrital gold from the Wleń (Kania, 2018) and Lwówek Śląski-Bolesławiec regions (Kania, 2023), in the Skora riverbed sediments, in addition to grains of natural origin, a larger population of grains with features characteristic of amalgams of anthropogenic origin was identified. Their formation is mainly attributed to the development and activity of artisanal mining, and the accompanying mercury contamination carries with it strongly negative environmental effects (Alpers et al., 2016; Gerson et al., 2022; Abdelaal et al., 2023). The presence of anthropogenic amalgams in Polish river sediments and records of the occurrence of native mercury within them (Muszer and Ćwiertnia, 2018) therefore raise questions about their origin and environmental impact. The co-occurrence of natural and anthropogenic gold grains further complicates research on the origin of detrital gold and requires prior distinction of grains of both populations.

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Received: March 25, 2024; accepted: September 7, 2024; first published online: November 22, 2024

GEOLOGICAL SETTING

Sampled gold-bearing alluvial deposits constitute part of the Cenozoic sedimentary cover, formed on the top of the Upper Paleozoic-Mesozoic succession of the North Sudetic Basin (NSB), which developed in turn on the Paleozoic structure of the Kaczawa Metamorphic Complex (KMC).

The KMC, also referred to the literature as the Złotoryja-Luboradz Unit (Baranowski et al., 1990) or the Kaczawa Schist-Greenstone Fold Belt (Żelaźniewicz et al., 2011), comprises a thick succession of volcanic and sedimentary rocks. The extent of the Complex is limited by the Intra-Sudetic Fault to the south-west, to the north and the east by the Odra Dislocation Zone, and to the south by units of the Strzegom-Sobótka Granite and the Ślęża Massif (Żelaźniewicz et al., 2011). It extends to the west, passing into the Zgorzelec Phyllitic Fold Belt (Baranowski et al., 1990; Żelaźniewicz et al., 2011). Evolution of KMC involved two phases. First, a pre-orogenic phase consists of an initial stage of Cambrian-Ordovician age and a mature stage of oceanic crust formation, dated to the Silurian-Early Carboniferous. During the following, Variscan, orogenic phase, the KMC was deformed and altered in greenstone facies conditions (Furnes et al., 1994; Kryza, 2008).

As the Carboniferous gave way to the Permian, the Kaczawa Metamorphic Complex was locally cut by polymetallic quartz veins enriched with gold, located mainly along the Intra-Sudetic Fault. In addition, there are smaller gold-bearing quartz-sulphide occurrences in the KMC. Metalliferous hydrothermal mineralization events date from the Bashkirian to Artiskian stages (Mikulski, 2007a, b; Mikulski and Williams, 2014).

The Asturian phase of the Variscan orogeny caused rebuilding of the Complex, which subsided as a result of local crustal stretching. Stretched Variscan basement gave rise to the development of a sedimentary North Sudetic Basin, nowadays filled with unaltered, weakly tectonically deformed strata, deposited from the Late Carboniferous to the Laramian phase of the Alpine orogeny in the Late Cretaceous (Baranowski et al., 1990; Solecki, 2011).

The oldest sedimentary rocks filling the NSB are represented by lithified clastic deposits of the Rotliegend facies, constituting the Upper Carboniferous-Lower Permian succession (Górecka, 1970; Baranowski et al., 1990; Solecki, 2008). The basin was repeatedly flooded by the Zechstein Sea, resulting in the deposition of thick sequence of evaporites, comprising PZ1–PZ3 cyclothems (Peryt, 1978; Raczyński, 1997; Śliwiński et al., 2003; Fijałkowska-Mader et al., 2019).

The section of the Permian profile that includes the stratigraphic boundary between the Rotliegend and Zechstein sedimentary units comprises Cu-polymetallic, red-bed type deposits, known in the NSB area as the ”old copper mining district”. Gold was recognized within it mainly as an additive in native silver in amounts of up to 10 ppm (Konstantynowicz, 1971; Kucha et al., 1982; Oszczepalski et al., 2011). To this day, the exploration and identification of gold in the NSB area has included the Rotliegend-Zechstein contact zone in the shallower parts of the orogen and at outcrop (Speczik and Wojciechowski, 1997; Wojciechowski, 2001, 2011; Oszczepalski et al., 2011).

Red-bed type deposits in Poland have a two-part, geochemically diverse structure. The upper part of the deposit profile was formed under reduced, and the lower under oxidized conditions. The nature of this differentiation (synsedimentary or postsedimentary) has been widely debated (e.g., Oszczepalski and Rydzewski, 1995, 1997; Oszczepalski, 1999; Piestrzyński et al., 2002; Oszczepalski et al., 2011, and the references therein). The redox front is discordant with respect to the stratification. It is typically located within the marl layers, though in some instances in the underlying Basal Limestone. Generally, the reduced zone is enriched in Cu, Pb and Ag. Noble metals (Au, PGEs) occur mainly in the transition and oxidized zones; the gold concentrations within them are significant compared to the reduced zone, being nearly three orders of magnitude higher (Oszczepalski et al., 2011).

After the regression of the Zechstein Sea, the North Sudetic Basin initially filled with terrestrial Buntsantstein sediments, then during the Middle to Late Triassic, marine sedimentation recommenced. After a stratigraphic gap encompassing the Jurassic and Lower Cretaceous, the NSB witnessed further transgression, in the Cenomanian (Baranowski et al., 1990). The Cretaceous profile starts with conglomerates and sandstones, then passes upwards into increasingly finer deposits, culminating in Santonian clay-rich layers with seams of brown coal (Milewicz, 1997; Solecki, 2008, 2011). Basin development ends with the tectonic Laramian event around the Cretaceous/Paleogene boundary, the change in tectonic regime from tensional to compressive causing basin inversion. In addition, auxiliary tectonic structures were formed within the NSB, such as troughs, fault ridges and synclines (Baranowski et al., 1990; Solecki, 2011).

Further sedimentary deposition occurred during the Cenozoic, represented by Oligocene gravels, Miocene sands, gravels, clays and muds with lignite, and Miocene-Pliocene kaolinitic sands and gravels. Meantime, as the Neogene began, sedimentation was interrupted by increased basaltic volcanic activity. Pre- and postglacial deposits are related to the South Polish (Mindel) and Mid-Polish (Riss) glaciations. The youngest strata are represented by Pleistocene-Holocene fluvioglacial and alluvial deposits (Grodzicki, 1969, 1998; Baranowski et al., 1990; Solecki, 2008).

Local gold-bearing secondary deposits are of Oligocene to Holocene age. They are distributed within the NSB's Cenozoic cover, extending mainly from the area between Bolesławiec and Lwówek Śląski in the west to the close vicinity of Złotoryja in the east. According to Grodzicki (1998, 2011) four phases of their development can be distinguished.

During the first, Oligocene-Neogene phase, the source rocks enriched with gold were intensely eroded and formed gravelly and sandy eluvial–deluvial covers. Such covers were distinguished by Grodzicki (1972, 1998, 2011) within Cenozoic deposits located north of Lwówek Śląski and south-west and north-east of Złotoryja. Later phases of development include winnowing of these particular, Oligocene-Neogene deposits and are characterized by lower contents of gold.

The second, preglacial phase constituted the first phase of redeposition, initiated by the Rodanian and Wallachian orogenic phases in the late Pliocene and early Pleistocene. Increased tectonic activity caused intensified fluvial erosion and partial washout of older deposits, occurring east of Lwówek Śląski and north-east of Złotoryja (Grodzicki, 1972, 1998, 2011). During the third, Pleistocene phase, climate cooling inhibited chemical weathering. As a result, the local gold-bearing deposits, represented mainly by tills and fluvioglacial gravels, are poorer in gold compared to older deposits. Recent, Holocene deposits of the fourth phase were formed both by erosion and redeposition of earlier gold-bearing deposits and by direct migration from currently eroded primary deposits (Grodzicki, 1998).

The study area and its geographical location are outlined in Figure 1

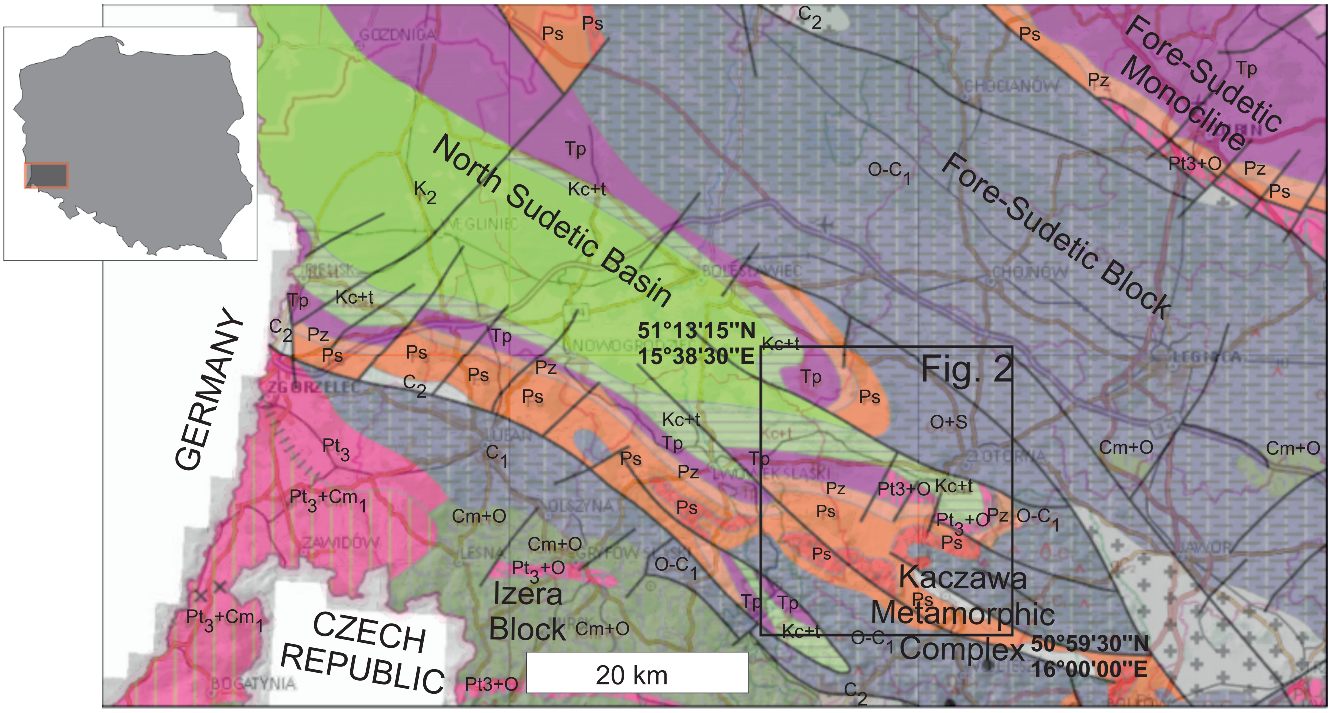

Fig. 1. Generalized geological map of the western part of the Lower Silesian Block without Cenozoic deposits (GeoLOG; Dadlez et al., 2000, modified)

Pt_3 – Upper Proterozoic, Cm_1 – Lower Cambrian, O – Ordovician, C_1 – Lower Carboniferous, C_2 – Upper Carboniferous, Ps – Rotliegend, Pz – Zechstein, Tp – Triassic (Buntsandstein), Kc + t – Cretaceous (Cenomanian and Turonian), K_2 – Upper Cretaceous (undifferentiated)

METHODS AND MATERIALS

Gold-bearing channel-fill sediment collected from a 200 metre section of the river (Fig. 2), located between the villages of Pielgrzymka and Wojcieszyn, were subjected to analysis.The field work included collecting of channel-fill sediment samples and preliminary on-site concentration of gold-bearing material by the Mobile Gravity Concentrator (Muszer et al., 2016; Muszer and Ćwiertnia, 2018; Kania, 2020). Sufficient gold grains were collected strictly to allow detailed mineralogical and chemical studies, although without determining the content of gold in the sediments. For this reason, sampling was limited to points in the riverbed section liable to concentration of heavy minerals: cracks in boulders and spaces between boulders, evorsion hollows, inner bends of the river etc.

The samples of concentrate were subsequently washed using a pan, then the largest, macroscopically identified particles of gold were selected. The remaining gold-bearing material was sieved on a 2 mm mesh sieve and then prepared in the laboratory of the Department of Mineral Resources Management of the Institute of Geological Sciences, University of Wrocław. A concentration table of Wilfrey type was used, with a multiple re-processing procedure.

Detailed recognition of heavy minerals at this sampling site had already been made by Muszer et al. (2016) – they recognized a diverse assemblage of Fe-Ti oxides, cassiterite, Mn oxides, cuprite, monazite, wolframite, zircon, scheelite, garnets, pyrite, chalcopyrite, arsenopyrite, sphalerite, galena, marcasite, native silver, metallic lead and copper. Therefore, the present research focused on gold grains isolated from the concentrate, which were subsequently measured using a binocular microscope and mounted in polished sections made with epoxy raisin. Preparation of sections involved using Struers metalographic materials: a set of Piano type diamond discs for grinding and MD-Dur, -Mol and -Nap cloths for polishing, additionally applying dedicated solutions.

The assessment of the gold particle morphology was made by applying a simplified DiLabio (1991) classification. This classification distinguished a pristine class of irregular grains, a modified class of partly abraded grains and a reshaped class of wholly rounded shapes with original features erased. In this particular study, to enable effective comparison of grains with regard to their shape and chemical/mineralogical composition, the evaluation of morphology was based on the particle cross-sections revealed in polished section. To make this comparison more objective and reliable, an original procedure of K index evaluation was applied. This index is based on the relation between the grain outline lengths and their cross-sectional areas (Kania, 2020, 2023). The geometries of particular grains were measured using BSE images and *Surfer*® software.

Mineralogical analyses in reflected light (determination of Au alloy compositions, mineral inclusions) were made using a universal *Nikon Eclipse LV100 POL* microscope. To upgrade the total magnification up to 2500× and make observations of microinclusions finer than 10 μm feasible, the microscope was combined with a digital display. The results of analyses in reflected light were subsequently compared with SEM-EDS analyses, performed in the Laboratory of Electron Microscopy of the Wrocław Research Centre EIT+. Observations were made on a FEI Quanta SEM with SDD *Bruker XFlash* EDS detectors produced by Bruker. Measurement sessions were preceded by calibration (Energy-Channel Calibration/Energy-Axis Calibration) using a copper standard in accordance with the proce-

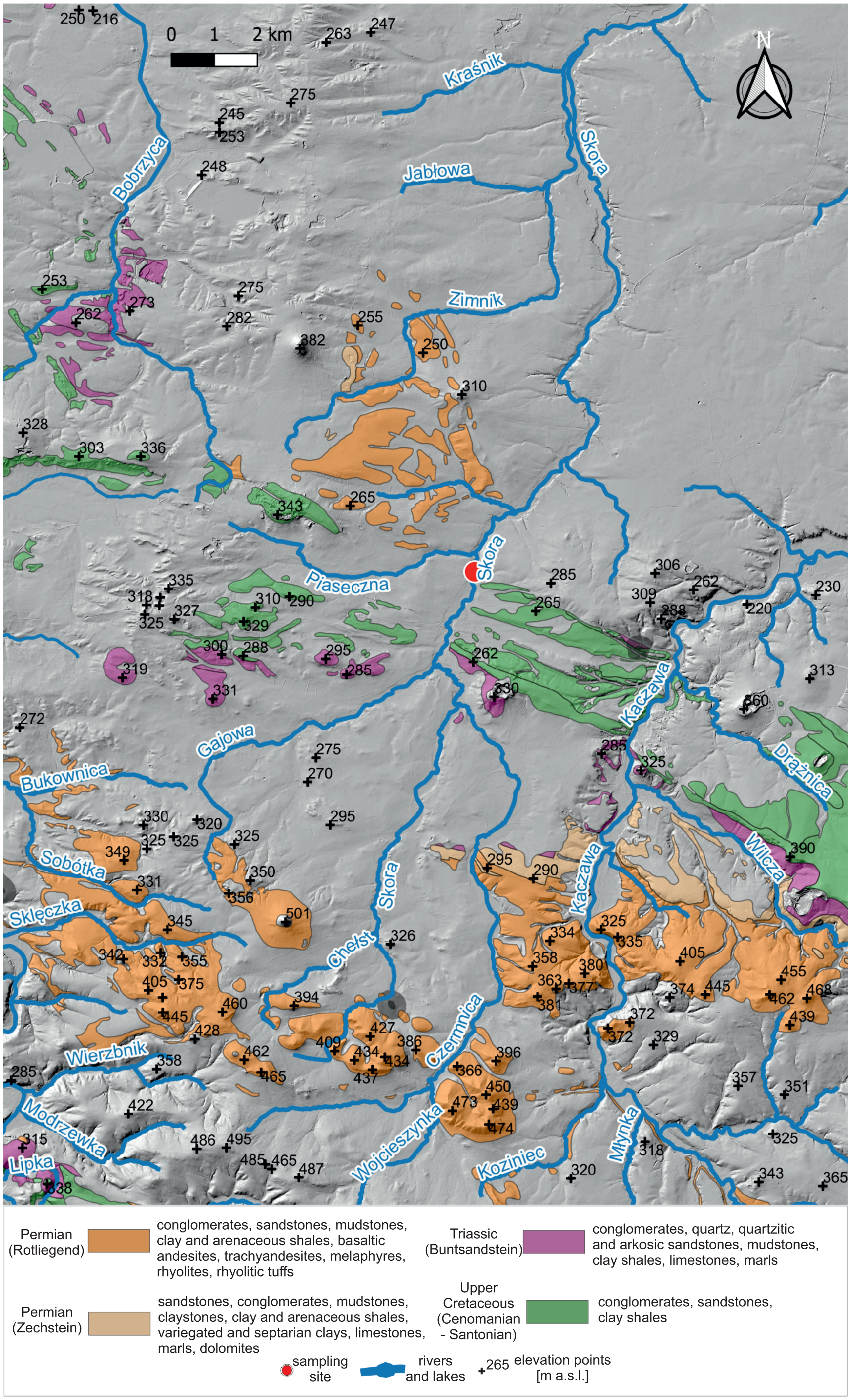

Fig. 2. Location of the sampling site, with simplified geological map and relief map

Compiled after Sztromwasser (1998), Cymerman et al. (2012, 2013), Kozdrój et al. (2012), Badura (2013), Cwojdziński and Kozdrój (2013) dures and recommendations of Bruker. Due to the size of microinclusions (up to 3 µm) and specificity of EDS analyses, the results given of chemical composition have to be considered as semi-quantitative. Therefore, having regard to the limitations of analyses, a content of 0.1 wt.% was additionally adopted as a detection limit for a particular element. Measurement errors of particular analyses were included in results given in Appendix 1. The details of the EDS analytical methodologies have already been described in an earlier article detailing microinclusions in the detrital gold grains (Kania, 2023).

The EDS analyses (19 point analyses, a single linear analysis and sets of concentration distributions of Ag, As, Au, Bi, Cd, Co, Cr, Cu, Fe, Hg, Ir, Mn, Mo, Ni, Os, Pb, Pd, Pt, Rh, Ru, S, Sb, Se, Si, Sn, Te, Ti, V, W and Zn) were performed with the focus on chemical characterization and searching for microinclusions in gold grains that possessed features of natural origin, not of anthropogenic amalgams.

RESULTS

Detailed mineralogical tests were performed on 22 selected grains of gold. Particles differ in shape: a single grain of dendritic, primary shape (*sensu* DiLabio, 1991) with irregular and angular outline (grain S-16) was observed among more numerous modified grains of partially rounded edges (grains S-5, S-13) and reshaped, oval and elongated discoidal grains (S-3, S-7, S-19). Grains S-4, S-8, S-9, S-10, S-14, S-20, S-21 and S-22 represent a distinctive group of highly porous, oval particles, characterized also by higher values of K index and generally larger size (Fig. 3).

The grains examined vary in diameter from 175 to over 900 µm (average of 483 µm), although the grain fraction 300–400 µm represents the largest group. Microinclusions of rock-forming minerals (quartz and clay minerals) were found and identified only within four grains, and microinclusions of ore minerals in just one of them.

Silver, mercury and palladium were identified within the gold particles. The content of silver, the most common additive, is generally low, zones of characteristic pale yellow colour, characteristic of Au-Ag alloys being rare. In addition, most point analyses did not reveal the presence of Ag (as in the case of single spot analyses of grains S-3 and S-15, which revealed the presence of pure gold), or confirmed its presence in only small amounts, which exceptionally reaches several wt.% (S-17; Fig. 4). As a result, the population of investigated gold grains from the Skora River is relatively homogeneous, compared to detrital gold in recent sediments of the North Sudetic Basin cover (Jęczmyk and Krzemińska, 1996; Urbański, 2010; Muszer, 2011; Wierchowiec and Zieliński, 2017; Kania, 2018, 2023), their composition representing a native gold phase (*sensu* Yushko-Zakharova et al., 1986). The S-16 grain of irregular, branching shape, and characterized by a zonal structure of varied Ag contents, is an exception; its content of silver reaches up to 39.4 wt.% (as a metastable Au-Ag phase). In this particular case the borders of each zone have sharp, distinctive edges. The S-16 grain is mostly compact, although some outer, low-Ag parts are porous. Zones enriched in silver are irregularly distributed and occur both in the outer and inner parts of the grain (Fig. 5).

Mercury is commonly found within oval grains characterized by a highly porous, spongy structure. Their presence was earlier revealed by Muszer et al. (2016). Amongst the grains obtained, selected for further analyses and shown in Figure 3, one potential amalgam of characteristic structure was tested for the presence of Hg (gold grain S-1; Fig. 6). In this particular case, point analyses revealed mercury contents of of up to only 0.37 wt.%; however, the Hg content determined by Muszer et al. (2016) in other spongy amalgam grains collected from the same sampling site reached 1.85 wt.%. The amalgams analysed are relatively homogeneous (see Fig. 10); characteristic light yellow zones enriched in silver are extremely rare and relatively small, although the Ag content within them may amount to several wt.% (Fig. 6). Moreover, it seems that the distributions of Hg and Ag are not spatially related, as can be observed in some amalgams of presumably natural origin (Kania, 2018, 2023). In none of these artificial amalgam-type grains have any microinclusions of ore minerals been found.

The relatively fine gold particle S-19 (Fig. 7) is the only one in which microinclusions of ore minerals were identified. This 175 µm wide, elongated grain with rounded edges is also enriched with palladium; a spot test revealed a Pd content of 1.1 wt.%.

Further investigations based on combined observations in reflected light and images of elemental distribution revealed 5 microinclusions, not exceeding 3 µm in size. Sharp-edged mineral outlines, characteristic of hipautomorphic/automorphic forms, can be observed.

Analyses of three microinclusions indicated a similar qualitative composition, represented by palladium, silver, selenium, tellurium and copper. Semi-quantitative EDS results show that their chemical composition is most similar to selenides like palladseite $Pd_{17}Se_{15}$ or oosterboschite $(Pd,Cu)_7Se_5$, containing traces of silver, tellurium and copper (Fig. 8). Analyses of two other microinclusions revealed a dominance of palladium and tellurium, occurring in similar atomic quantities (Figs. 8 and 9). This chemical composition is most similar to kotulskite PdTe, devoid of Bi (Vymazalová et al., 2005), and containing traces of Se and Cu, or yanzhonghite – (informal, not recognized by the International Mineralogical Association mineral, mentioned by Yu et al., (1974), and then by Dodin et al. (2000), who quoted the elemental composition of yanzhonghite, as follows: 47.4 wt.% – Pd, 52.0 wt.% – Te and <1.0 wt.% – Ag, Bi, Hg.

DISCUSSION

Wierchowiec and Zieliński (2017) described bimodal gold grains from Zimnik Creek and its drainage basin, which constitutes the left tributary of the Skora River, located ~5 km NNW of the sampling site (Fig. 2). Bimodal particles consist of typically pure gold rims (>98 wt.%) with low contents of silver, palladium and mercury (<2 wt.% in total). By contrast, the grain cores are significantly enriched in Ag (to >15 wt.%), and with Pd and Hg contents up to 1 wt.%. These authors noted that the distribution of palladium is generally similar to that of silver; however, the mercury appears disseminated within the grains and shows no correlation with Ag and Pd. Similar Au-Ag-Pd-Hg alloy grains were also identified in the alluvial sediments of Czerwony Creek near Złotoryja (Wierchowiec, 2010). The presence of similar multiphase amalgams formed of high Ag alloy enriched in mercury and pure gold alloy was also confirmed in alluvial sediments of the Jamna and Żeliszowski creeks (Kania and Muszer, 2017; Kania, 2018, 2023); however, in these instances the authors noted that presence of mercury is closely related to alloys enriched in silver (metastable and electrum phases *sensu* Yushko-Zakharova et al., 1986). Contents of mercury were also higher: from 1.53 to 4.90 wt.%. Furthermore, the presence of palladium was not confirmed.

Fig. 3. Gold grain outlines relative to calculated K index values

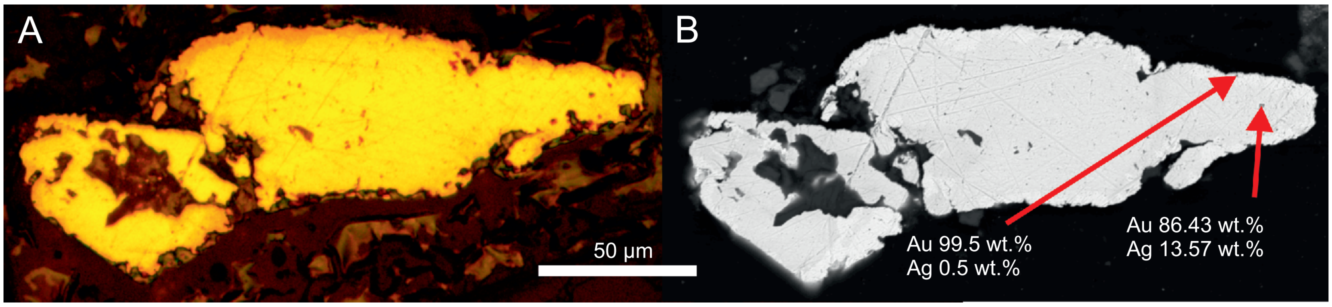

Fig. 4. The single-phase S-17 gold grain

A – image in reflected light, **B** – BSE image

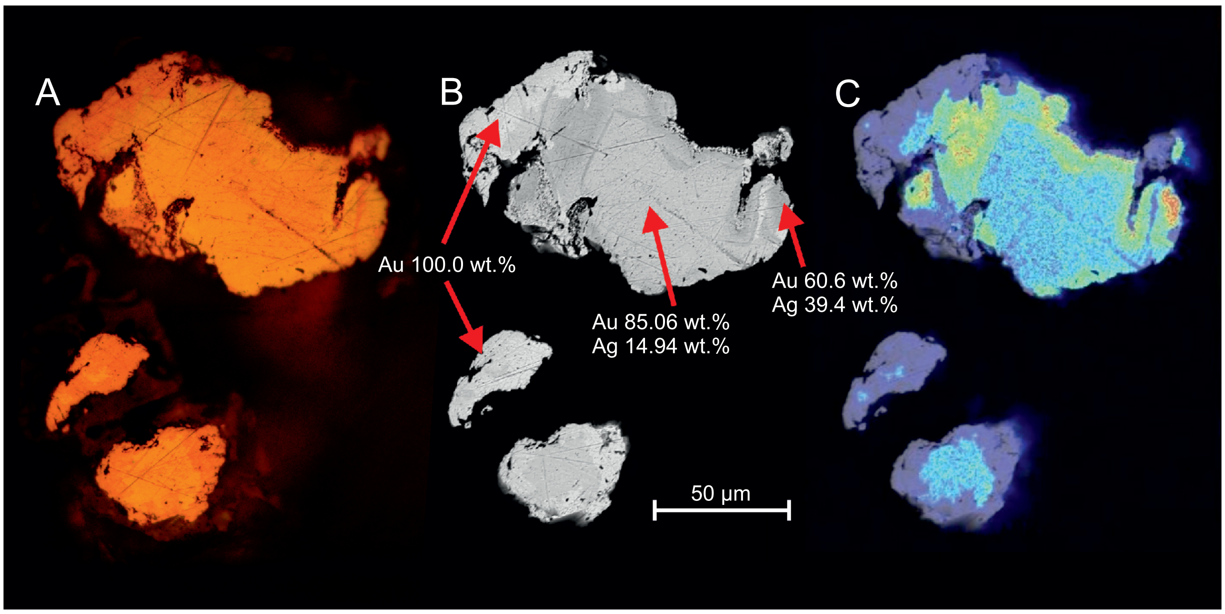

Fig. 5. The multi-phase S-16 gold grain

A – image in reflected light, **B** – BSE image, **C** – silver distribution: violet, blue, yellow, up to red colours indicate increasingly high concentrations of Ag

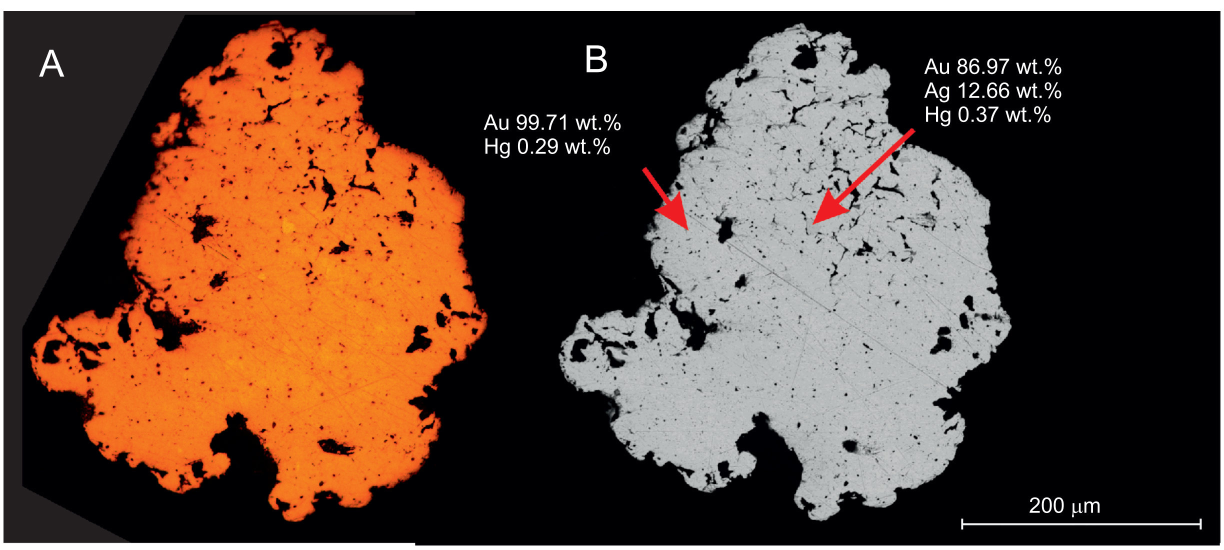

Fig. 6. The amalgam S-1

A – image in reflected light, **B** – BSE image

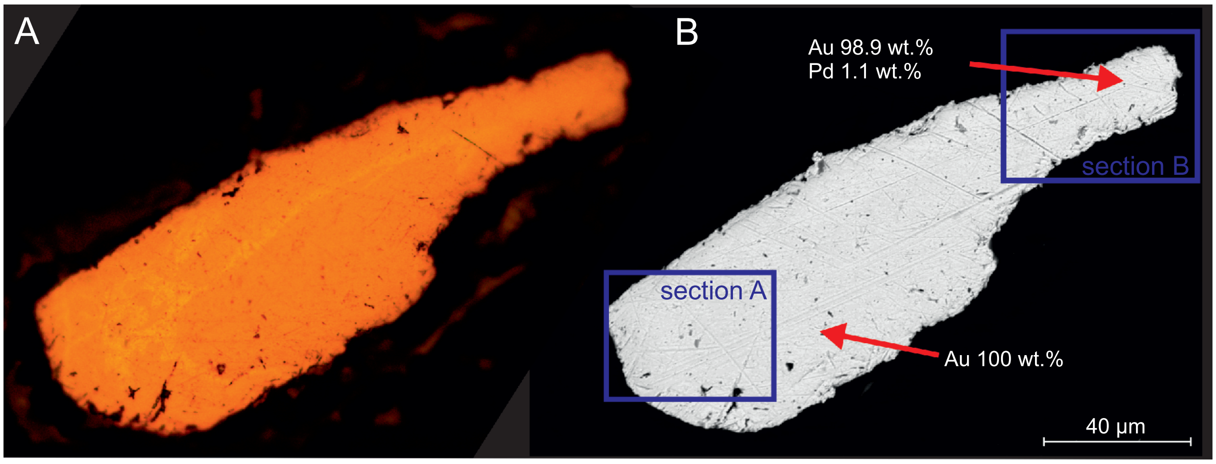

Fig. 7. The ore-bearing S-19 gold grain

A – image in reflected light, **B** – BSE image, marked location of the sections (zoomed sections in Figs. 8 and 9)

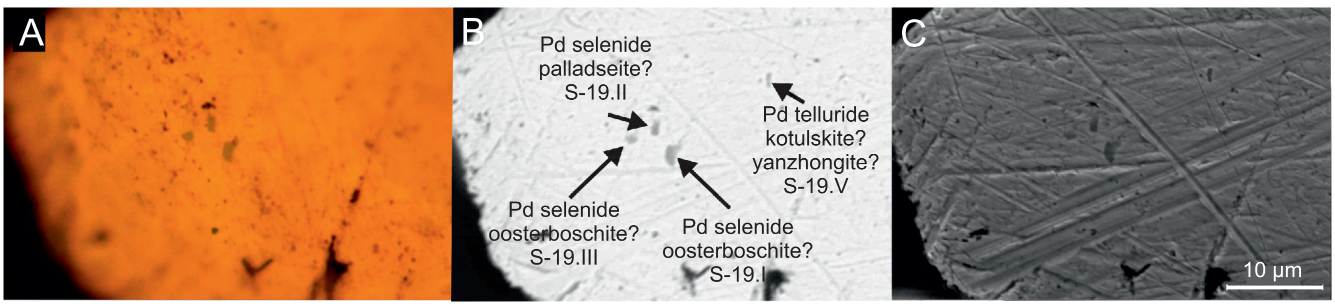

Fig. 8. Enlargement of section A – inclusions of selenide and telluride composition within the S-19 gold grain

A – image in reflected light, **B** – BSE image, **C** – SE image; BSE image with the marked location of the point analyses (results in Appendix 1), and the location of the zoomed section in Figure 7

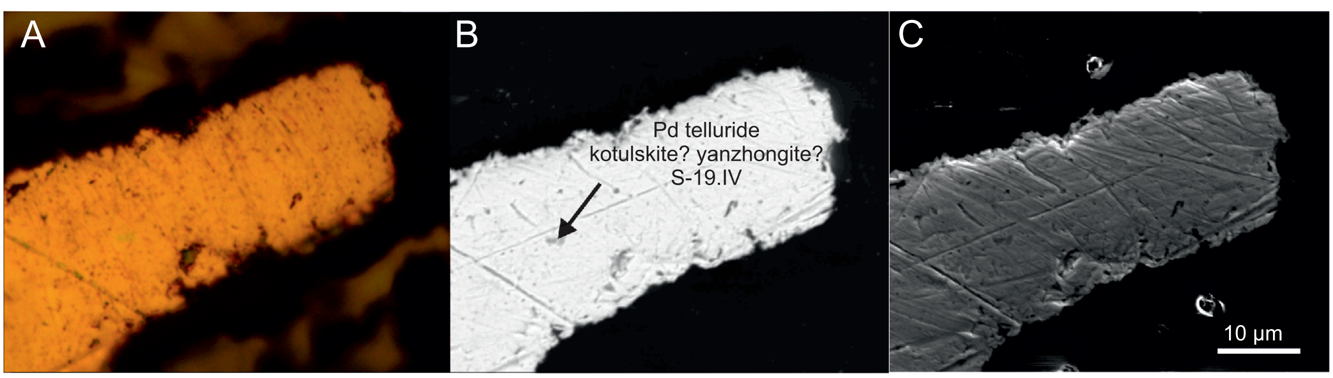

Fig. 9. Enlargement of section B – inclusion of telluride composition within the S-19 gold grain

A – image in reflected light, **B** – BSE image, **C** – SE image; BSE image with the marked location of the point analysis (results in Appendix 1), and the location of the zoomed section in Figure 7

Among the analysed population of gold grains from the Skora river's channel deposits, no multiphase amalgams were found. Although the S-16 grain (Fig. 5) indicates a distinct zonal structure, typical of bimodal-like gold grains characterized by these authors, the presence neither mercury nor palladium was confirmed. However, palladium was found in another, re-shaped-type, single-phase gold grain (S-19; Fig. 7), in which Pd occurs both in the form of an additive in alloy and as a compound of microinclusions of selenides and telluride. This suggests that not only the presence of mercury, but also that of palladium seems to be closely related to the bedrock gold's sources, which constitute primary deposits of widespread detrital gold of the North Sudetic Trough's Cenozoic cover.

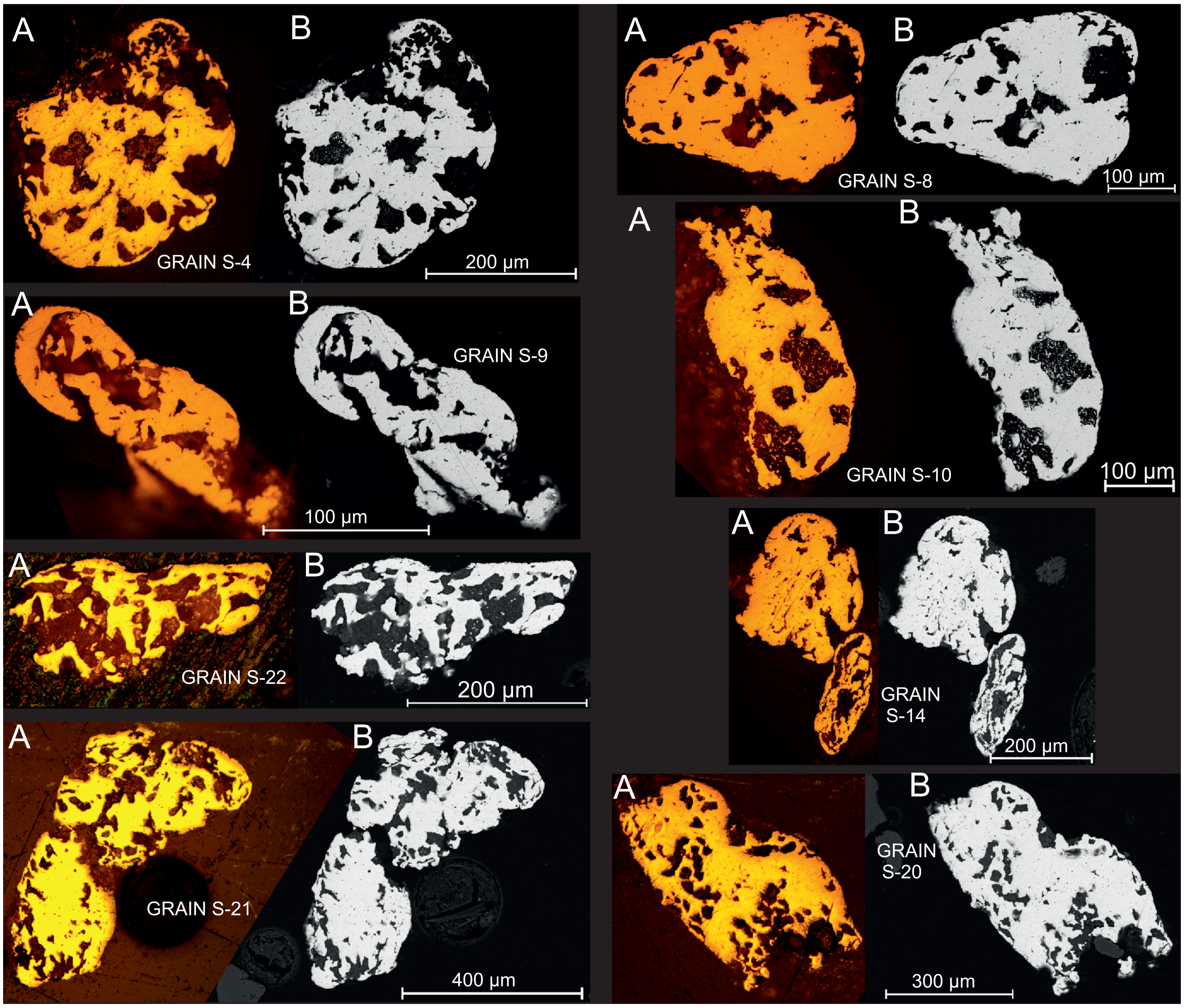

Fig. 10. Amalgams of presumed anthropogenic origin from the Skora River

A – image in reflected light, **B** – BSE image

According to the previously described inferences (Urbański, 2010; Oszczepalski et al., 2011; Wierchowiec and Zieliński, 2017; Kania, 2023), the source rocks should be sought mainly among local Cu-polymetallic Permian deposits. The presence of mercury and palladium admixtures in the local gold grains had already been described by Wierchowiec and Zieliński (2017) and associated with local red bed-type mineralization. The relationship between detrital gold enriched in palladium and red-bed type deposits was also suggested by Leake et al. (1995). Coexistence of gold and PGEs (platinum and palladium) within the secondary oxidized system of the Sieroszowice-Polkowice copper deposit was described in detail by Piestrzyński and Pieczonka (Piestrzyński and Pieczonka, 1998; Piestrzyński et al., 2002; Pieczonka and Piestrzyński, 2011, 2015 and the references therein). Outcrops of the Rotliegend and Zechstein units with the metalliferous contact zone between them are commonly found in the upper part of the Skora River drainage basin and near its central part, where they form the tectonic unit of the Grodziec Syncline (Fig. 2).

The results of mineralogical studies to date indicate that the paragenesis of selenides is characteristic of placer gold from Holocene occurrences in the Kaczawskie Foothills region; a similar mineral composition is found in placer gold from alluvial deposits between Lwówek Śląski and Bolesławiec, where numerous microinclusions of Cu, Ag-Au and Hg selenides are present (Kania, 2023). Earlier mineralogical studies of the Skora River sediments revealed the presence of sulphide and sulphoarsenide grains (Muszer et al., 2016). Their occurrence, particularly chalcopyrite with characteristic structures resulting from the decomposition of a chalcopyrite – sphalerite solid solution, suggest the possibility that at least part of the gold grains present in the Skora River may have migrated from weathering hydrothermal veins of the Kaczawa Metamorphic Complex: their mineralogical composition has been documented in detail by Mikulski (2005, 2007a, 2014 and the references therein). Although no microinclusions of sulphides and sulpharsenides were found in gold grains collected from the Skora River, such a paragenesis of microinclusions was identified in detrital gold from modern alluvial sediments of the Jamna Creek in the region of the Klecza-Radomice polymetallic veins, represented by galena and numerous Co-Fe-Ni sulphoarsenides and arsenides (Kania, 2018).

The gold grains occurring within the Holocene alluvial deposits of the Skora River are distinct from the other particles collected from nearby modern detrital deposits in the presence of numerous spongy and oval grains of gold. Due to their shape, characteristic structure and presence of mercury they are considered as anthropogenic amalgams (Leake et al., 1995; Styles, 1995; Kelley et al., 2003; Muszer et al., 2016): products of the amalgamation process, commonly used for obtaining the finest gold grains of the dust fraction, that are difficult to obtain manually or by methods of gravitational separation. In the case of gold grains of this type, performing analyses using polished sections is of particular importance. As can be observed based on Figure 3, anthropogenic amalgams are characterized by their relatively high K index (often >4.0), conditioned not so much by their complex outlines as by the high porosity. The K index inherently considers only effective porosity (Kania, 2020), while observations made in reflected light reveal the actual complexity of the anthropogenic amalgams' internal structure (Fig. 10). This diagnostic feature can be noted only where gold grains have been sectioned. Morphological analyses limited only to macroscopic observations and analyses of uncut grains may lead to their recognition as well-rounded, reshaped gold particles (*sensu* DiLabio, 1991) and erroneous conclusions regarding long-distance transport of grains from the source rocks.

Also, gold grains with characteristics indicating their natural origin (such as S-16, S-17 and S-19) are finer than their analogues with distinct anthropogenic features, set together on Figure 10 (compare with Fig. 3). The maximum diameter of the three grains noted ranges from ~175 to 700 μm (average 372 mm), whereas the amalgams shown in Figures 6 and 10 range from ~300 to over 900 μm (average 546 μm). The size differences between the grains from the two populations seem to result from the nature of the amalgamation process, in which finer gold grains, difficult to identify macroscopically, are dissolved in mercury. By evaporating the mercury from the resulting Hg-Au solution, larger gold grains are obtained, making them easier to separate.

The presence of numerous porous Hg-bearing grains in the local alluvial sediments may indicate intensive use of mercury, though determination of the timing of their formation remains problematic (Muszer et al., 2016). The application of amalgamation methods in gold recovery in Lower Silesia dates back to the 1770s, but its use on an industrial scale was abandoned after a short time due to the significant consumption of mercury and high production costs (Quiring, 1913; Dziekoński, 1974). However, mercury is also used nowadays for gold amalgamation both by amateur prospectors and by artisanal and small-scale gold mining (ASGM). “Amateur” amalgamation seems to be taking place in Poland from the evidence of pure mercury in the modern channel-fill deposits (Muszer and Ćwiertnia, 2018). Amalgamation on a larger scale, realized by ASGM, is a huge environmental problem (Alpers et al., 2016), especially in the Amazon Basin and in Africa, despite the fact that application of Hg in gold recovery is considered illegal in most countries (Gerson et al., 2022; Abdelaal et al., 2023 and references therein).

Besides amalgams, the channel-fill deposits of the Skora River are also enriched in other grains of presumed industrial origin, represented by Fe-Ti-V-Si spherules. The spherules' size and composition indicate their formation through specialized metallurgical activity (Muszer, 2007; Muszer et al., 2016).

CONCLUSIONS

1. The occurrence of the Skora River gold-bearing sediments represents the third case, after the Jamna (Kania, 2018) and Żeliszowski (Kania, 2023) creeks, where identification of microinclusions of ore minerals within gold grains from Polish placer deposits has been made. The addition of such analyses to the standard chemical and morphological tests can provide a valuable tool for investigations into the origin of detrital gold.

2. The source rocks of the detrital gold collected from the Skora riverbed are represented most likely by the local Permian red beds, what makes their presumed origin similar to that of most gold grains occurring in the modern alluvial sediments of the Kaczawa and Izera foothills (Urbański, 2010; Muszer, 2011; Wierchowiec and Zieliński, 2017; Kania, 2018, 2023). This interpretation is supported by the chemical composition of the microinclusions present in the gold grains, though other types of source rock, especially hydrothermal veins of the Kaczawa metamorphic complex, cannot be excluded.

3. Holocene gold-bearing sediments of the Skora River constitute a model example of a significantly anthropogenically modified placer gold deposit, in which amalgamation products amount to several tens of percent of all gold grains collected and analysed. Moreover, the influence of human activity on the development of local river sediments is also shown by the presence of spherules of industrial origin (Muszer et al., 2016). Determining the extent of the use of the amalgamation method for gold extraction both locally and generally for Lower Silesian gold-bearing deposits, and as regards sources of the mercury, the impact of mercury emissions on the environment, and the formation of modern gold-bearing sediments, requires further study.

4. To identify amalgams of presumed anthropogenic origin, analyses must be performed on sectioned particles, otherwise they may appear as naturally rounded grains, typical for long-distance transport from a source area. In addition to their curved shape and relatively large size (in comparison to gold grains of natural origin), the diagnostic features of artificial amalgams include a strongly developed spongy texture throughout the entire volume of the grains, as well as trace amounts of mercury, whose distribution within the grains shows no spatial relation to the distribution of silver.

5. Natural amalgams, identified so far in the Cenozoic deposits of the Kaczawa and Izera foothills region (Wierchowiec and Zieliński, 2017; Kania, 2018, 2023), differ from artificial amalgams by more diverse morphology and a bimodal structure, in which mercury appears to preferentially concentrate in phases with higher silver content, while the silver-depleted phases commonly show a porous structure.

Acknowledgements. The authors would like to thank the editors and reviewers for constructive comments which helped to improve this manuscript.

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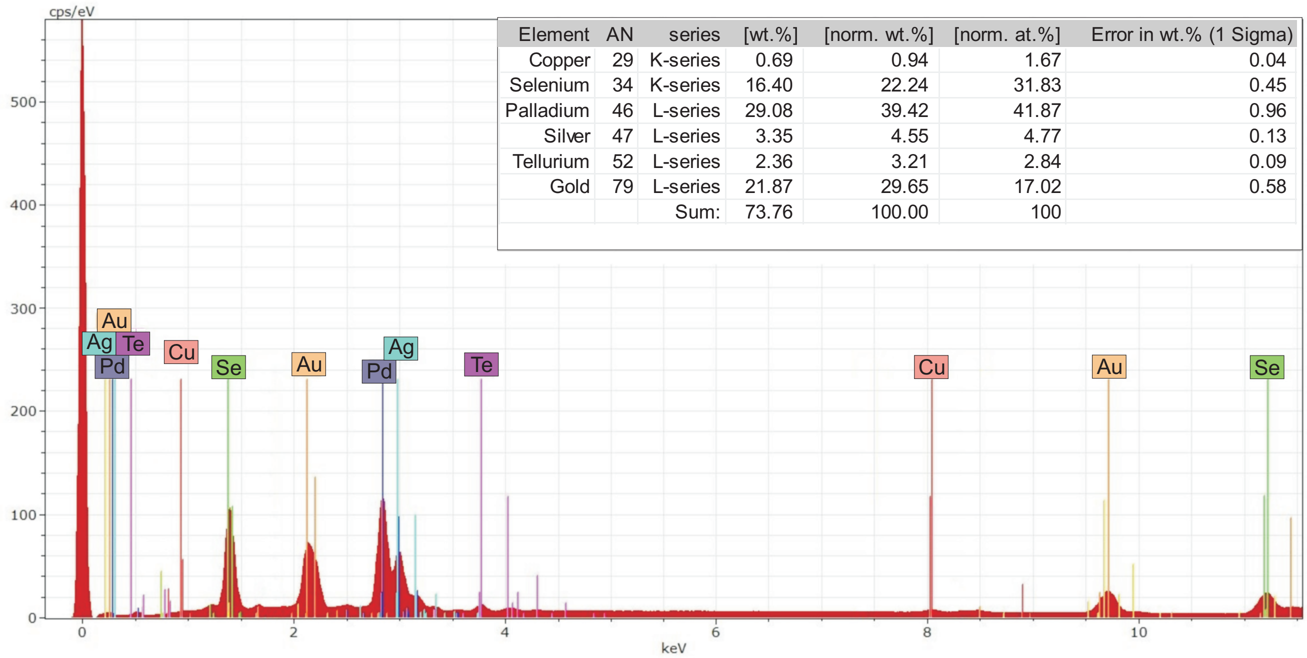
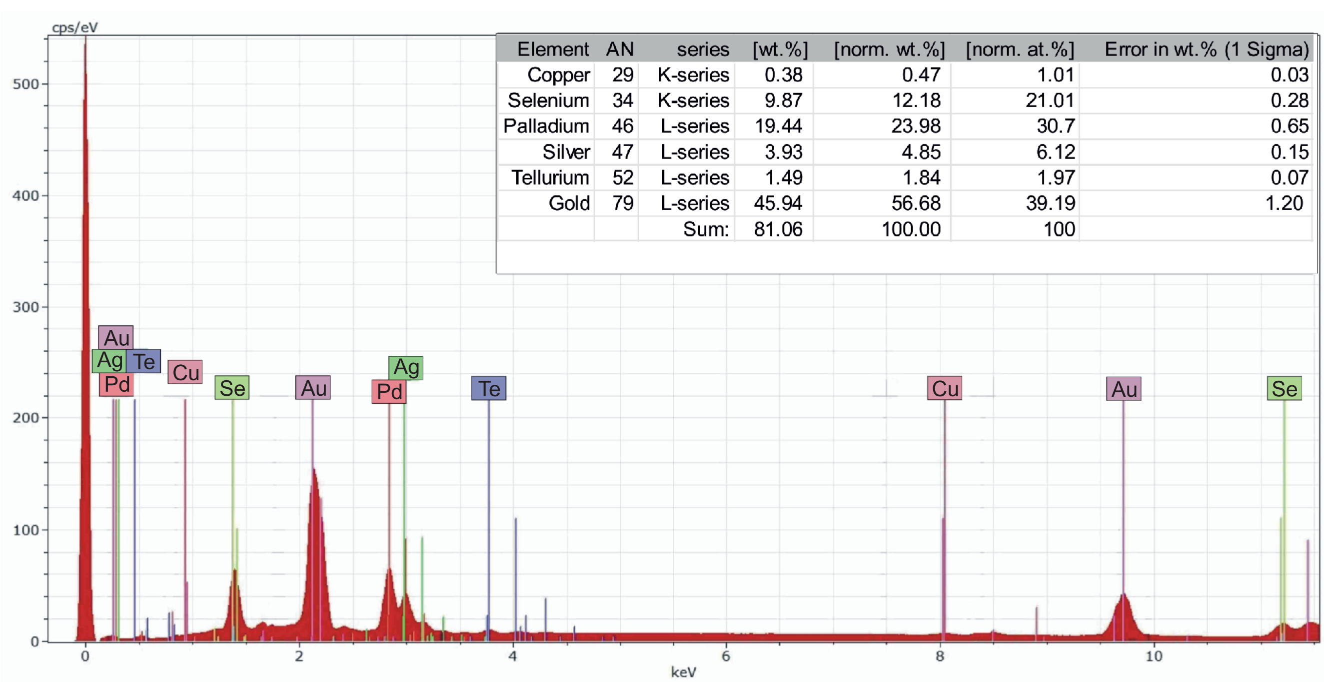
APPENDIX 1

Characteristic EDS spectra and elemental compositions of the microinclusions identified within the gold grains examined from the Skora channel-fill deposits. The detailed methodology of the EDS analyses is described in Kania (2023)



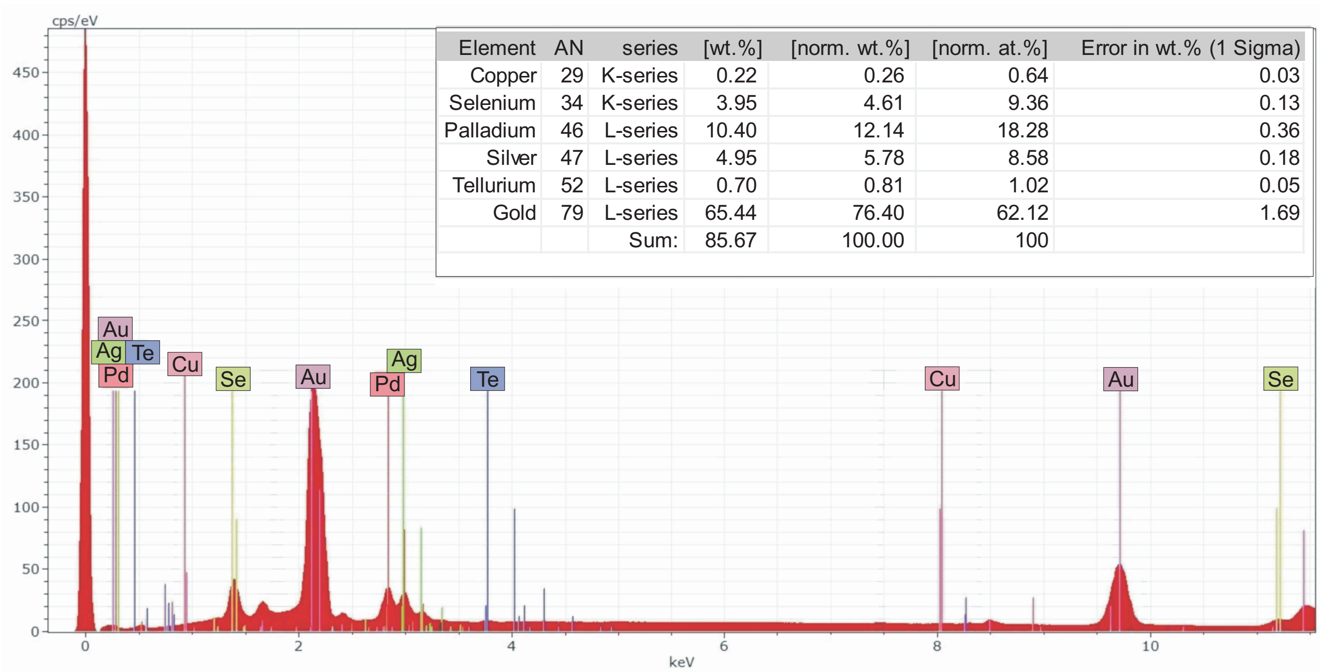
Element	AN	series	[wt.%]	[norm. wt.%]	[norm. at.%]	Error in wt.% (1 Sigma)
Copper	29	K-series	0.69	0.94	1.67	0.04
Selenium	34	K-series	16.40	22.24	31.83	0.45
Palladium	46	L-series	29.08	39.42	41.87	0.96
Silver	47	L-series	3.35	4.55	4.77	0.13
Tellurium	52	L-series	2.36	3.21	2.84	0.09
Gold	79	L-series	21.87	29.65	17.02	0.58
		Sum:	73.76	100.00	100	

Fig. I. X-ray spectrum and results of point analysis S-19.I: a selenide with the elemental composition of oosterboschite within the S-19 gold grain



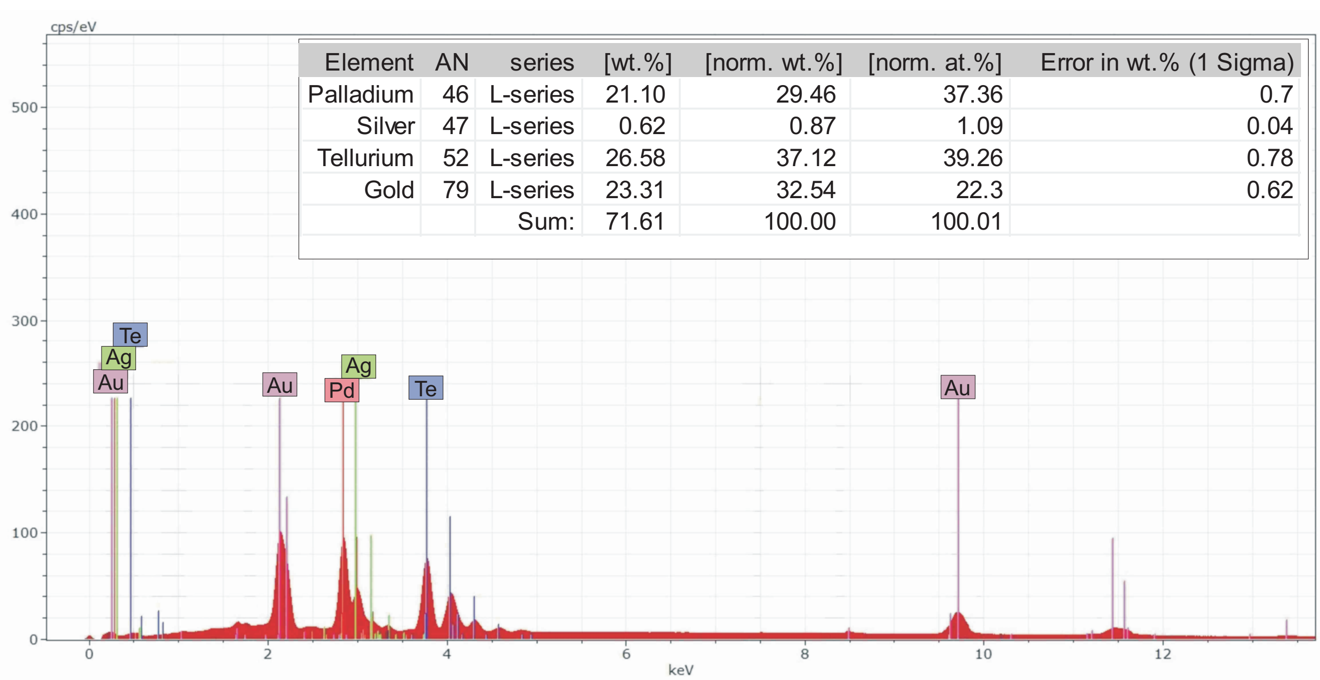
Element	AN	series	[wt.%]	[norm. wt.%]	[norm. at.%]	Error in wt.% (1 Sigma)
Copper	29	K-series	0.38	0.47	1.01	0.03
Selenium	34	K-series	9.87	12.18	21.01	0.28
Palladium	46	L-series	19.44	23.98	30.7	0.65
Silver	47	L-series	3.93	4.85	6.12	0.15
Tellurium	52	L-series	1.49	1.84	1.97	0.07
Gold	79	L-series	45.94	56.68	39.19	1.20
		Sum:	81.06	100.00	100	

Fig. II. X-ray spectrum of point analysis S-19.II: a selenide with the elemental composition of palladseite within the S-19 gold grain



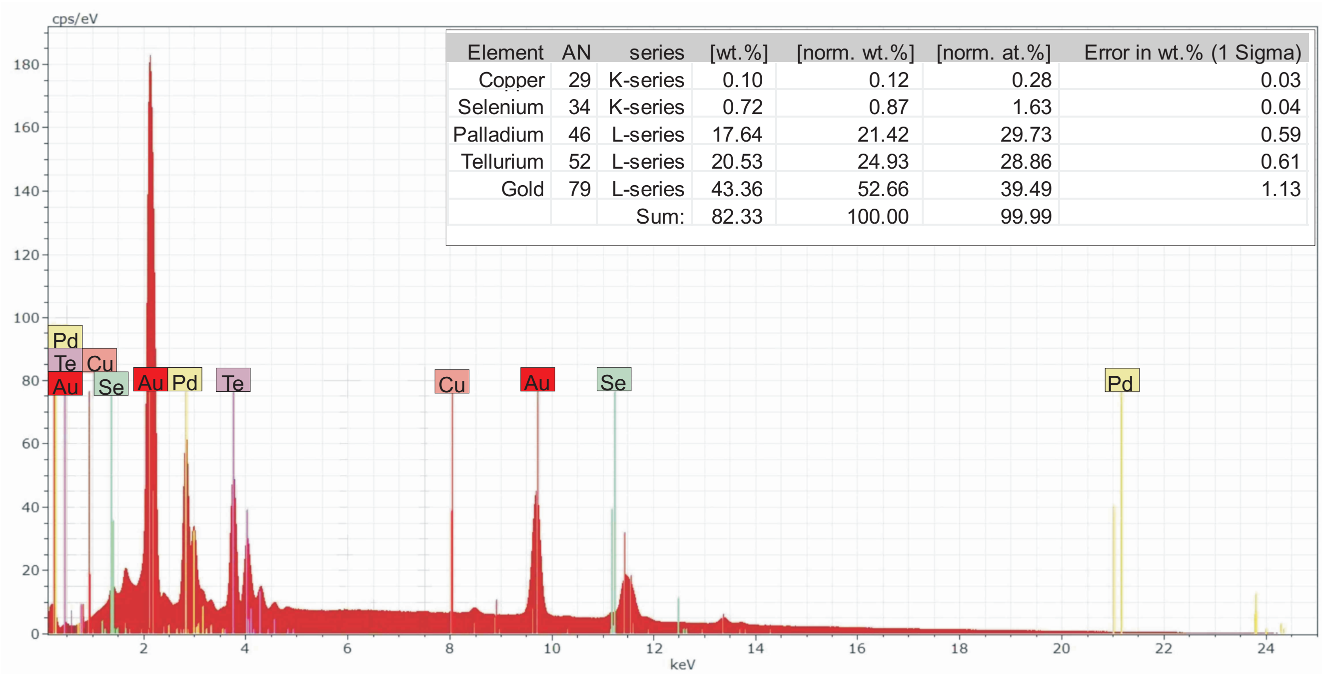
Element	AN	series	[wt.%]	[norm. wt.%]	[norm. at.%]	Error in wt.% (1 Sigma)
Copper	29	K-series	0.22	0.26	0.64	0.03
Selenium	34	K-series	3.95	4.61	9.36	0.13
Palladium	46	L-series	10.40	12.14	18.28	0.36
Silver	47	L-series	4.95	5.78	8.58	0.18
Tellurium	52	L-series	0.70	0.81	1.02	0.05
Gold	79	L-series	65.44	76.40	62.12	1.69
		Sum:	85.67	100.00	100	

Fig. III. X-ray spectrum of point analysis S-19.III: a selenide with the elemental composition of oosterboschite within the S-19 gold grain



Element	AN	series	[wt.%]	[norm. wt.%]	[norm. at.%]	Error in wt.% (1 Sigma)
Palladium	46	L-series	21.10	29.46	37.36	0.7
Silver	47	L-series	0.62	0.87	1.09	0.04
Tellurium	52	L-series	26.58	37.12	39.26	0.78
Gold	79	L-series	23.31	32.54	22.3	0.62
		Sum:	71.61	100.00	100.01	

Fig. IV. X-ray spectrum of point analysis S-19.IV: a telluride with the elemental composition of kotulskite within the S-19 gold grain



Element	AN	series	[wt.%]	[norm. wt.%]	[norm. at.%]	Error in wt.% (1 Sigma)
Copper	29	K-series	0.10	0.12	0.28	0.03
Selenium	34	K-series	0.72	0.87	1.63	0.04
Palladium	46	L-series	17.64	21.42	29.73	0.59
Tellurium	52	L-series	20.53	24.93	28.86	0.61
Gold	79	L-series	43.36	52.66	39.49	1.13
		Sum:	82.33	100.00	99.99	

Fig. V. X-ray spectrum of point analysis S-19.V: a telluride with the elemental composition of kotulskite within the S-19 gold grain