Geological Quarterly, 2017, **61** (1): 62–80
DOI: http://dx.doi.org/10.7306/gq.1315

Origin of placer gold and other heavy minerals from fluvial Cenozoic sediments in close proximity to Rote Fäule-related Au mineralisation in the North Sudetic Trough, SW Poland

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Wierchowiec, J., Zieliński, K., 2017. Origin of placer gold and other heavy minerals from fluvial Cenozoic sediments in close proximity to Rote Fäule-related Au mineralisation in the North Sudetic Trough, SW Poland. Geological Quarterly, **61** (1): 62–80, doi: 10.7306/gq.1315

Detailed morphological and geochemical studies of placer gold grains and other heavy minerals from Cenozoic fluvial clastic sediments in the area of the Zimnik Creek drainage basin (North Sudetic Trough, Lower Silesia) allowed the description of their specific features: shape and morphology, flatness index, internal textural features and chemical composition of the gold grains. It enables an estimation of the distance from the source area and determination of the source of the ore mineralisation, along with establishing the feeder areas for placer mineralisation including Rote Fäule-related gold hosted by Rotliegend-Zechstein transitional sediments. The comparison of the heavy mineral contents of placer grains from the Zimnik Creek drainage basin makes it possible to identify the area of origin for the gold particles. The crystalline Au-Ag-Pd-Hg (polymetallic) alloy grains of fluvial gold are assumed to come from the transitional sediments between the Rotliegend and the Zechstein in the North Sudetic Basin. The morphological and geochemical features of the polymetallic grains strongly suggest that the grains from the upper course of the Zimnik Creek valley sediments represent what has eroded from the local gold mineralisation and this mineralisation is probably in the vicinity of the upstream sampling site. The bimodal chemical composition of the Au-Ag-Pd-Hg alloy grains with electrum and medium-Ag grains (<15 wt.% Ag) found in the study area is typical of the Rote Fäule and Kupferschiefer-related gold mineralisation on the southern side of the North Sudetic Trough and the Sieroszowice-Polkowice copper mining district of the Fore-Sudetic Monocline. The study of the Ag contents of placer grains from the Zimnik Creek drainage basin highlights the contrast between the placer gold grains derived from Paleozoic orogenic gold mineralisation in the Sudetes (typically simple Au-Ag alloys containing between 5 and 20 wt.% of Ag) and the one formed by the oxidizing chloride hydrothermal systems. The grains identified in this manner as originating from the oxidizing hydrothermal system of the transitional zone can be distinguished from the placer gold derived from other styles of mineralisation, which are not Rote Fäule-related. It is particularly important considering the ongoing reconnaissance exploration in the North Sudetic Trough (SW Poland), which employs gold grain analyses as a prospecting tool for the detection of potentially economic primary gold mineralisation.

Key words: gold, Au-Ag-Pd-Hg alloys, placer minerals, Rote Fäule, North Sudetic Trough, Sudetes.

INTRODUCTION

Morphological and geochemical studies of placer gold and other heavy minerals are widely used in mineral exploration and may considerably contribute to the determination of the source of ore mineralisation and to establishing the parent area for placer mineral accumulations (e.g., Youngson, 1998; Chapman et al., 2000; Wierchowiec, 2002; Townley et al., 2003; Nikolaeva and Yablokova, 2007; Dill et al., 2014). The study of the physical/mechanical dispersion around ore deposits has been considered a valuable tool in prospection and exploration (Averill, 2011, 2014; Beaudoin, 2014). The resultant eluvial-colluvial and alluvial sediments containing minerals and lithoclasts can be checked for diagnostic heavy minerals which may assist in the creation of an image of the primary deposit much better than using chemical exploration as a stand-alone method (McClengahan, 2005; McClengahan and Cabri, 2011; Mikulski and Wierchowiec, 2013; Youngson, 2014). Joint mineralogical and chemical studies of placer mineral assemblages from tributary rivers to ephemeral drainage systems of small creeks containing placer minerals offer a tool to delineate fertile source areas in basement rocks (Chapman and Mortensen, 2006; Dill et al., 2009; Chapman et al., 2010).

The detailed survey and studies of the geological material collected from numerous locations in the North Sudetic Trough revealed high concentrations of gold in limited samples of the Rotliegend-Zechstein transitional rocks (Speczik and Wojciechowski, 1997; Wojciechowski, 2001; Oszczepalski et al., 2011). The increased amounts of gold with a maximum of up to 5.190 ppb of Au are closely associated with the red-coloured (Rote Fäule) oxidized sequence – in the Weissliegend to Basal Limestone transitional zone of the Kupferschiefer series that

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Received: December 15, 2015; accepted: February 17, 2016; first published online: September 22, 2016

underlies the reductive Cu-Ag-bearing strata (Wojciechowski, 2001). The presence of gold in the oxidized rocks is characterized by submicroscopic dissemination (Oszczepalski et al., 2011). Macroscopically or microscopically visible gold or composites of native gold and electrum with iron oxyhydroxides and copper sulphides were not observed. These types of heavy minerals are the centerpiece of the current investigation.

This paper presents the mineralogical data for Cenozoic Au-Pd-Hg placer mineralisation in the Zimnik River stream sediments and its ephemeral tributary unnamed creeks (upstream proximal placers). The Au-Pd-Hg placer mineralisation, although sub-economic in size and grade, may be used as an ore guide leading the exploring geologists to the potential primary deposits.

METHODS AND MATERIALS

The reported results were obtained using a wide spectrum of methods involving field and laboratory investigations. From each sampling site, a batch of samples was taken for further laboratory work, and another batch was obtained using a sluice box and a pan in order to get a rough image of the major heavy minerals already in the field, and to schedule the subsequent activities in the laboratory.

The sample material processed in this work was collected from 1.5–2.5 m deep prospective outcrops, not reaching the surface of the fresh protore rock wall. In order to obtain representative samples, each horizon was sampled by means of the channel chip sampling technique along its thickness and thoroughly mixed to yield a homogeneous 10–20 l sample.

A total of 64 panned heavy mineral samples have been taken from the eluvial-colluvial and alluvial sediments and from the active channels of the Zimnik River stream sediments and its ephemeral tributary unnamed creeks.

Field samples were reprocessed in the laboratory by repeated careful panning of concentrates in combination with the laboratory Knelson centrifugal concentrator which can handle particle sizes from >10 µm to a maximum of 5–6 mm and was originally designed for concentration of gold and platinum from placer and bedrock samples (McClengahan, 2014; www.knelsongravitysolutions.com). Special care was taken to save as much of the fine gold as possible, but some extremely fine gold grains (<10 µm) may have been lost.

During the routine analyses, the heavy mineral concentrates were divided into ferromagnetic, paramagnetic and non-magnetic fractions using the Ventouse magnet (made by Allevard Ugine, France). The light part of non-magnetic fraction was removed by separation in bromoform (density 2.89 g/cm^3). The heavy minerals were identified, with 200 to 300 grains per sample counted under the petrographic microscope in reflected and transmitted light as described by Mange and Maurer (1992). Photomicrographs were taken using the *Nicon* automatic microscope camera.

All visible gold grains were separated from the reprocessed samples by hand-picking under a binocular microscope and weighed. The gold content was expressed as the number of grains counted in the sample per cubic metre (Kanasiewicz, 1982). The grains were classified according to their morphology; some were selected for further study.

Roundness was assessed qualitatively using the class system of Powers (1953). Particle flatness was determined under a binocular microscope fitted with a micrometer ocular by measuring the length of the three mutually perpendicular axes of gold particles. This data was used to calculate the flatness index:

$$F.I. = (a + b)/2c$$

where: “a” and “b” are the long and intermediate axes of the gold particle and “c” is the short axis that is reduced by flattening (see Cailleux, 1945; Wierchowiec, 2002).

The Cailleux index is a measure of the transport-induced mass redistribution (i.e. shape change) of gold grains by progressive hammering and/or folding in the fluvial system. It has been used for Bolivian (Hérail et al., 1990), New Zealand (Youngson and Craw, 1999) and Lower Silesian (Mikulski and Wierchowiec, 2013) placer gold studies.

Gold grains representing different morphological classes were investigated under the *Jeol JSM-6380LA* scanning electron microscope in an energy-dispersive mode (EDS Link Analytical ISIS) in order to study the morphology and obtain the semi-quantitative chemical data. The operating conditions were: 20kV accelerating voltage, 5 mm spot size and 6 nA sample current. The ZAF-4 correction program was applied. Additionally, gold grains representing different morphologies were embedded in epoxy resin, polished and viewed under reflected polarized light. Quantitative chemical analyses (EMPA) of gold grains were conducted by means of the *Cameca SX100* electron microprobe equipped with five wavelength-dispersive spectrometers. Representative gold grains were analysed for: Ag, As, Au, Bi, Cu, Fe, Hg, Pb, Pd, Pt, S, Sb, Se, Sn, Te and Zn. Pure metals (Ag, Au, Cu, Pd, Se, Pt), pure galena (Pb, S), sphalerite (Zn), HgTe (Hg), GaAs (As), InSb (Sb), cassiterite (Sn), and hematite (Fe) were used as standards. The operating conditions for EMPA were: 25kV accelerating voltage, 2 x 10–8A primary beam current, 25 sec counting time, and the detection thresholds (wt.%): for Au – 0.121, Ag – 0.033, Cu – 0.015, Te – 0.019, Se – 0.006, Bi – 0.046, Hg – 0.038 and for Pd – 0.017. Natural mineral standards and the ZAF-4 were used.

Core and rim compositions of gold grains were obtained separately. “Core” analyses refer to the central part of the grain in a polished section. Mappings were made for representative grains to check for changes in the chemical composition from the grain centres to the edges. SEM and microprobe analyses were performed at Warsaw University of Technology (Poland).

GEOLOGICAL SETTING

The studied eluvial-colluvial and alluvial sediments are underlain by the rocks of the Kaczawa Metamorphic Complex (the Złotoryja-Luboradz Unit) and the Grodziec Syncline, which constitutes the northeastern margin of the North Sudetic Trough where Rotliegend-Zechstein transitional sediments are exposed in several outcrops (e.g., the Grodziec area, the Leszczyna–Nowy Kościół–Lwówek Śląski area; Sławińska-Krolisz, 1958; Konstantynowicz, 1965; Krasoń, 1967; Skowronek, 1968; Speczik and Wojciechowski, 1997; Wojciechowski, 2001, 2011). Currently, these Rotliegend-Zechstein brown to grey coloured rocks (conglomerates, sandstones and claystones) form a narrow zone in the outer part of the North Sudetic Basin (NSB) (Figs. 1 and 2).

The Kaczawa Complex is composed of low-grade metamorphic rocks of sedimentary and volcanic origin (Cambrian to Early Carboniferous age) and comprises fragments of a Variscan accretionary prism (Baranowski et al., 1990; Mazur et al.,

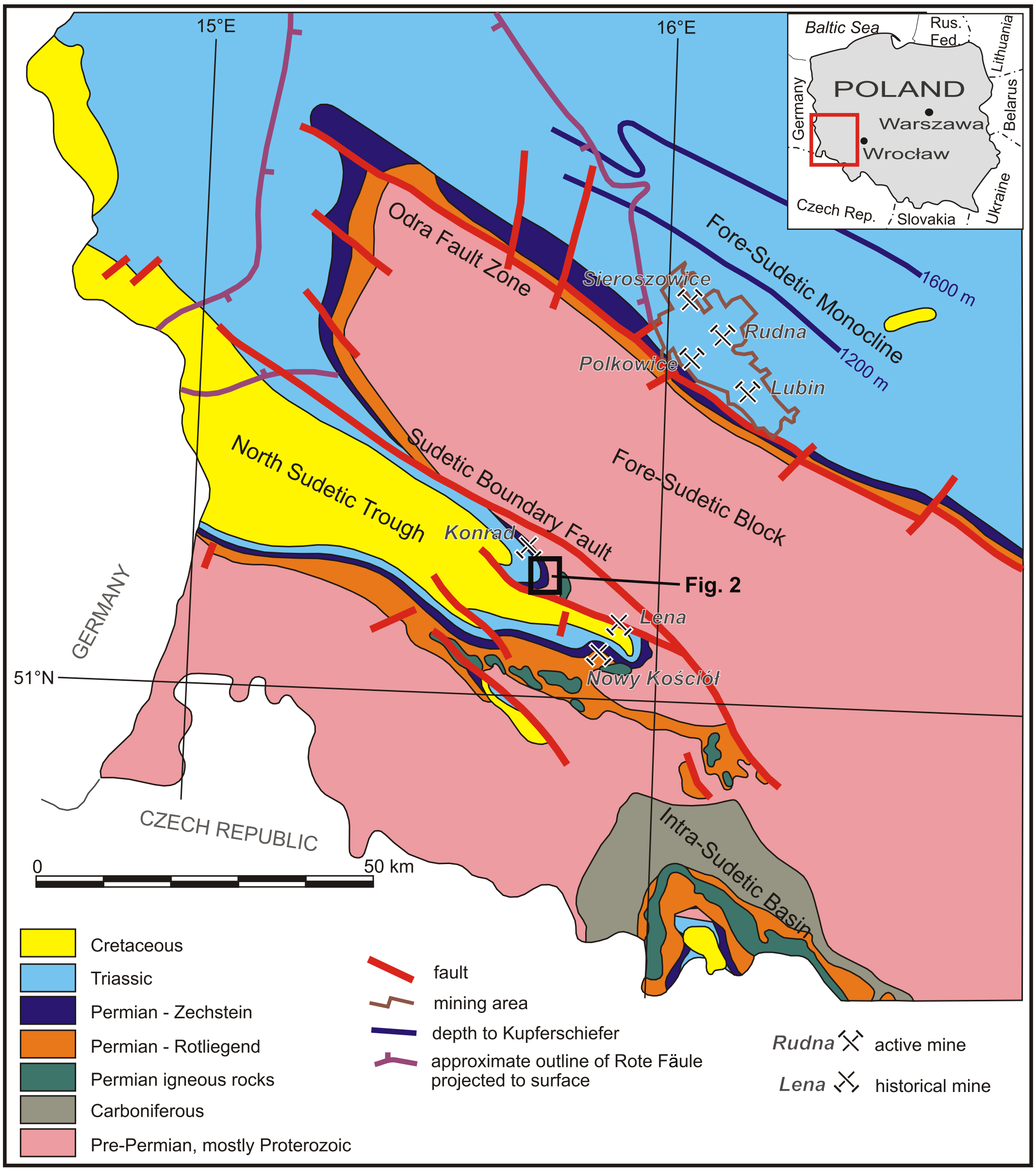

Fig. 1. Generalized geological-structural map of the Lower Silesia (compiled after Sawicki and Teisseyre, 1978; Oszczepalski et al., 2011) showing the location of the study area

2007). Within the Złotoryja-Luboradz Unit there are distinctive mélanges interpreted as products of continuous concurrent sedimentary and tectonic processes which formed structures comparable to those recorded in the recent accretionary wedges (Collins et al., 2000; Kryza, 2008).

The NSB developed as a late Paleozoic intramontane trough at the end of the Variscan orogeny. The post-Variscan Rotliegend molasse, followed by Zechstein marine deposits, Buntsandstein sandstones and Muschelkalk calcareous sediments, was ultimately covered by the Upper Cretaceous transgressive marine sandstones and marls. Sedimentation of the Rotliegend clastic sediments was accompanied by stretching of the substrate along WNW–ESE trending faults and by Early Permian bimodal volcanism.

The Lower Zechstein series within the NSB overlies the Upper Rotliegend polymictic brown to red conglomerates and sandstones, mostly consisting of fluvial, alluvial fan and minorly aeolian sediments (Pokorski, 1997). The Zechstein section within the North Sudetic Basin is condensed in comparison to that of the central part of the Zechstein Basin due to intraformational and epigenetic erosion, and formed by sediments of the first (PZ1) and third (PZ3) Zechstein cycles (Peryt, 1978; Peryt and Kasprzyk, 1992). Therefore, direct application of the Zechstein cyclothem lithostratigraphy has turned out to be problematic (Raczyński, 1997, 2010).

The lowest part of the PZ1 cycle was developed in near-shore palaeoenvironment and is represented by facies similar to those of the Kupferschiefer series of the Fore-Sudetic Monocline. In the North Sudetic Trough, where the Konrad, Lena and Nowy Kościół copper mines operated, the lowermost parts of the mine sections typically comprise Zechstein sandstones (conglomerates) of grey or mottled colour (lighter in tint compared to Rotliegend) above the red-coloured Rotliegend sandstones (Konstantynowicz, 1965; Krasoń, 1967; Speczik et

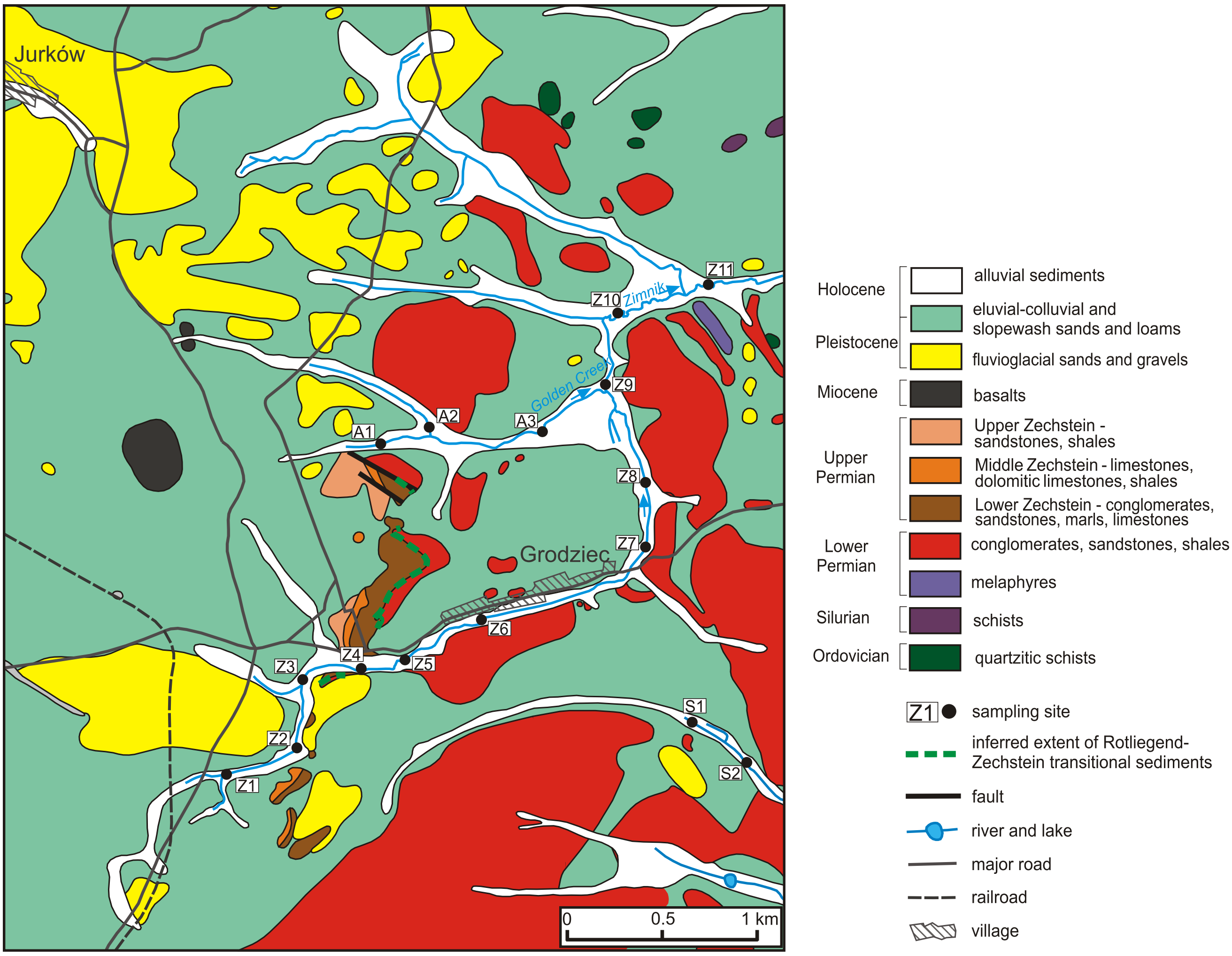

Fig. 2. Simplified geological map of the Zimnik Creek catchment basin area (North Sudetic Trough) (compiled after Sławińska-Krolisz, 1958; Milewicz and Jerzmański, 1959) showing the location of sampling sites (outcrops) for this study

The area is outlined in Figure 1

al., 1986; Kubiak et al., 1996). The Zechstein conglomerates and sandstones correspond to the Weissliegend sandstones of the Fore-Sudetic Monocline, which are continental in the lower part and marine in origin in the uppermost part (Oszczepalski, 1989). The Weissliegend is covered by micritic limestones (Basal Limestone). The bottom part of the Basal Limestone is commonly composed of mottled, brown to grey sandy claystones, classified as the lowermost Zechstein (Speczik and Wojciechowski, 1997; Wojciechowski, 2001). The carbonates of the Basal Limestone are overlain by spotted marls and copper-bearing marls, regarded as an equivalent of the Kupferschiefer horizon, lead-bearing marls, and the middle part of the Zechstein Limestone (Biernacka et al., 2005; Raczyński, 2010; Oszczepalski et al., 2011).

The marly-limy series along with the underlying Basal Limestone represent the carbonate rocks of the Zechstein Limestone (Ca1) of the evaporite-carbonate sequence of the first evaporitic Zechstein cycle (PZ1). The Ca1 sediments are usually 15 to 40 m thick and they were deposited in a narrow (20–30 km) and long (about 100 km) lagoon extending WNW–ESE. The PZ1 units are overlain by PZ3 carbonate and heterolithic sediments of the Permian/Triassic transitional series (Raczyński, 2010).

The main stage of the epi-Variscan cover deformation controlled by the NE–SW compression took place during the post-Cretaceous inversion of the basin. As a result of this process, the main framework of the North Sudetic Trough has been formed. During the Cenozoic the deformed substrate with numerous horsts and grabens was subjected to intensive chemical weathering and was punctured by basaltic necks (Badura et al., 2004). A low-relief landscape evolved during the Neogene in subtropical climates. During the Pleistocene glaciations, an alluvium consisting of coarse-sized, well-stratified gravel with sandy matrix was deposited by deeply scouring streams. After the last glaciation the competence of streams decreased and sand-sized sediments began to predominate in the stream deposits. Eluvial-colluvial and alluvial sediments which host placer gold and other heavy minerals in question were accumulated in bedrock depressions and intergraded with alluvia during the Late Pleistocene (Wierchowiec, 2010). At the end of the glacial period, channels of the present-day fluvial drainage system incised into the rocks and shaped the northeastern part of the

North Sudetic Trough base. The modern streams (the Zimnik Creek drainage basin) drain the Cenozoic slopewash clays with rock wastes, loess-like loams as well as Quaternary alluvial and glacial sediments.

ROTE FÄULE-RELATED MINERALISATION

Geological studies of the red-coloured basal Zechstein sediments referred to as "Rote Fäule" altered rocks (facies) and the related mineralisation show that the distribution of these facies and the Rote Fäule-related mineral zoning is useful as exploratory guidelines for both the Cu-Ag and Au-Pt-Pd deposits (Oszczepalski, 1999). In the North Sudetic Trough, the clearly oxidized Rote Fäule sediments are well-documented by numerous boreholes that penetrate the Kupferschiefer series in the area of the Konrad-Wartowice, Lena and Nowy Kościół deposits (Konstantynowicz, 1965; Skowronek, 1968; Oszczepalski et al., 2011) and in outcrops at the southern side of the North Sudetic Trough (Speczik and Wojciechowski, 1997; Wojciechowski, 2001). Oxidation affects predominantly (entirely or partly) the Weissliegend, Basal Limestone and Kupferschiefer (spotted marls and copper-bearing marls), but locally also the lowermost portion of the Zechstein Limestone (Oszczepalski et al., 2011).

Oxidized sediments contain hematite and iron oxyhydroxides in the form of grains and spherules, and as red pigment dispersed in the rock matrix. Iron oxyhydroxide pseudomorphs after framboidal pyrite and partial replacements of copper sulphides by hematite were also observed (Skowronek, 1968; Oszczepalski, 1989, 1999). Similar to the Fore-Sudetic Monocline, a transitional zone between the oxidized and reductive sediments is observed in the borehole profiles (Oszczepalski et al., 2011). This zone is characterized by coexistence of dispersed iron oxyhydroxides and sulphides (mainly covellite, bornite, chalcopyrite, pyrite and marcasite), the presence of copper sulphide relics corroded by hematite, and an intermediate copper content. This zone is also distinguished by a gradual upward change from red, through reddish to grey or black rocks.

The Rote Fäule-related gold mineralisation manifests itself as a thin bed (0.5 to 3.4 m in thickness) that intersects the lithostratigraphic units and underlies the copper orebodies (Oszczepalski et al., 2011). While the reductive sediments including Cu-Ag ores are commonly barren in gold, the highest gold concentrations are associated with the oxidized sediments of the Weissliegend – Basal Limestone contact zone (mottled, brown to grey sandy claystones), but not directly with the redox interface. Gold concentrations are locally accompanied by elevated amounts of Pd and Pt. The gold horizon is also characterized by low copper and low organic matter contents (Oszczepalski et al., 2011). The results of recent studies (Wierchowiec, 2010; Oszczepalski et al., 2011; Wojciechowski, 2011; Oszczepalski and Chmielewski, 2015) strongly suggest that further research and exploration for gold should be concentrated in the areas of post-depositional Rote Fäule oxidation. It seems likely that noble metals were primarily deposited in the oxidized sections of the Rotliegend-Zechstein transitional sediments over a large area of the Fore-Sudetic Block and were later removed by erosion, starting with intraformational Zechstein processes, and redistributed during the Cimmerian and Alpine tectonic movements, being one of the major sources for Cenozoic placer mineralisation in the region.

RESULTS

LITHOLOGY AND DISTRIBUTION OF PLACER DEPOSITS

Placer (heavy mineral) deposits are widespread in the channels of the present-day fluvial drainage system of the northeastern part of the North Sudetic Trough incised into the narrow zone of the Rotliegend-Zechstein transitional sediments. The trap sites of these heavy minerals are in the stream sediments of the Zimnik Creek and its tributary unnamed creeks (upstream proximal placers; Figs. 1 and 2).

Stream channels in the study area contain fluvial sediments that vary in composition and character from one channel to another and along the same stream valley. The channel-fill sediments are crudely bedded and consist essentially of pebble to sandy gravels with thin mud and clay lenses forming the top section. The pebble beds have a fine to coarse sandy matrix with a sizable proportion of silt particles; boulders are rare. Iron and manganese-stained beds occur at the base of some upward-fining sequences. Pebbles account for ~20–30% of these sediments by volume. Subangular to subrounded pebbles are dominated by milky quartz (60–80%) accompanied by rock fragments of siliceous schists, melaphyres, quartzites and quartzy sandstones as well as clasts of granitoids and locally basalts. A few-percent admixtures of glacially derived rocks were also noted.

In a longitudinal section from the headwaters to the river mouth, no regular variation of placer minerals is recognized (patchy heavy mineral accumulations are a few metres in length). The highest concentration was noted at the base of the channel gravels, between large pebbles and cobbles, which are known to create local turbulent zones with good placer traps (Wierchowiec, 2010).

GOLD AND OTHER HEAVY MINERAL CONTENT

Concentrations of placer gold and other heavy minerals in the sampled sediments vary considerably depending on the sampling site, being the highest at the base of the gravel horizons and significantly lower in the fine sandy sediments. In the gravels, heavy mineral concentrations vary from 506 to 2 430 g/m^3 for samples Z4/2 and Z8/3 (Table 1). The gold is locally abundant in coarse-grained sediments, but varies widely in concentration as reflected by the number of grains recovered at different horizons (Fig. 3). The Au grades range between traces and 0.03 g/m^3 with the maximum Au concentration noted in pockets of gravels at the base of the gold-bearing horizons (see Fig. 3, Z4).

Sands and sandy diamictons contained negligible amounts of gold. In all sampling sites the maximum Au concentration was noted in zones enriched in other heavy minerals, especially Fe-Ti oxides which predominate in the heavy mineral fraction of the studied sediments (Appendix 1*). Grains of homogeneous hematite, most of which are angular to slightly rounded, significantly prevail among the opaque phases (Fig. 4). Concentration of iron oxyhydroxides ranges from 16 to 35 vol.%. The polyphase grains (with magnetite-hematite, magnetite-ilmenite or magnetite-martite intergrowths), magnetite (all isotropic phases, including Ti-magnetite) and ilmenite are present in variable amounts.

* Supplementary data associated with this article can be found, in the online version, at doi: 10.7306/gq.1315

Table 1

Gold and other heavy mineral content with the proportion divided between the magnetic, para- and nonmagnetic fractions of the richest gold-bearing samples

Sampling site	Sample No.1	Volume of the sample [m^3]	Number of gold grains in the sample	Wt of gold [mg]	Heavy mineral content [g/m^3]			Gold content [g/m^3]
					magnetic fraction	paramagnetic fraction	non-magnetic fraction	
Zimnik Creek	Z2/3	0.02	6	<10	52.4	804.4	49.1	<0.01
	Z4/2	0.04	7	<1.0	22.0	506.3	51.2	<0.01
	Z4/3	0.04	15	1.3	42.7	1223.0	116.0	0.03
	Z4/4	0.04	7	1.2	35.9	997.2	123.1	0.03
	Z5/3	0.02	11	<1.0	24.2	793.0	118.6	<0.01
	Z6/3	0.04	7	<1.0	56.8	1352.3	293.2	<0.01
	Z7/3	0.04	5	<1.0	89.3	1827.4	352.4	<0.01
	Z8/3	0.04	5	<1.0	175.0	2430.0	607.5	<0.01
Golden Creek	A1/3	0.02	7	<1.0	8.5	216.3	19.7	<0.01
	A3/3	0.02	6	<1.0	18.6	495.7	55.7	<0.01

1 – sampling locations are shown in Figures 2 and 3

Some hematite grains contain “nucleus-like” inclusions of fresh or goethitised pyrite, chalcopyrite and sphalerite (Fig. 5).

The sediments contain considerable amount of apatite. Appendix 1 shows that the apatite content in the fine fraction (62–125 μm) of the Zimnik Creek averages at 7.3 vol.%, while a concentration of 4.3% occurs in the coarse fraction (126–250 μm). Lower concentrations (averaging 2.3 vol.%) of apatite occur in samples from the Golden Creek. The apatite forms anhedral to subhedral homogeneous grains (Fig. 6A). Zircon, rutile and cinnabar are other common non-magnetic minerals. Locally, zircon amounts up to 12.1% of the total volume of the fine-grained (62–125 μm) heavy mineral fraction and averages 3.1%. Lower concentrations (up to 6.5 vol.%) of zircon occur in samples from the Golden Creek (Appendix 1). Most of the zircons comprise transparent, short prismatic crystals with poorly to moderately rounded edges (Fig. 6B).

Rutile is present in all samples from the sediments with the concentrations varying between 1.5 and 6.1 vol.%, reaching its maximum in the fine-grained sand (Appendix 1). Typically, rutile occurs as rounded brownish red grains and does not show any peculiar morphology (Fig. 6C). Cinnabar occurs as red subangular to angular, unevenly shaped grains (see Fig. 6D). This mineral reaches the concentrations of 1.0 to 2.6 vol.% only in part of the samples, with a maximum in the fine-grained sand of the Zimnik Creek (Appendix 1). Cinnabar grains are also found in samples from the Golden Creek, but their content does not exceed 1.8 vol.%. This mineral demonstrates close relation to apatite.

The heavy mineral grains also contain garnets, epidote, amphiboles, pyroxenes, monazite, kyanite, tourmaline, andalusite, silimanite and topaz, but their concentrations for the individual minerals are <1wt.%.

GOLD CHARACTERISTICS

GRAIN SIZE, SHAPE AND MORPHOLOGY

Gold grains vary in size and shape along the sections studied. They are mostly free, only a few have inter- or overgrowths with other minerals (Figs. 7–10). In general, the gold grain-size varies in the studied placer from 0.13 to 0.90 mm. The average grain size of gold in different local areas of the Zimnik placer varies insignificantly (between 0.41 and 0.50 mm, with an average from the whole placer equalling 0.46 mm). Distributions within this range are typical of the Lower Silesia placer gold (see Grodzicki, 1963, 1969; Wierchowiec, 2006, 2007, 2011).

Most grains encountered in the heavy mineral sands from the Zimnik drainage system are flaky in shape, with folded edges. Some particles have been folded and then reflattened, or repeatedly folded (Fig. 7). A characteristic feature of these folded gold particles is the presence of peculiar forms known as “sandwich-like” gold grains. The “sandwiches” are formed as a result of intense deformations in the marginal parts of the grains with anomalously high flatness index. The high proportion of “sandwiches” in the studied sediments suggests that such particles have been exposed to lengthy transport. Similar conclusions were made by Hérail et al. (1990), Wierchowiec (2002) and Youngson (2014).

Most of the rounded and folded gold particles have rough surfaces, with scratches, hammer-marks, irregular surface etching pits and abraded embayments, from <1 to 30 μm across (Fig. 7). Sometimes, surface iron oxyhydroxide coatings which can form from the oxidizing fine clayey material are noted on placer gold particles (Figs. 7 and 10).

A detailed study reveals that some of the gold grains from the sediments of the upper course of the Zimnik Creek valley, close to the area where the channels of the present-day fluvial drainage system of Zimnik incised into the narrow zone of the Rotliegend-Zechstein transitional sediments, have a preserved “ore” appearance with crystal intergrowths and only partially corroded surface or distorted crystalline outlines (Fig. 7A–D). A few flaky gold particles with elements of skeletal growth were also found here.

The morphology of gold grains from the middle course (in the village of Grodziec) is generally similar to that of the gold from the upper part of the placer. However, there is a significantly increased amount of flaky forms and a higher degree of their roundness, with moderately rounded and even well--rounded grains (Fig. 7E–H). Some of the gold particles show marks of slight pressing and abrasion, due to which numerous quartz and Ti-mineral inclusions are overprinted by the surrounding elevations in the host gold grain surface.

In an attempt to give some quantitative measure on the degree of flatness of gold particles, the Cailleux flatness index

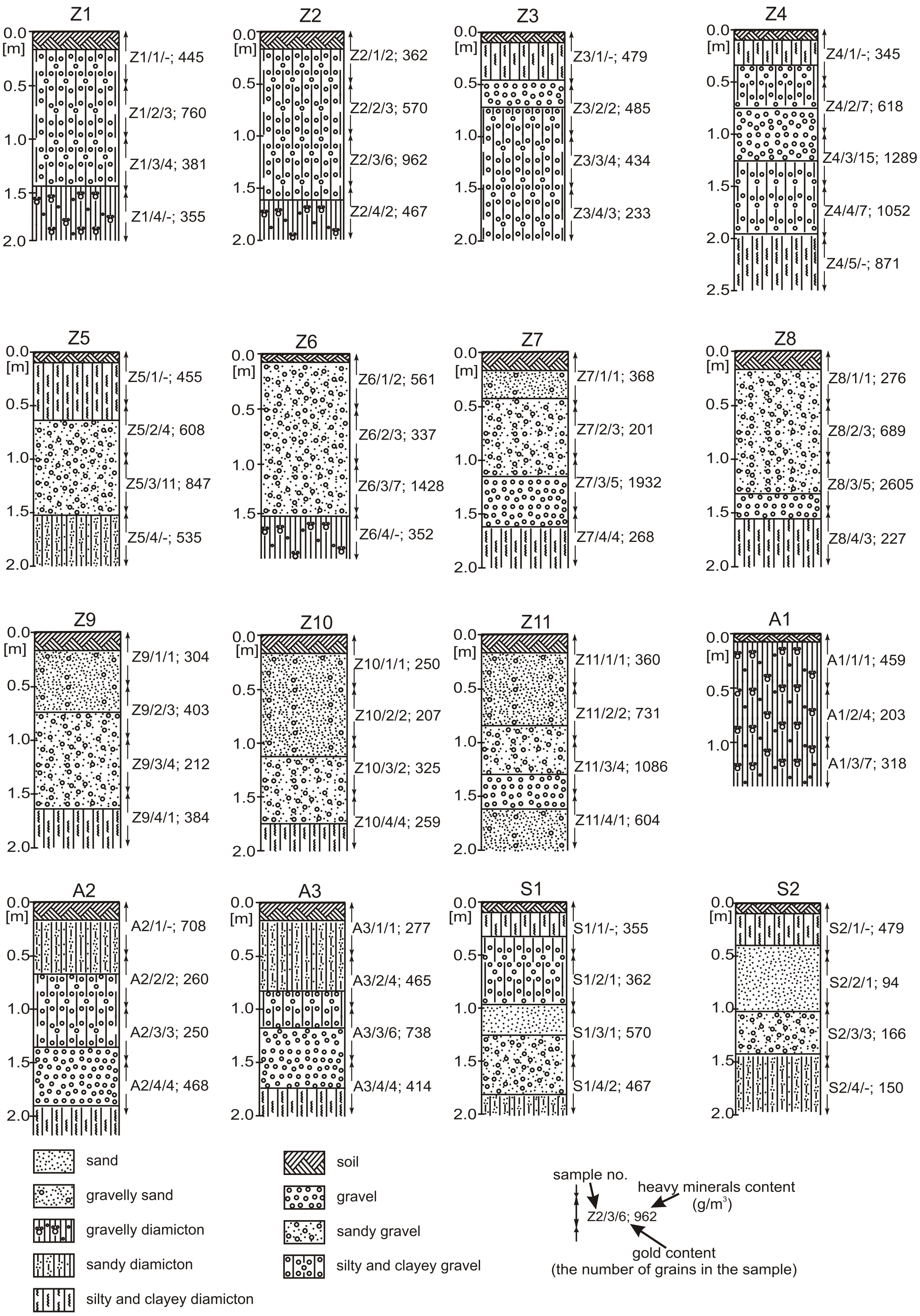

Fig. 3. Schematic outcrop sections of the representative gold-bearing sediments showing the location of samples presented in Figures 5–7 and 10

Locations of the sections are shown in Figure 2

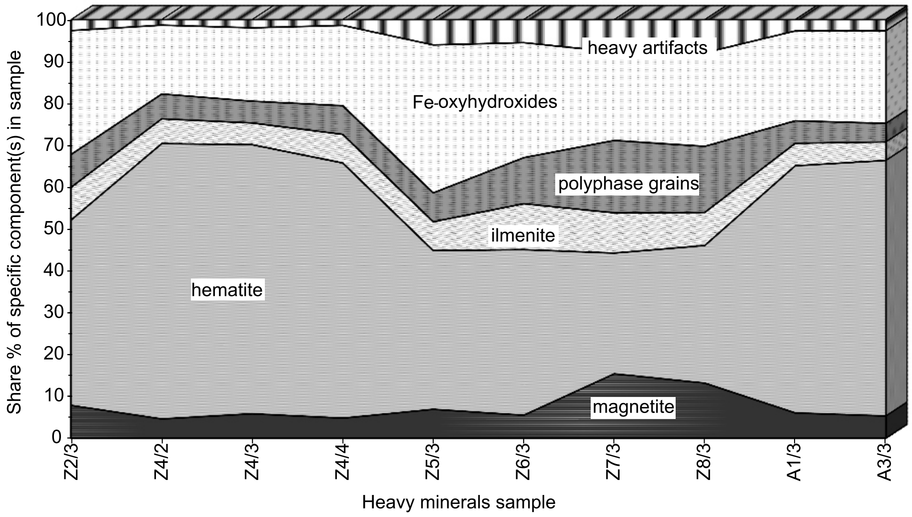

Fig. 4. Distribution of specific components of the opaque phase in the 63–250 µm grain size range of heavy mineral samples in the studied sediments from the Zimnik Creek catchment basin

(F.I.) has been devised as a measure of progressive flattening (Hérail et al., 1990; Youngson and Craw, 1999; Wierchowiec, 2002). Low F.I. is indicative of nearly spherical grains, whereas high values point to highly flattened particles. For the purpose of this paper, particles with the Cailleux index of >5 are regarded as flaky.

The F.I. for the total sampled gold grain population ranges from about 2 to as much as 19, with the predominance of grains with the F.I. <15. The average flatness index (X) is slightly lower for the gold from the upper course of the Zimnik Creek valley (X = 8.4) than for that from the lower part of the placer (X = 11.6). The correlation between the distribution of flatness index values and the lengths of the a-axis was recognized only for gold particles in the samples from the middle course of the Zimnik Creek. For these gold grains an increase in F.I. is observed as progressive hammering increases, which indicates increased flattening along with an increase in the grain size (x-axis length) (see Fig. 8). A histogram of the edge roundness data for gold particles shows that rounded and well-rounded grains are the most common. Sub-angular particles are rare and angular grains are totally absent. There is no correlation between flatness and roundness for the gold from different sampling sites (Fig. 9). Some populations of the studied gold grains have been reflattened after folding. These well-rounded gold particles are likely to have been recycled from palaeoplacer sources (Wierchowiec, 2002; Youngson, 2014).

The full range of flatness indexes for the individual samples can represent several gold inputs en route and particle folding. In the studied sediments, these gold inputs are: particles transported as free gold from local primary sources, particles recycled into the trunk rivers from palaeoplacers, particles recycled from Pleistocene till and particles rethickened to the subcritical flatness index by folding.

INTERNAL TEXTURE

A detailed SEM investigation of the internal textural features of the collected gold grains showed that, despite the above-mentioned differences in morphology, a number of them exhibit internal zonation ranging from relatively silver-rich cores to virtually silver-free rims. Similar features were reported for gold from elsewhere in the world, including the Lower Silesia region (e.g., Giusti, 1986; Hérail et al., 1990; Knight et al., 1999; Wierchowiec, 2007, 2010). The gold particles are rarely homogeneous, with no marked core to rim Au/Ag variation.

The rims are generally discontinuous, either conformable to the grain margin or irregular, usually ranging from 5–50 µm in thickness and massive or porous. In addition, they have irregular interconnected pits and canals, predominantly at the edges of the grains. Usually, the marginal pits and pockets are filled with fine-grained assemblages of amorphous silica or iron oxyhydroxides and clayey masses (Fig. 10). It suggests that this gold was subject to deep supergene corrosion and leaching. Internal heterogeneity in the zoned particles is clearly visible in polished sections (in reflected light or SEM backscattering; see Fig. 10) and was quantified by an EPMA analysis (Appendix 2). A back-scattered electron image of some grains (Fig. 10A) shows an internal and unusual linear or more irregular zonation (patches), which has a lower gold content (ca. 80 wt.%) than the brighter, outer area (>95 wt.%). The internal geometry of the heterogeneity (chemical composition) within the polished sections of these grains indicates the sequence of emplacement with a multitude of growth or diffusion zones. The composition of growth zones within the grains indicates that the Au, Ag and Pd elements must all have been carried together in the mineralising solution.

Some gold particles also show an apparent silver enrichment along fractures. The processes that formed the silver-enriched zones are not completely understood, but are thought to be late- or post-mineralisation due to their association with fractures and grain boundaries. This internal variation is interpreted to be a primary feature within the grain, and not related to alteration of the grain during or after transport.

Due to extensive dissolution, chemically purified grains with homogeneous chemistry from the interior to the margins are also present. In polished sections this type of particles shows a typical sponge-like texture with random pits and irregular canals (Fig. 10B, D). These porous “pure” gold grains (>99 wt.% Au) constituted only 4–5% of the studied gold parti-

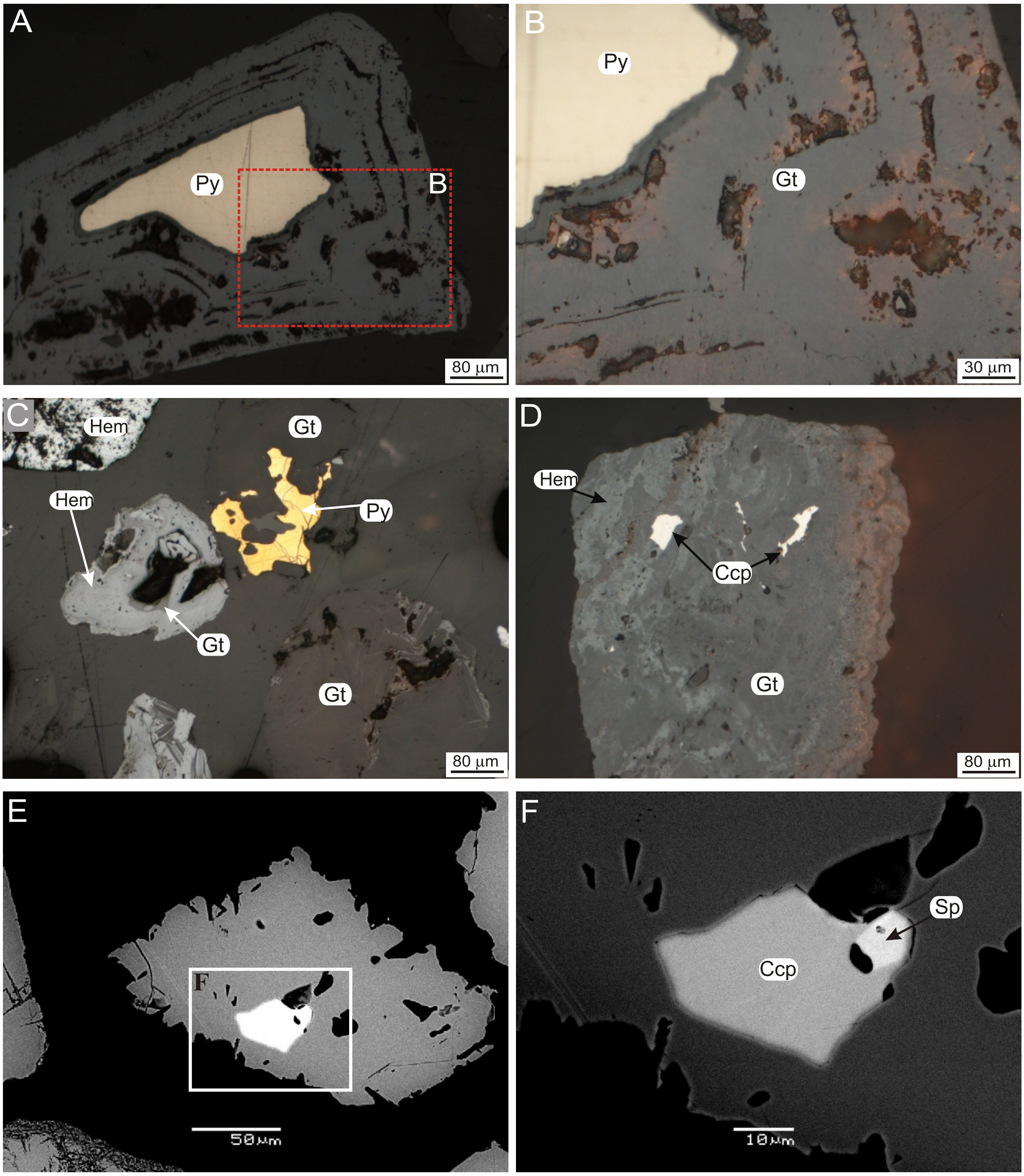

Fig. 5. Reflected light photomicrographs and back-scattered electron (BSE) images (E, F) of typical opaque heavy minerals in the 63–250 µm grain size range of the studied samples

A – extensive replacement of pyrite (Py) by goethite (Gt); the alteration proceeds along crystal edges; sample no. Z5/3; **B** – a close-up view of a grain showing details of the relationship between pyrite, goethite (gt) and filling of voids and pockets by iron oxyhydroxides and amorphous silica; **C** – an irregular inclusion of goethitised pyrite (yellow) in goethite (dark); sample no. Z5/3; **D** – chalcopyrite (Ccp) (light relics) extensively replaced by goethite (Gt) and hematite (Hem); sample no. Z4/4; **E** – a homogeneous, subhedral hematite grain with inclusion of chalcopyrite and sphalerite intergrowth (light), sample no. Z6/3; **F** – a close-up view of chalcopyrite (Ccp) and sphalerite (Sp) crystals; the sampling locations are shown in Figure 3

cles. This texture is equivalent, in two dimensions, to the textures observed on certain gold grains associated with sandy and gravely sediments from other regions of Lower Silesia (Wierchowiec, 2002, 2010, 2011).

CHEMISTRY OF GOLD

The chemical composition of the grains shows that gold is predominantly an Au-Ag alloy (70–90 wt.%), with minor “pure” gold (i.e., >99 wt.% Au). Some grains also have elevated Pd

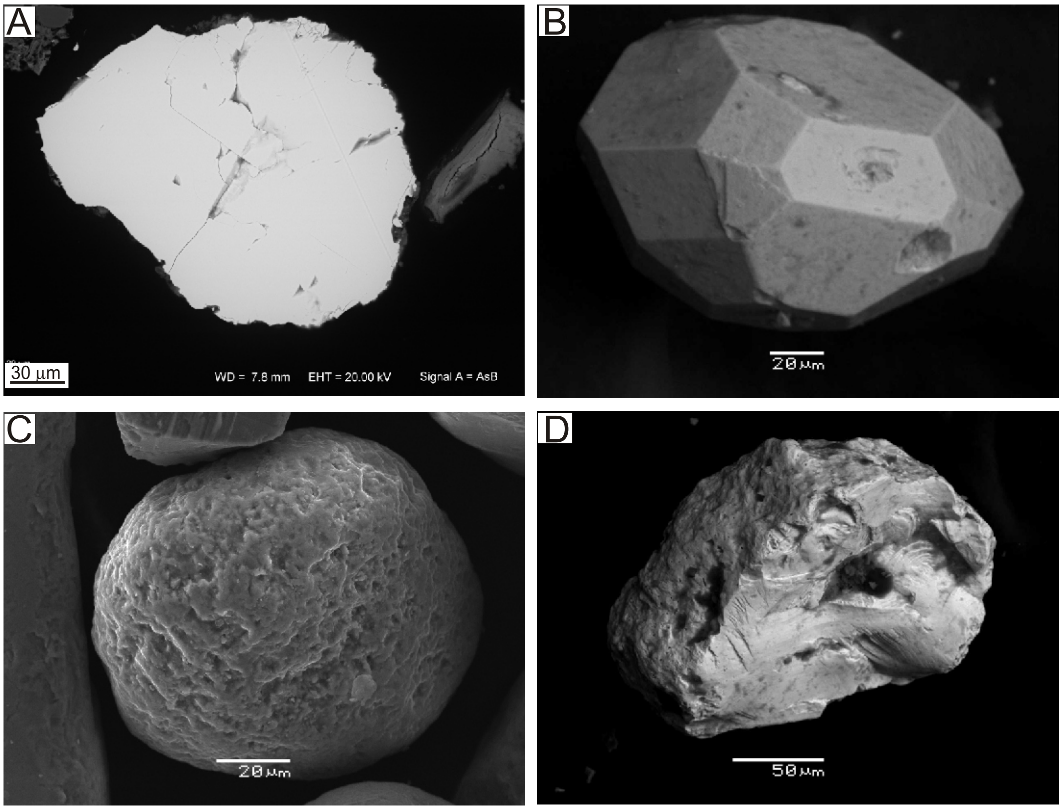

Fig. 6. Back-scattered electron image (A) and secondary electron micrographs of representative non-magnetic minerals from the studied heavy mineral grain size ranges

A – a subangular apatite grain without any intergrowths (polished section); **B** – short prismatic zircon with smooth faces and roughly equal development of the two main prisms; sample no. Z4/4; **C** – a well-rounded grain of monazite with advanced surface corrosion; sample no. Z6/3; **D** – angular, unevenly shaped cinnabar grain; sample no. Z4/3; the sampling locations are shown in Figure 3

and Hg contents (Appendix 2). These two different gold types (Au-Ag alloy and "pure" gold) are optically distinguishable (in polished sections) but do not appear to be characterized by any specific morphological forms.

Typically, the Au-Ag alloys are heterogeneous particles with one or few boreholes (light yellow in reflected light) and the porous Ag-depleted rim (dark yellow; see Fig. 10). Similar categories were reported for gold from various sites in Lower Silesia (Banaś et al., 1985; Wierchowiec, 2007, 2010).

In the gold-bearing samples studied from the upper course of the Zimnik Creek valley, rare Au-Ag-Pd-Hg alloy grains occur with the dominant Au-Ag alloy flakes. These particles are irregular in shape, with delicate crystal inter- and overgrowths (for simplification, we describe the latter as crystalline in general). The shapes of the particles suggest that they have not been subjected to the same degree of rounding and flattening as the flakes, and therefore have a somewhat different origin (the bedrock source). The gold grains with elevated amounts of Pd and Hg (polymetallic alloys) are a subject of the following detailed description and discussion.

An optical inspection and X-ray microprobe analyses of each investigated Au-Ag-Pd-Hg alloy grain indicate inter-particle and intra-grain variations with respect to the alloy composition; some difference is evident in the average composition of placer gold from the different sampling sites, especially in the samples from the upper course of the Zimnik Creek. Generally, Au-Ag-Pd-Hg alloy grains are free from quartz and sulphide inclusions. In polished sections, the Au-Ag-Pd-Hg alloy grains are zoned similarly to what is observed in the polished sections of Au-Ag alloys (Fig. 11). The rims typically have high gold (>98 wt.% Au) and low Ag, Pd and Hg (<2 wt.% in total) contents. The chemical composition of the cores makes two types of gold grains distinguishable: Ag-rich grains (>15 wt.% Ag) corresponding to electrum, and medium-Ag grains (<15 wt.% Ag). Of high significance is the remarkable internal irregular or more linear core-to-rim variation in the composition of alloys. Silver and Pd, Hg-depleted or enriched domains form emplacement with growths in the cores and also occur as veinlets along the solution fissures within the grains (Figs. 10 and 11).

The silver content of the rims ranges from 0.03 (detection limit) to 2.31 wt.%, with an average of 0.65 wt.% (the mean of 19 analyses), whereas the palladium content ranges from 0.02 (detection limit) to 0.09 wt.%, with an average of 0.05 wt.%. Pd and mercury are around the detection limit (0.04–0.06 wt.%). The composition of cores is bimodal, with medium-Ag cores containing <15 wt.% Ag (the average of 29 analyses being 10.46% Ag) or Ag-rich (electrum) cores with the silver content of the alloy ranging from 15.78 to 25.69 wt.% (the average of 10 analyses was 19.93 wt.%). The extent of the intra-grain variation is not constant and varies from grain to grain; some grains vary by <2 wt.% Au, whereas others vary by 8–10 wt.%

There are some differences, but not significant or consistent in all cases, in the compositions among the diverse morphological populations, except for the samples from the upper course

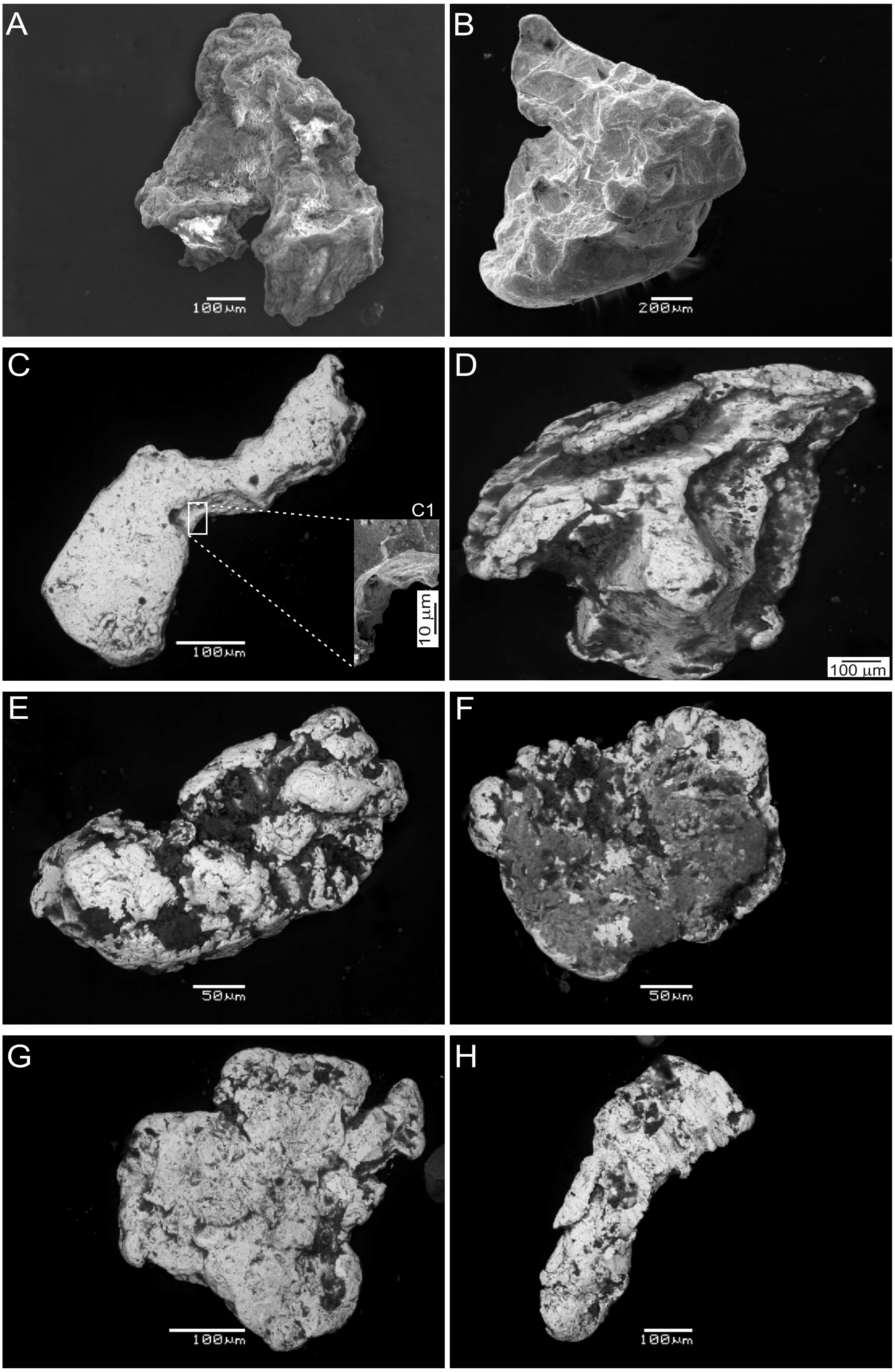

Fig. 7. Secondary electron micrographs of typical placer gold particles from the studied samples

A – two particles with irregular grain edge geometry; note the coatings of iron oxyhydroxides (dark) and bright patches of kaolinitic-micaceous clayey masses; sample no. Z4/3; **B** – a lobate, craggy gold particle with crystalline, platelet morphology and multilayered texture; sample no. Z4/4; **C** – a branched gold grain with multilayered particle texture (photo C1) and etching pits on the surface; sample no. Z4/3; **D** – moderately rounded gold particle with elements of skeletal growth on the surface; sample no. A1/3; **E** – a rod-shaped particle produced by folding of a flaky gold grain, note the cavities filled with iron oxyhydroxides (dark); sample no. Z5/3; **F** – a typical "sandwich-like" particle with coatings of iron oxyhydroxides; sample no. Z7/3; **G** – an intensely hammered flaky particle with rounded edges; sample no. Z8/3; **H** – a subrounded, stubby gold grain with scratches, furrows and evidence of hammering; sample no. Z8/3; the sampling locations are shown in Figure 3

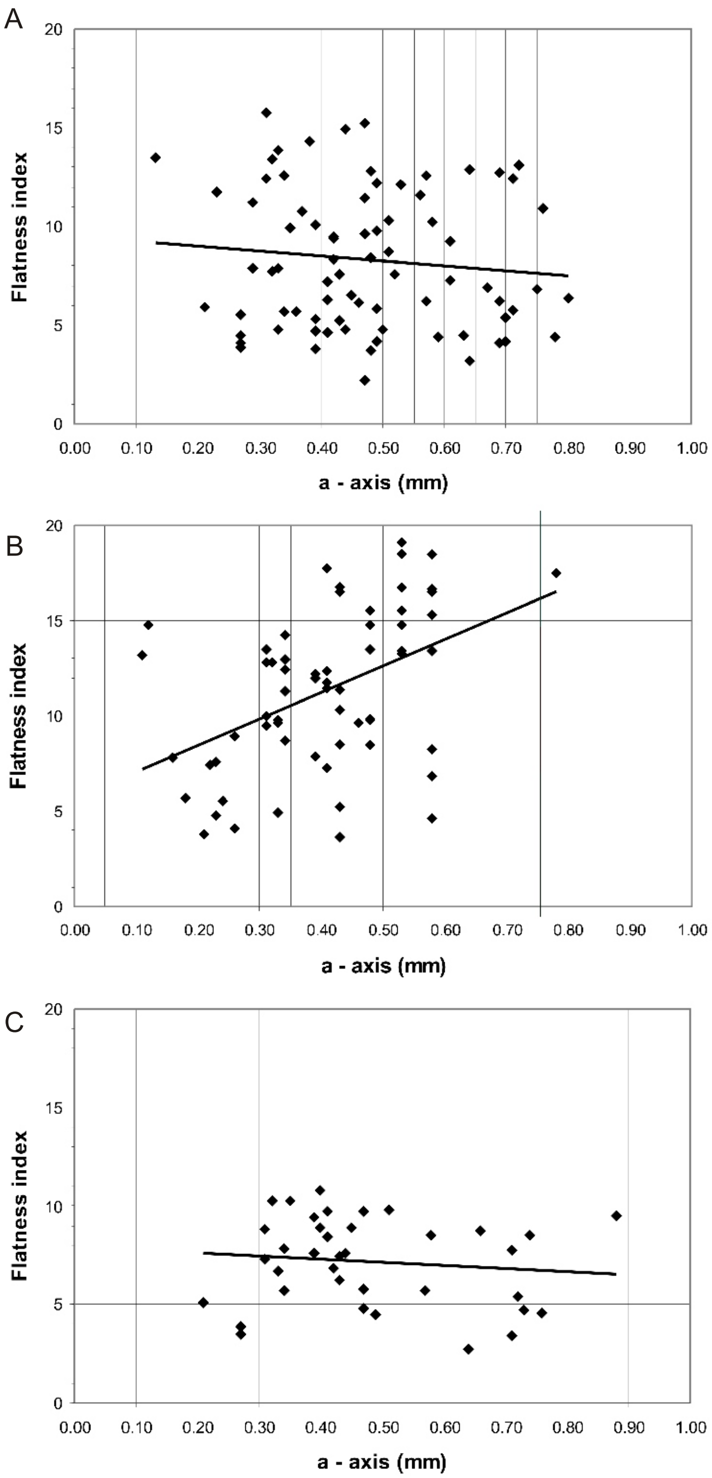

Fig. 8. The Cailleux flatness index F.I. = (a + b)/2c vs. the length of a-axis for the gold particle population from the Zimnik Creek catchment basin

A – samples Z1–Z5; B – samples Z6–Z11; **C** – samples A1–A3; the sampling locations are shown in Figure 3

of the Zimnik Creek (samples Z4 and Z5). In those samples, the core compositions of the rounded, flaky grains have a lower dispersion in their fineness than the crystalline grains. The core composition of the gold grains in samples Z4 and Z5 ranges between 78 and 91 wt.% for the crystalline varieties, and between 88 and 92 wt.% for the populations of flaky grains.

The palladium ranges from 0.02 (detection limit) to 0.97 wt.% in grain cores, with an average of 0.68 wt.% Pd, and the mercury from 0.04 (detection limit) to 0.96 wt.% in grain cores, with an average of 0.53 wt.% Hg (Appendix 2). It should be noted that the extremely low percentage of the accompanying elements, including Bi, does not in any way affect the presumed origin of the gold. The distribution of Pd in the alloy generally follows that of Ag. However, there are subtle differences in the distribution of Ag and Pd within the depleted rims, with Ag forming more extensive and wider zones of depletion than Pd (Fig. 11). Studies on the distribution of Hg reveal the disseminated character of this metal with no evidence of prevailing concentration in the zones enriched with silver or palladium. No data was collected to establish the relationships between Ag- and Pd-depleted and enriched zones and the nature of their contact.

DISCUSSION

The morphological and microchemical studies of placer gold grains, which are supposed to track the bedrock sources and styles of mineralisation, mainly considering the Au-Ag alloy content, occasionally Pd, Cu and Hg, help to discriminate the gold from different sources (e.g., Chapman et al., 2009; Moles et al., 2013). This study focuses on placer gold in Cenozoic fluvial clastic sediments in the Zimnik Creek drainage basin (North Sudetic Trough), where the auriferous bedrock remains undiscovered and the complex geology is consistent with either orogenic- (Mikulski, 2007) and sediment-hosted stratiform copper mineralisation of Kupferschiefer-type that cuts across the strata following the Rote Fäule alteration (Speczik, 1995; Oszczepalski et al., 2011).

The present morphology, internal textural features and chemical composition of gold grains in the placer are a product of a long and complex history of weathering and sedimentation under changing climatic and tectonic conditions (Hérail et al., 1990; Knight et al., 1999). At the simplest level, recognition of the nature of gold grains and other heavy minerals in the placer, the eluvial-colluvial and alluvial sediments in which they occur and their relationship both to the weathering history of the region and the specific geomorphological setting of the prospective area, will benefit the exploration by aiding the selection of sampling sites and the interpretation of geological and microchemical data (Youngson, 1998). The same approach and procedures apply to the exploration for the primary mineralisation, since the placer deposits are essentially the expression of such a source.

The data presented here indicates that Pd- and Hg-bearing placer gold grains are hypogene in origin, but some particles were subjected to intense dissolution and purification (remark-

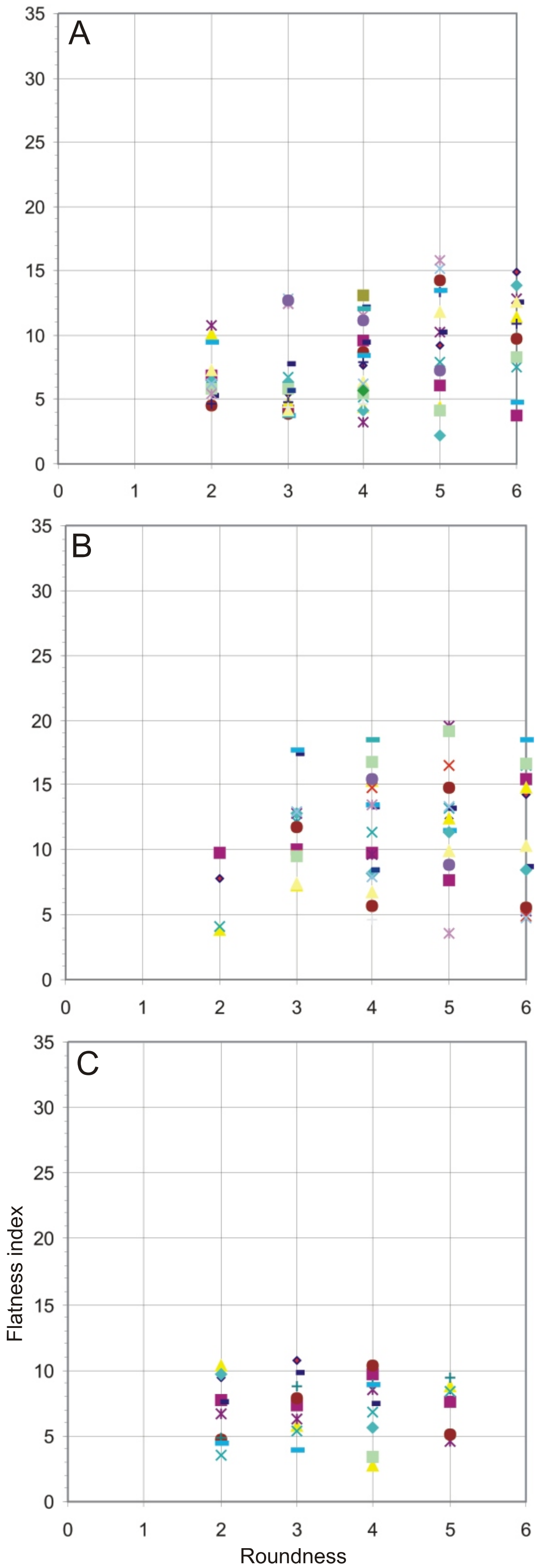

Fig. 9. Roundness vs. the Cailleux flatness index F.I. = (a + b)/2c for gold particles in the studied gold-bearing sediments

Roundness categories (after Powers, 1953) are represented by numbers (1–6): the values of roundness (1–6) represent: 1 – very angular, 2 – angular, 3 – subangular, 4 – subrounded, 5 – rounded, 6 – well-rounded; A – samples Z1–Z5; B – samples Z6–Z11; C – samples A1–A3

able zonation from relatively silver-rich cores to virtually silver-free rims and rare sponge-like internal textures). There is no evidence of supergene modification of grain cores, therefore the observed inner textures and Au-Ag-Pd-Hg alloy composition are interpreted as indicative of grain augmentation or replacement through complex hypogene processes (hypogene gold). Consequently, placer gold grains can be used to study the hypogene environment.

In the studied samples, there is no evidence of the presence of entirely secondary (newly formed) gold grains related to chemogenic redeposition of preliminarily dissolved primary gold, such as crystalline (isometric, prismatic, acicular and tabular) particles or wormlike gold reported by Lawrence and Griffin (1994) or McCready et al. (2003). The chemical mechanisms by way of which gold precipitates *in situ* to form supergene (authigenic) grains have been investigated by many authors (e.g., Bowell et al., 1992; Youngson and Craw, 1999; Southam and Saunders, 2005; Wierchowiec, 2010). Authigenic grains were recognized either by their morphology, which was crystalline and often very delicate, or by the presence of concentric internal zones reflecting the deposition of Au-Ag alloys varying in composition.

To date, over 200 gold grains have been examined by the authors and at no time have any features been observed which would indicate the deposition of significant authigenic gold. The Permian, Rote Fäule-related gold from the Fore-Sudetic Monocline and the North Sudetic Trough has many features which are similar to those found in recent authigenic gold in areas with aggressive fluids, since it was deposited from high-chloride brines with temperatures reaching a maximum of 135°C (Oszczepalski, 1999; Oszczepalski et al., 2011). Therefore, the source of Au alloys containing Ag-Pd-Hg in the present study area is likely to be related to bedrock sources, and processes leading to the development of authigenic gold in the supergene environment are either absent or insignificant.

The ranges of the present core compositions of the studied gold grains suggest that there were significant differences in the primary compositions. In particular, palladiferous gold grains from the upper course of the Zimnik Creek valley are compositionally not at variance with the Au-Ag alloy gold grains observed in the middle course of the "Zimnik" placer. Remarkable is the bimodal chemical composition of Au-Ag-Pd-Hg alloy grains and the elevated (averaging 0.68 wt.%) palladium and mercury contents (averaging 0.53 wt.%) in gold particles from the upper course of the Zimnik Creek. Placer gold with a similar microchemical signature to the "Zimnik" placer gold has been reported from the White Gravels palaeochannel of the Czerwony Creek (the Kaczawa-Bóbr fluvial drainage system) towards the south (Wierchowiec, 2010). At the Czerwony Creek, the palladiferous Au mineralisation occurs near the gold-bearing Rotliegend-Zechstein transitional sediments, represented by the oxidized portion of rocks typical for the Nowy Kościół area (see Wojciechowski, 2001).

The conditions for Hg precipitation within the Au-Ag-Pd system are not understood. The occurrence of Hg within complex grains shows that they were formed relatively late in the mineralising process, often by replacement of the original Au-Ag-Pd alloy. As regards the source for the mercury, there do exist several possibilities. Au-Ag-Hg alloys of hydrothermal origin occur in epithermal hot spring deposits, fault-hosted veins in metamorphic belts, massive sulphide deposits, and in placers derived from such sources (e.g., MacKenzie and Craw, 2005). Mercury of hydrothermal origin has been recognized within the oxidized lowermost Zechstein Rote Fäule facies of the North Sudetic Basin (Kucha et al., 1982; Speczik et al., 1999; Wojciechowski, 2001) and in Au-Ag-Hg alloys studied in the Fore-

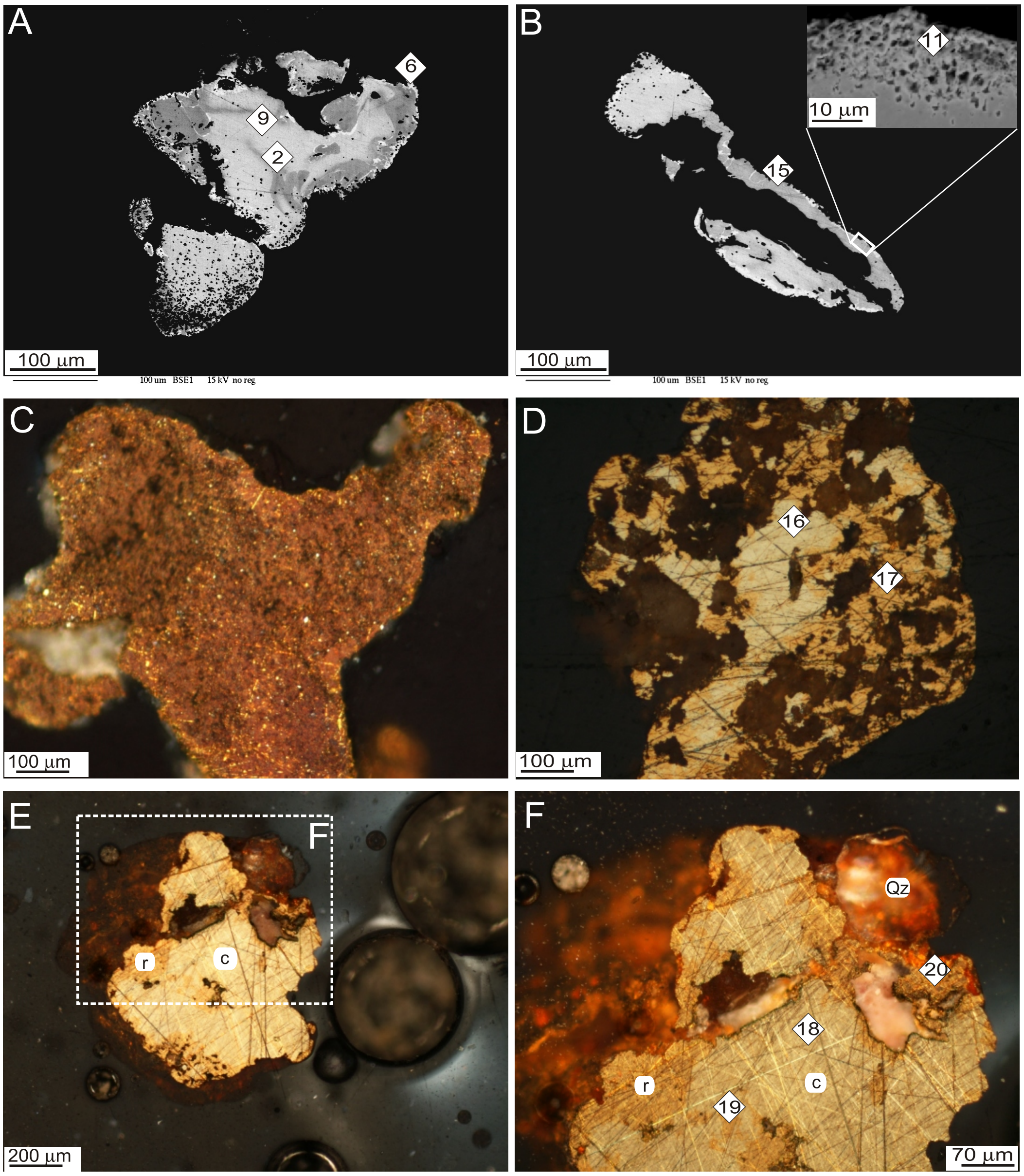

Fig. 10. Back-scattered electron images (A, B) and reflected light photomicrographs of placer gold showing the surface texture of grain (C), intra-grain texture and chemical heterogeneity on polished particle sections

A, B – the lighter the tone the higher the fineness (gold content); **A** – BSE image showing the internal chemical heterogeneity of a particle with irregular zonation (patches); sample no. Z4/4; numbers in diamonds correspond to the microanalyses in Appendix 2; **B** – polished section of particle showing the intricate texture of grain with the patches of argentiferous gold (dark grey) and pure gold (light grey); the close-up view shows micropores in the rim; sample no. Z4/3; **C** – branched gold particle covered by fine-grained iron oxyhydroxides and clayey masses; sample no. Z5/3; **D** – polished section of the gold particle shown in Figure 10C; note the relict primary core (light yellow patches) and the spongy texture of the particle in the advanced stage of corrosion with irregular pits and pockets filled with iron oxyhydroxides mixed with clayey masses; **E** – irregular, Ag-rich primary grain core (c) discontinuously surrounded by fine rim (r); sample no. Z4/3; **F** – a close-up view of the details of an irregular Ag-rich core with well-defined, sharp core/rim contacts; note the complex grain edge geometry with quartz (Qz) inclusions and voids filled with iron oxyhydroxides and clayey masses; see Appendix 2 for microprobe data for the numbered points

-Sudetic copper district (Piestrzyński et al., 2002; Pieczonka et al., 2008). The presence of placer grains of cinnabar in the studied detrital sediments (see Appendix 1) suggests that Hg is probably widely available in the mineralising system. It is well-known that ore-grade areas of the Kupferschiefer occur adjacent to shear zones and to a strongly tectonically disturbed substrate (Speczik, 1995). These fault-controlled structures were the active zones of subsidence during the deposition of the Rotliegend, and remained active during the post-Variscan time. Moreover, the main mineralisation event took place in the Late Triassic between 219 and 190 Ma (Bechtel et al., 1999; Mikulski and Stein, 2015). Based on the chemical composition

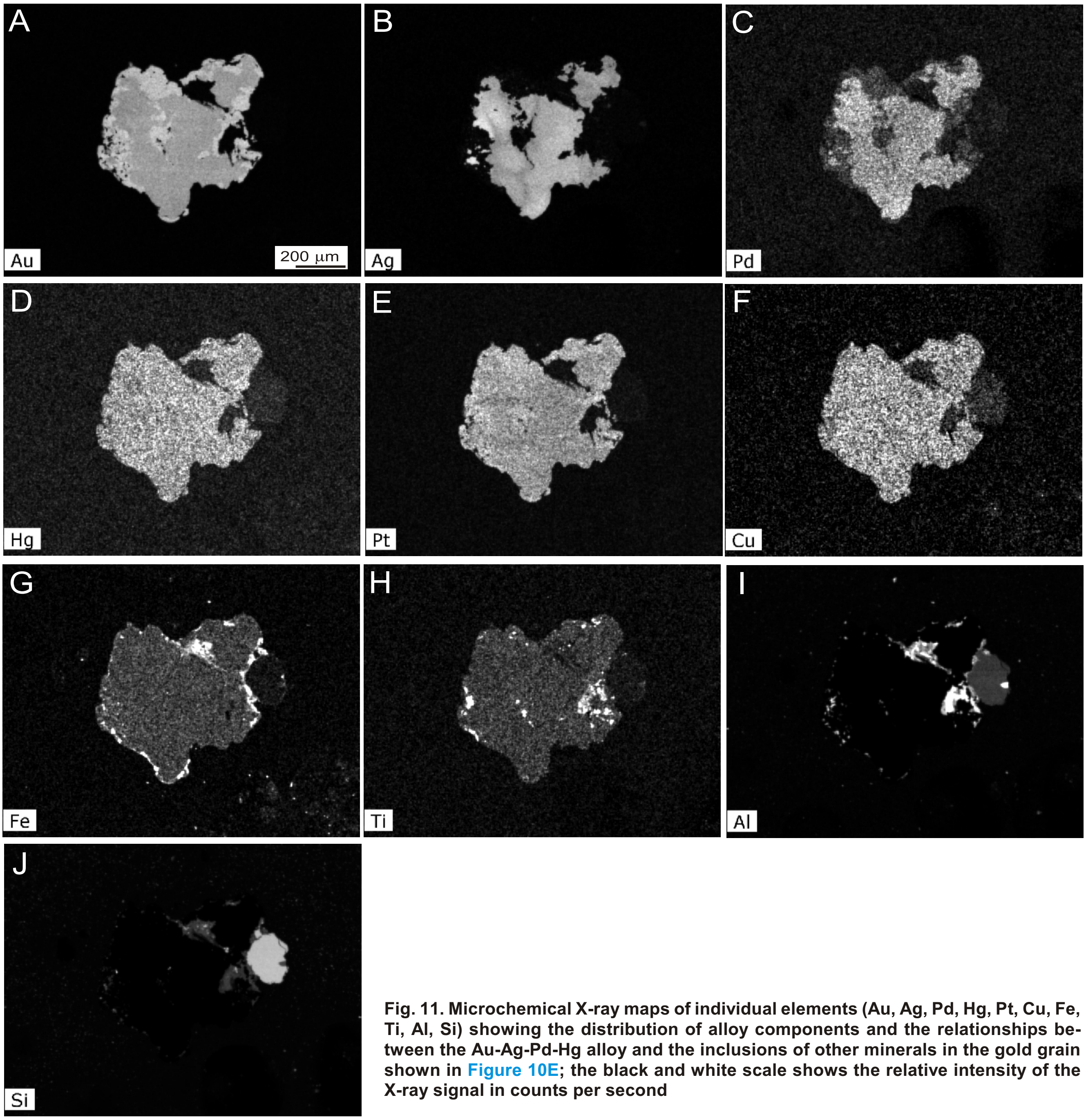

Fig. 11. Microchemical X-ray maps of individual elements (Au, Ag, Pd, Hg, Pt, Cu, Fe, Ti, Al, Si) showing the distribution of alloy components and the relationships between the Au-Ag-Pd-Hg alloy and the inclusions of other minerals in the gold grain shown in Figure 10E; the black and white scale shows the relative intensity of the X-ray signal in counts per second

of the Au-Ag-Pd-Hg alloy, the source may be described as highly oxidized chloride hydrothermal mineralisation, sense of Chapman et al. (2009).

THE SOURCES OF PLACER GOLD

For several reasons, we assume that there are multiple sources for the detrital gold encountered in the Zimnik Creek drainage area. Most important is the coexistence of rounded grains and others that have a more delicate habit at the same sampling site (Fig. 7). The delicate nature of the arborescent grains and the ease with which they are deformed in the placer environment suggest that they may come from a source closer than either the rounded grains or the associated folded flakes. This interpretation is supported by the coexistence of families of grains with different core compositions at the same sampling site, which also suggests multiple sources of the gold grains (Knight et al., 1999).

Based on multiple analyses of single grains, they seem to be heterogeneous in composition and the extent of the heterogeneity varies between the individual grains. Composition of the core is interpreted here as reflecting the composition of the primary gold source, because of being the least affected by supergene leaching or chemical accretion. The variation of both intra- and inter-grain chemical heterogeneity suggests that primary grain cores are derived from multiple sources. Widespread distribution and various genetic styles of primary mineralisation present in the North Sudetic Basin (see Banaś et al., 1985; Mikulski, 2007, 2011) are consistent with this theory. The above results agree with the data of Wierchowiec (2010), suggesting that the bulk of the gold is detrital in origin, and the differentiation in the composition of gold particles is the result of different gold sources.

The crystalline Au-Ag-Pd-Hg alloy grains of fluvial gold are assumed to originate from the transitional sediments between the Rotligend and Zechstein from the North Sudetic Basin. The key features of gold grains supporting this interpretation is their chemical composition which suggests derivation from a highly oxidizing hydrothermal environment characteristic for the above transitional sediments, pristine surfaces and low F.I. of crystalline polymetallic alloy grains reflecting flatness inherited from local primary sources rather than particle flattening during transport.

Secondary placer gold concentrations in fluvial sediments with the dominant Au-Ag alloy flakes were particularly developed in the Late Neogene and redeposited during Pleistocene to Holocene time. Some gold grains were probably derived from reworked pre-existing placers or were formed during Neogene weathering of the gold-bearing regolith. The latter situation appears to be true for some of the porous pure gold grains found in the studied samples, but this type of grains constitutes only few percent of the gold, therefore the bedrock source of gold in the study area is likely to be related to the local sources in the Zimnik Creek drainage basin.

The bimodal chemical composition of Au-Ag-Pd-Hg alloy grains with electrum (>15 wt.% Ag) and medium-Ag grains (<15 wt.% Ag) found in the study area is typical of the Rote Fäule- and Kupferschiefer-related gold mineralisation in the Sieroszowice-Polkowice copper mining district of the Fore--Sudetic Monocline (Piestrzyński et al., 2002) and the southern side of the North Sudetic Trough (Oszczepalski et al., 2011). The evidence presented above indicates the possibility that the alluvial Au-Ag-Pd-Hg alloy grains from the upper course of the Zimnik Creek valley sediments represent what has eroded from local gold mineralisation, some of them being similar in style to what is found at the Sieroszowice-Polkowice mine, and this mineralisation is probably in the vicinity of the upstream sampling site.

APPLICATION OF THE PLACER GOLD MINERALOGY TO EXPLORATION

A detailed study of detrital gold in Cenozoic clastic sediments from the northeastern part of the North Sudetic Trough documents several morphological and microchemical features which may potentially be a predictive tool in primary gold source exploration. The result is particularly important considering the ongoing reconnaissance exploration in the North Sudetic Trough, which employs gold grain analysis to assist in defining the exploration targets.

This study comprised a relatively small number of analyses from limited sampling sites. However, the data clearly demonstrates that a relationship exists between the composition of placer gold and the style of hypogene mineralisation from which the placer gold was derived. A larger dataset for the deposits used in this study would be needed before this relationship could be widely applied to gold exploration in the region. Gold prospecting and exploration in the region over the past two decades has also identified a very large number of gold anomalies in mineral surveys (Speczik and Wierchowiec, 1991; Speczik and Wojciechowski, 1997; Wojciechowski, 2001; Wierchowiec, 2010). Many different styles of hypogene gold are known to exist in the region (Mikulski, 2007), but only a small number of these are likely to have economic potential. A larger dataset could create a more defined statistical range of compositions and create a more specific microchemical fingerprint for the Rote Fäule and Kupferschiefer-related gold mineralisation type. This would allow the following exploratory work to be focused on anomalies that were related to potentially economic sources, and would thus make exploration programs more time- and cost-effective.

The benefit of the current study for future gold exploration is twofold. Firstly, it has established that data on placer gold composition can provide a microchemical fingerprint for constraining the likely primary source(s) of placer gold. Secondly, the study of placer gold grains of this type allows evaluating the economic potential of the source mineralisation.

Of the various oxidizing rock types which facilitate dissolution and transport of precious metals by chloride brines, the red bed environment is the most widespread within the geologic column, and the identification of gold mineralisation within the Permian red beds (the North Sudetic Through) extends the potential exploration targets beyond the Fore Sudetic Monocline. Speczik (1995) suggested that the development of Au mineralisation was influenced by the original metal content in the basin as indicated by the occurrence of volcanic rocks or volcanic detritus. It is also the case that the North Sudetic Basin is surrounded by auriferous Lower Paleozoic rocks which have been eroded, contributing to the gold concentration within its sediments. The comparison of the Ag contents of placer grains from the Zimnik Creek drainage basin, presented in Appendix 2, highlights the contrast between the orogenic gold and the one formed by the oxidizing chloride hydrothermal systems. The populations of placer gold grains derived from Paleozoic orogenic gold mineralization in the Sudetes are typically simple Au-Ag alloys containing between 5 and 20 wt.% Ag, often showing a constant composition from a single source (Mikulski, 2005, 2007; Mikulski and Speczik, 2016).

CONCLUSIONS

The technique of morphological and geochemical characterization can be applied to alluvial localities over a wide area, in order to establish the present styles of mineralisation and their geographical range, thereby facilitating a regional analysis. Interpretation of microchemical signatures of placer gold will always require consideration of the relevant aspects of regional and local geology wherever they are known. Although our study was somewhat limited both in the scope and in the total number of the conducted analyses, several significant first-order implications for gold exploration in the area can be derived from the data.

1. The results of our studies have shown that the technique of detailed morphological and microchemical gold grain characterization is a robust method used for obtaining valuable information regarding the source mineralization of the population of alluvial gold grains.

2. A regional analysis of alluvial gold populations may establish the extent of specific styles of mineralisation, thereby helping to evaluate the targets for further exploration.

3. The methodology described here not only indicates the possible origin of gold from Rote Fäule and Kupferschiefer- related gold mineralisation that formed in an oxidizing hydrother-

mal system, but can also apply such a study of the alloy composition to limit the likely primary source(s) of placer gold, and thus evaluate the anomalies. This information may be obtained at an early stage in the prospection process from the gold grains collected during routine placer sampling.

The result is particularly important considering the ongoing reconnaissance exploration in the North Sudetic Trough (SW Poland), which employs gold grain analysis to assist in defining the potentially economic primary gold targets.

Acknowledgements. The authors would like to thank G. Borg and an anonymous reviewer for the constructive comments that highly improved our manuscript. S. Oszczepalski is thanked for editorial comments.

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