GOSPODARKA SUROWCAMI MINERALNYMI

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Tailings from sand and gravel processing plants as the potential source of gold

Introduction

Gold mining and beneficiation of gold-bearing sand and gravel deposits in numerous parts of south-western Poland dates back to the early Bronze Age (Quiring 1948). Although placer deposits are not mined at present in the Sudetes region, there is abundant archaeological evidence showing that they were actively exploited in the past. Relics of mining shafts with complexes of washer system elements and washed sand heaps have been discovered in different sites in the well-known gold producing areas dating back to the medieval times through to the nineteenth century (Kaźmierczyk 1974, 1976; Kaźmierczyk, Grodzicki 1976; Radis 1989).

The major mining centre was located in the North Sudetic Basin, where gold was mined in the vicinity of the towns of Złotoryja and Lwówek Śląski. Estimates of the gold grade and the amount of gold recovered from that area and other gold deposits in the Sudetes vary considerably (Quiring 1948, Domaszewska 1965). According to Quiring (1948), historical gold production during the Medieval Ages amounted to 50 000 kg. This gold corresponds to that recovered from a combination of placer deposits and primary gold deposits (arsenic-quartz and polimetalic gold veins) and even if this value is overstated, it still represents a considerable amount of gold. The prospected resources of clastic gold in the Sudetes area are estimated at about 2600 kg (Wojciechowski 1993, 1994a).

In the vicinity of Lwówek Śląski, these historic gold-bearing deposits are currently being worked for sand and gravel at the Rakowice Plant. This plant operates in the riverbed and

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terraces of the Bóbr River (Rakowice deposit) and processes high tonnages of material (about 700,000 Mg per year) using dredges.

The Rakowice deposit is located along the Pleistocene and Holocene terraces of the Middle Bóbr River valley. Part of the terraces, approximately 250–500 m wide and ~2500 m long, with a depth ranging between 2 and 25 m, are currently exploited (Fig. 1).

This paper presents the results of investigations of artificial (technogenic) gold-bearing sands generated by natural aggregates processed in this deposit. The intention of this research (in addition to prospecting) was the study of the sand and gravel deposits as a potential source of gold and the presentation of new data such as the gravity recoverable gold value and the distribution of gold in different types of tailings.

The term 'gravity recoverable gold (GRG)' refers to the portion of gold in a sample that can report to a gravity concentrate at a very low yield (i.e. concentrate weight recovery)

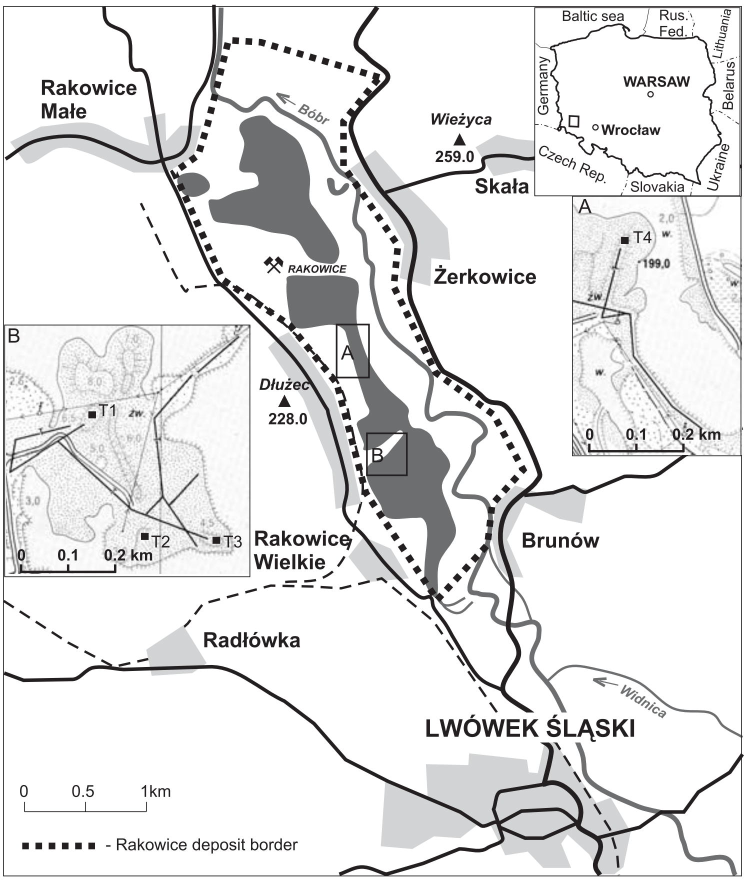

Fig. 1. Sketch map showing the location of area studied and the approximate extent of Rakowice deposit and the sampling sites for this study

Rys. 1. Szkic lokalizacyjny obszaru badań przedstawiający przybliżone granice złoża Rakowice oraz miejsca pobrania próbek

<1% and grades more than 10 ppm. This includes gold that is not totally liberated and is part of a particle of such density that it reports to the low yield concentrate, but it excludes fine, completely liberated gold that does not have the proper characteristics (shape factor or size) to do so. In this paper, GRG is measured using a MD-3 laboratory Knelson concentrator (LKC). It has been shown that the LKC can recover, at a very low yield of 0.2 to 0.5%, 95% of gold recoverable by amalgamation (Silva 1986).

2. Geological background of the Middle Bóbr River valley

The Middle Bóbr River valley is a morphological unit lying entirely within the North Sudetic Basin, filled with post-Devonian sediments comprising unmetamorphosed, slightly deformed platform-type sediments and volcanics of Late Carboniferous, Permian, Triassic and Late Cretaceous age (Teisseyre et al. 1957; Oberc 1972). The basin is bounded by a system of NW-SE faults, which separate it from the metamorphic units of the Kaczawa Metamorphic Complex. A cover of Late Cenozoic deposits, mainly of fluvial origin (but in places also slope deposits) is common in the valleys in the entire area. The thickness of these deposits varies from 1 to 20 m, and locally may reach up to 65 m (Grocholski, Milewicz 1958). In studied area, the present-day Bóbr River valley is filled with Late Pleistocene and Holocene alluvial deposits. The Late Pleistocene sediments, most probably of Weichselian age (North Polish Glaciation), are represented by sandy gravels of terraces of the Bóbr River and its tributaries (Badura, Przybylski 2000).

The gravels are generally massive, sometimes with crude horizontal bedding. This clastic material is poorly sorted, sub-angular and composed mainly of quartz grains, with significant admixture of granitoids, metamorphic schists, melaphyres, locally quartzites and angular grains of Cretaceous quartz sandstones (Buksiński, Cegła 1979). A small (1–5%) admixture of glacially derived rocks is also present. Holocene terrace deposits are represented by contemporary valley floor deposits (floodplain), mainly gravels and sands. Generally, in contrast to the Late Pleistocene gravels, the Holocene deposits are richer in Cretaceous material.

Besides the late Quaternary deposits in the Bóbr River valley, there are other fluvial gravels in the area. They are situated 25–30 m above the present day valley floor and are underlain by Cretaceous or metamorphic rocks (the so-called high deposition gravels). The high deposition level is connected with vast fluvial deposition during the Wartanian Glaciation when the Bóbr River valley spread towards the present valley of the Kwisa River (Badura, Przybylski 2000).

3. Placer formation and placer-forming minerals

Sand and gravel processing plants in the Sudetes focus on rocks of Pleistocene and Holocene age that are, depending on their location, alluvial or fluvioglacial in origin. These sediments consist mostly of gravels, pebbles and boulders of resistant rocks and minerals (quartz, quartzite, siliceous rocks, granite, etc.), and to a smaller extent of less resistant rocks – mostly Sudetic and Scandinavian crystalline or metamorphic and sedimentary rocks. Sand and gravel also contains some impurities: silty and clayey intercalations, humus, and high content of unsuitable (as shape concern) or weathered grains.

The composition of these fluvial deposits varies as a function of the source rocks (which may be dominated by local lithologies or by exotic material that has been transported on considerable distances), the depositional processes involved and the degree of weathering. During these processes, the materials are arranged in accordance with the flow direction and selected as a function of grain size, density, shape and chemical resistance. This leads to the separation and concentration of minerals of different composition, such as light and heavy minerals. The latter materials are known as heavy mineral sands, which contain high concentrations of detrital grains with a density exceeding 2.9 g/cm^3. Natural heavy mineral sands are referred to as 'placers' if they contain a sufficient concentration of the target mineral to make them of economic interest.

Concentrations of gold and other heavy minerals in specific sediments (gravel, sand and sandy silts) vary both laterally and between different stratigraphic levels (Pleistocene and Holocene), being highest in gravels and significantly lower in sands and silts. The richest gold concentrations were found near the bedrock of currently exploited sand and gravel deposits. High gold concentrations are also common in beds that directly overlie clay-rich sediments (Rutkowski, Wojciechowski 1988), probably because the clays inhibit erosion and act as a trap for the gold particles.

Additionally, gold-bearing sediments contain other potentially economic minerals – Fe-Ti oxides, zircon, rutile, and monazite (Łuszczkiewicz 1990; Jęczmyk, Wojciechowski 1994; Łuszczkiewicz 2000, 2005). Fe-Ti oxides dominate the heavy mineral fraction in the studied technogenic deposits. Grains of homogenous magnetite prevail among the opaque phase. Polyphase grains with magnetite-hematite and magnetite-ilmenite intergrowths are also common. Other Fe-Ti oxide minerals, including ilmenite, hematite, martite, and goethite are also present.

According to Wojciechowski (1989a), the total content of zircon, rutile and monazite in the heavy mineral fraction is below 10 g/m^3, making them uninteresting from the economic point of view. Most placer gold was deposited in the Pleistocene terraces of the Bóbr River. In the Rakowice deposit, the river terraces from the North Polish Glaciation (3–6 m) are well-developed, with widths reaching 200–400 m and a relatively thin overburden (1–5 m). Grades of gold and other heavy minerals increase with terrace depth and especially at the contact with the bedrock, similarly as in almost all placer deposits (Boyle 1987; Shilo 2002). The grades range from 0.007 g/m^3 in the poorest areas to 0.2 g/m^3 in the areas at the contact with the bedrock (Grodzicki 1972; Speczik, Wierchowiec 1991; Wojciechowski 1993, 1994a; Łuszczkiewicz, Muszer 1999). Thus, these grades with few exceptions (paystreaks) are uneconomic. However, they undergo enrichment during sieving and washing of the sand and gravel in the processing plant.

4. Gold-bearing deposits generated by plant processing

As stated above, alluvial gold is not exploited any more from placer deposits in the Sudetes, with the exception of small-scale artisanal mining in the Kaczawa Mts. However, many of the auriferous alluvial deposits are currently being worked for sand and gravel (e.g. Rakowice, Przyłęk-Pilce, Wójcice, Sędzisław).

These activities are carried out by sand and gravel plants that produce materials known as natural aggregates. Polish standards divide natural aggregates into the following classes, depending on the degree of processing and grain size: 1) non-crushed aggregates – common sand 0–2 mm, gravel (fractions 2–4, 4–8, 8–16, 16–31.5, 31.5–63 mm, and mixed fractions e.g. 2–8, 2–16, 8–16 mm etc.), sand and gravel mixes (fractions 0–4, 0–8, 0–16, 0–31.5, 0–63 mm), and pebbles (63–250 mm); 2) natural crushed aggregates – crushed sand 0–2 mm, pebble grits (the same fractions as for gravel), and pebble mixes (the same fractions as for sand and gravel mixes).

5. Beneficiation of gold

After dredging, sand and gravel materials are sieved and washed to produce diverse sand and gravel products that have a relatively low value per tonne.

The bulk of the sand and gravel in the riverbed and terrace settings has a very low grade in gold and other heavy minerals and hence low real economic value. Nevertheless, after sieving, the sand fraction of the product obtains higher grade and consequently higher economic value. This is because gold and other heavy minerals in the alluvial deposits of the Sudetes are generally <1.0 mm in size (Grodzicki 1972, 1977; Wojciechowski 1993; Wierchowiec 2002, 2007). Therefore, the whole sand size fraction, including virtually all the gold, is found in the finest product of the sand and gravel processing plants.

The manufacture of aggregates in the sand and gravel Rakowice Plant consists of two steps. In the first step, two size fractions are obtained during wet sieving: the first of sizes exceeding 16 mm and the second < 16 mm (Fig. 2). The first fraction is crushed to obtain artificial aggregates. The fraction not exceeding 16 mm, known as natural aggregate, is then sieved and washed to obtain a series of commercial fractions: 16 to 8 mm, 16 to 2 mm, 8 to 2 mm and 2 to 0 mm. The fine sand fraction (2 to 0 mm), which concentrates all the gold and heavy minerals, typically accounts for 5–10 wt % of the total sand and gravel production.

Depending on the size distribution in the initial feed to the plant, gold and other heavy minerals can be enriched by 10–20 times compared with the grade in the initial sand and gravel feed. This fine sand product may then have sufficient gold and other economic minerals grade to merit the use of efficient gravity concentrators (e.g. Knelson concentrator) in order to recover fine gold (Burt 1999). Enrichment by sieving and washing arises as a consequence of the normal passage of natural sand and gravel through the plant, therefore generation of the technogenic placer sand comes about as a result of normal plant

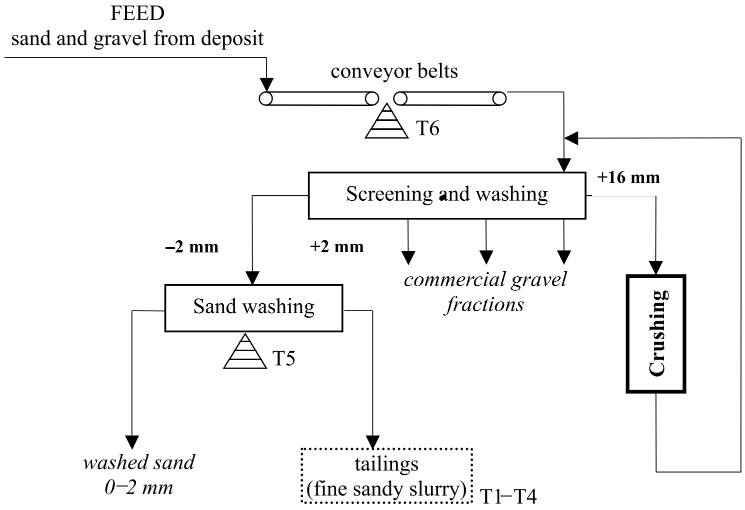

Fig. 2. Schematic flow sheet of Rakowice sand and gravel plant operation showing the location of different type of tailings studied. T1–T6 – the sample numbers (modified from Łuszczkiewicz 2000)

Rys. 2. Schemat układu technologicznego zakładu przeróbczego kruszywa naturalnego w Rakowicach z lokalizacją punktów opróbowania. T1–T6 – numery próbek (wg Łuszczkiewicz 2000, zmienione)

operation and involves no additional operating costs. Additionally, the resulting technogenic auriferous deposits are located in the beneficiation plant, thus eliminating transport costs.

6. Material and sampling methods

Sandy tailings characterized in this paper come from the Rakowice sand and gravel plant (Fig. 1). 10 and 30 litre samples (size depending on the sediment type) were collected to measure the GRG amount. Sampling was identified as: type T1,..., T5 and T6 respectively. Types T1–T4 are fine sandy slurries dumped in a settling pond as wastes (Table 1). Type T5 are tailing sands from cleaning the interiors of a dewatering unit, whereas type T6 represents abrasion wastes resulting from pressure water cleaning of the conveyor belts. The samples were taken from depths of 0.0–0.5 m following the methodology described by Wojciechowski (1994b) and Łuszczkiewicz (2000).

7. Laboratory procedures

Primary samples were processed using a 3.0 in. laboratory Knelson concentrator (LKC). The LKC is considered to be a particularly effective tool to concentrate liberated gold particles (i.e. GRG) into a small, assayable mass (Woodcock, Laplante 1993). It can process

TABLE 1

Particle size distribution of different kind of tailings after sand and gravel washing (in weight %)

TABELA 1

Skład ziarnowy wybranych typów odpadów z płukania kruszywa naturalnego, % masowe

Size fraction mm	Sample No.					
	T1	T2	T3	T4	T5	T6
+2.0	0.0	1.3	1.9	0.6	1.5	0.5
–2.0+1.0	0.0	7.3	4.8	5.0	10.2	9.2
–1.0+0.5	1.8	12.5	9.1	10.5	6.8	14.4
–0.5+0.25	39.1	25.8	46.1	20.1	29.4	31.2
–0.25+0.125	53.2	47.2	25.0	35.6	37.1	35.6
–0.125+0.063	2.8	3.8	9.4	18.4	8.7	3.4
–0.063	3.1	2.1	3.7	9.8	6.6	5.7

up to 100 kg of material and concentrate free gold in a small mass (typically 80–110 g) that can be entirely assayed. Large sample masses can then be completely assayed for GRG. Tails containing virtually no GRG can be sampled and assayed with a smaller error than the feed.

Samples were prescreened at 800µm. The undersize was processed in the LKC at feed rate ranging from 300 to 500 g/min and water jacket pressure between 21 and 30 kPa (3–5 psi). For each LKC test, tailing samples were collected, dried and weighed. Subsequently, the dried tailings from each processed sample were divided in the Jones type riffle splitter into subsamples of about 100 g according to the procedure described by Gerlach et al. (2002). The tailing subsamples were then sieved on a 0.06 mm mesh and the oversize particles were grinded in a ball-bearing pulverizer. The concentrate samples and the tailings subsamples were sent to the ACME Analytical Laboratories Ltd. in Vancouver to be fire-assayed (FA/ICP). The head grade of the original LKC feed was then back-calculated from the concentrate and tails assays.

In addition, the particle size distribution of each sample was determined before processing.

8. Knelson concentrator

Knelson concentrators are widely used in the industry for the extraction of precious minerals from different ores, river sands and tailing dumps. This is a relatively new concentrating device that has been commercially available since 1980 (Turner 1991). The LKC essentially consists of a riffled cone rotated at high speed connected with a drive unit. Figure 3 provides an illustrated example of the concentration process within a Knelson concentrator.

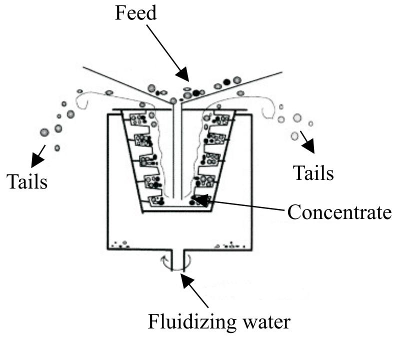

Fig. 3. Schematic diagram of a Knelson concentrator (modified from Coulter, Subasinghe 2005)

Rys. 3. Schematyczny diagram przedstawiający zasadę działania koncentratora Knelsona
(wg Coulter, Subasinghe 2005, nieco zmienione)

Ore or tailing slurry containing 20–40 wt % of solids is fed into the bottom of the unit. As in bowl concentrators, the concentrates are retained in the cone until cleanup, while tailings are continually washed out over the top.

The Knelson concentrator utilizes the principles of hindered settling and centrifugal force (Silva 1986). A central perforated cone containing horizontal ribs welded along the inside wall is rotated at the speed of 400 rpm, at which it generates the force of 60 G (for a 3.0 in. LKC). Heavy particles are forced out through the walls and are trapped between the ribs. Lighter particles are carried by the water flow out the top. The cone is surrounded by a pressurized water jacket that forces water through holes in the cone to keep the bed of heavy particles fluidized. The force of the water acts against the centrifugal force of the rotating cone. This counterforce is strong enough to inhibit severe compaction of the collected concentrate. As a result, the mineral grains remain mobile, allowing more heavy particles to penetrate. As the process continues, lighter particles in the mobile bed are replaced by the incoming heavier ones, until only the heaviest particles, such as coarse and fine gold, are retained in the feed.

Apparently, this process is very efficient. Silva (1986) demonstrated that Knelson concentrators are capable of achieving a 96% recovery of free liberated gold coarser than 38 μm. The LKC can readily measure the amount of GRG in an auriferous deposit and be used as a ‘perfect separator’ to study a gravity unit such as sluice or even in an industrial-scale processing plant.

9. Results and discussion

Since antiquity, gold gravity concentration has always been very common due to its large capacity, low operating cost, lack of need to use chemical additives and ability to treat a wide size distribution of the gold-bearing sediments. The high specific gravity of gold (19.3 g/cm^3 in the case of pure gold) compared to that of gangue minerals (2.1–5.0 g/cm^3) makes the process very attractive, although gold particle shape, porosity and hydrophobicity can lower the recovery (Feather, Koen 1973; Wang, Poling 1983; Turner 1991).

While the GRG content may be considered an upper limit or the maximum recovery possible, it does not take into account the inefficiencies of large plant-scale devices, thereby reporting higher recoveries than practically possible in industrial units.

Laplante et al. (1996) have shown that the recovery of flaky gold was different in comparison to that of spherical gold. However, fine gold particles were predominantly spherical in shape while the larger particles were flaky and thus the difference in recovery cannot be attributed exclusively to shape. Walsh and Kelly (1993) reported flaky gold as having a smaller apparent size than sieve measurements indicate, based on their settling behaviour.

Free gold from the studied sediments is fine grained, usually falling into 100–250 μm and <100 μm size fractions (gold dust). The largest gold grain found has a diameter of 0.5 mm. Such size distribution of gold grains is typical for Sudetic placer gold from technogenic deposits (Grodzicki 1972; Wojciechowski 1989a).

A characteristic feature of the grain composition in the studied samples (Tab. 1) is the low content of grains representing sizes below 0.1 mm and above 0.5 mm. A rule confirmed by the author's observations indicates that in tailings from the processing of sands and gravels in the Sudetes area, over 95% free heavy minerals (including gold) concentrates almost always fall in grain fractions below 0.5 mm. In the case of tailings from the Rakowice Plant, in grain fractions exceeding 0.5 mm occurred only 0.2 to 0.4 wt % of heavy minerals, thus ignoring this grain class would result in their up to 2.5% loss (Łuszczkiewicz 2000). Ignoring the grain class >0.5 mm causes limitation of the material grain composition and presumably, along with the very low content of very fine grains (<0.1 mm), is a factor aiding the process of gravity beneficiation of gold and other heavy minerals. Experiments using the laboratory Knelson concentrator on the studied samples have shown that it is possible from the tailings to obtain gravity concentrates containing about 23 ppm Au (average from 6 samples) and recoveries of gold between 85–98% in the concentrate (averagely 89.8%, n = 6). The average head grade back-calculated from the concentrate and tails assays was found to be 0.27 ppm of Au (Table 2).

According to the data of Łuszczkiewicz (2000, 2002) and based on the enrichment results presented in this paper it can be estimated that presently the settling ponds of the plant are annually filled with at least 40 000 Mg of slurry of grain size below 0.5 mm, containing about 0.006 Mg of Au and 1000 Mg of other heavy minerals. However, according to Wojciechowski (1993), the average contents of gold and other heavy minerals are 20 times lower in the case of gold and at least 100 times lower for other heavy minerals. Most probably such wide discrepancies come from the fact of different methods of processing gravity concentrates and methodology of determining the heavy minerals content (see Jęczmyk, Wojciechowski 1994; Łuszczkiewicz 2000, 2005).

The accumulations of fine-, microscopic, and floury gold, which have been reported from the Rakowice deposit (Wojciechowski 1989a; Łuszczkiewicz, Muszer 1999), are not purely

TABLE 2

Gravity recoverable gold (GRG) content and calculated head grade of gold in selected tailing types from Rakowice sand and gravel plant

TABELA 2

Zawartość złota grawitacyjnie odzyskiwalnego oraz teoretycznie wyliczona całkowita zawartość Au w wybranych typach odpadów z płukania kruszywa naturalnego w żwirowni Rakowice

Sample No.	CONCENTRATE		TAILS			FEED	
	Weigth [g]	Assey gold grade [ppm]	Weigth [g]	Assey gold grade [ppm]	GRG value [%]	Weigth [g]	Head gold grade (ppm)
T1	97.4	20.425	11 320	0.006	96.6	11 417.4	0.180
T2	73.7	9.758	9 423	0.008	90.5	9 496.7	0.057
T3	89.9	6.350	10 888	0.009	85.2	10 977.9	0.061
T4	92.3	14.310	12 452	0.016	86.9	12 544.3	0.121
T5	77.6	54.752	5 650	0.012	98.4	5 727.6	0.753
T6	82.0	32.240	5 946	0.010	97.8	6 028.0	0.448
Average	85.48	22.972	9 279.8	0.01	92.6	9 365.3	0.270

a local phenomenon. Most likely, this process is governed by regional regularities, mainly by gold removal from adjacent source areas, the existence of geomorphological traps favourable of gold deposition, and geochemical barriers where dissolved or colloidal gold is transformed into mineral forms.

As follows from this study, the Au content in tailings reaches and exceeds the minimal economic grade in alluvial placers (see Table 2). Thus, the problem concerning technogenic gold is not only of scientific but also of applied interest. It should be taken into account that the development of these artificial gold deposits does not require alienation of deficient territories, distortion of landscape and its recultivation after mining, demolishing of buildings, and the construction of roads and other infrastructure. This type of ore mining is also simplified due to the absence of the overburden. Au-bearing tailings will be proccessed immediately as a disintegrated material, and the technology of metal recovery will be considerably simplified and improved by the application of modern gravity separation.

10. Opportunities of gold recovery

The oldest method of beneficiation experimentally employed at the Rakowice plant involved the use of plastic and rubber carpets (see Wojciechowski 1989b), which are a modern version of the ‘golden fleece’ method used to trap alluvial gold by ancient miners. This method is still employed at a number of sand and gravel plants in Spain and Portugal (Viladevall et al. 2006). Carpets are also used in other auriferous rivers and their tributaries, such as the Garonne and the Rhone in France and the Rhine in Switzerland.

The rate of gold recovery using a gravimetric concentrator far exceeds that which applies the carpet method. At the Sorigue plant (Spain), gold recovery with carpets ranges between 10 and 15%. These recovery rates have been corroborated by the author's studies (unpublished) in the Sudetes and by the sand and gravel industries in France, Italy and Switzerland (Viladevall et al. 2006). On the other hand, gold recovery using the low capacity, laboratory Knelson concentrator is 85–98% (Tab. 2).

At the Sorgue plant mentioned above, gold-rich black sands are transferred to a second beneficiation plant where gold is concentrated using a shaking table separator. Finally, the gold concentrate is leached using *aqua regia*. The reduced gold is then melted in a jewellery furnace and transferred into small ingots. Amalgamation and cyanidation processes are not necessary at this type of beneficiation plant.

The evaluation of the cost effectiveness of the process at the Sorigue plant includes operating costs and depreciation of the gravimetric concentrator and beneficiation plant. This evaluation shows that this process is profitable for the annual fine sand production exceeding 250 000 tonnes, with a head grade of 0.045 ppm Au in the fine sand product and a gold price of $ 450/troy ounce (Viladevall et al. 2006).

Similar viability can be achieved in the Rakowice sand and gravel plant and in other plants operating in the Sudetes area with a smaller sand production if the head grade for gold in the fine sand product is significantly higher and/or the prevailing gold price is more favourable ($ 750/troy ounce in November 2008).

In the settling ponds of the Rakowice gravel plant, over 3 million Mg of fine-grained auriferous tailings have been deposited after 30 years of mining. Between the 1980-ties and 1990-ties, this plant mined and processes about 2 million Mg of gravel and sand, and according to data from 2007 – about 0.7 Mg. In the early 1990-ties annually about 120 000 Mg of recoverable tailings were deposited, which contained about 330 Mg of ilmenite, 250 Mg magnetite and haematite, 50 Mg of zircon, and about 13 Mg rutile and monazite each (Łuszczkiewicz 2000). Thus, taking into account the content of the deposited tailings and data from Table 2 it can be assumed that at least 180 kg of Au could be also deposited during over 30 years, along with considerable amounts of other heavy minerals. The gold resources in the tailing sands from cleaning the interiors of the dewatering units (type T5) and in the abrasion waste resulting from pressure water cleaning of the conveyor belts (type T6) are estimated at several kilograms and do not have a large significance in the general balance of gold in the described sediments. These estimations allow a discussion on the economic significance of the described resources.

The efficiency of the proposed recovery circuits at the Rakowice Plant (see Fig. 4) is difficult to evaluate since the gold content of the placer material treated in this plant is not recorded or calculated. Extensive sampling of the sand and gravel site must be carried out to decide the financial possibility of keeping gold as a by-product.

Gold recovery in sand and gravel plants presents problems not associated with placer gold mines. Recovery systems must be designed to interface with the existing sand and gravel processing. This usually limits the type and amount of equipment that can be used and,

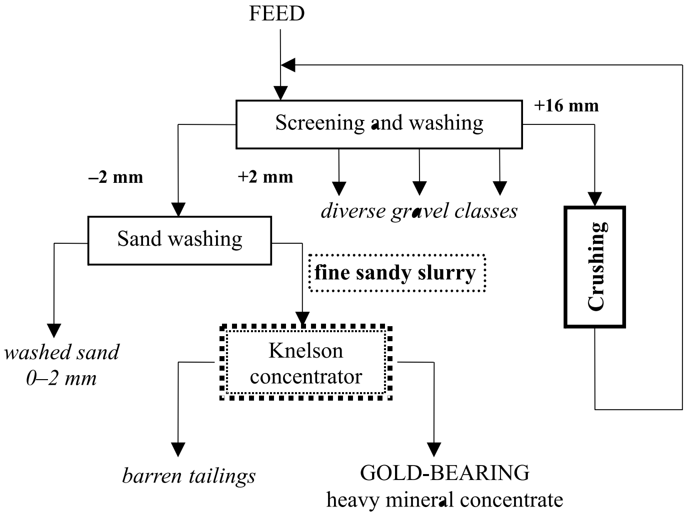

Fig. 4. Flow sheet of sand and gravel plant operation with proposed recovering of gold and other economic heavy minerals (modified from Łuszczkiewicz 2005)

Fig. 4. Schemat układu technologicznego zakładu przeróbczego kruszywa naturalnego z proponowanym pozyskiwaniem minerałów ciężkich (wg Łuszczkiewicz 2005, zmodyfikowano)

consequently, reduces the recovery. In addition, extreme variations in the feed rate occur because sand and gravel plants operate in response to the demands for sand and gravel, and not gold. Variable feed rates may reduce gold recovery by causing recovery equipment to function erroneously. Finally, in most sand and gravel plants, the material mined has not been evaluated for its gold content. In these cases, gold recovery cannot be calculated accurately, and the only measure of success is the fact that the value of the recovered gold exceeds the cost of processing.

Conclusions

Sands and gravels in the Middle Bóbr River valley contain a variable quantity of heavy minerals, including gold, which predominantly occur in the fine sand fraction and may be concentrated by factors of 10–20 times during production of fine sand in the plant. This enrichment comes about as a consequence of normal plant operation and does not incur additional operating costs.

Gold recovery from fine sand using a Knelson concentrator is a highly effective process. Tests have shown that 85–98% of the gold in different types of tailings are gravity recoverable. The fine sandy slurry directed to a settling pond is highly amenable to gravity concentration and will be easily accommodated by the existing flow sheet at the plant with only minimal modifications. Extraction of gold through this process may be profitable under the prevailing economic conditions.

Sand and gravel materials processed in aggregate plants could constitute a new and previously 'lost' supply of gold (and other heavy minerals) for the mining industry. In some cases, the value of the extracted gold could add considerably to the base unit value of the aggregate product.

Furthermore, the gravity processing methodology outlined here has considerable environmental advantages. In addition to being a more efficient use of Earth's resources (recovery of economic heavy minerals from aggregates), it produces minimal additional environmental impact over that associated with the existing sand and gravel plant.

Thus, the further purposeful prospecting for technogenic placers of gold is an urgent issue for many regions. Additionally, advanced methods of prospecting, sampling, and processing should be introduced into the practice of geological exploration of such artificial types of deposits.

REFERENCES

Badura J., Przybylski B., 2000 – Morphologic and age correlation of terraces of main rivers in the Lower Silesia (in Polish with English summary). Wydawnictwa Instytutu Geologicznego, Warszawa, 55p.

Buksiński S., Cegła J., 1979 – Kruszywa naturalne. In: Surowce mineralne Dolnego Śląska (ed. K. Dziedzic et al.), pp. 411–422. Zakład Narodowy im.Ossolińskich, Wrocław.

Burt R., 1999 – The role of gravity concentration in modern processing plants. Minerals Engineering, vol.12, no.11, pp. 1291–1300.

Boyle W.R., 1987 – Gold: the history and genesis of deposits. Van Nostrad Reinhold Publication, New York, 675 pp.

Coulter T., Subasinghe G.K.N., 2005 – A mechanistic approach to modelling Knelson concentrators. Minerals Engineering, vol. 18, no. 1, pp. 9–17.

Domaszewska T., 1965 – Występowanie i eksploatacja złota na Dolnym Śląsku. Przegląd Geologiczny, vol. 13, no. 4, pp. 180–184.

Grocholski A., 1956 – Szczegółowa mapa geologiczna Sudetów 1:25 000, ark. Kraszowice. Wydawnictwo Instytutu Geologicznego, Warszawa.

Feather C.E., Koen G.M., 1973 – The significance of the mineralogical and surface characteristics of gold grains in the recovery process. Journal of the South African Institute of Mining and Metallurgy, vol. 73, pp. 223–234.

Gerlach R.W., Dobb D.E., Gregory A., Raab G.A., Nocerino J.M., 2002 – Gy sampling theory in environmental studies. Journal of Chemometrics, vol. 16, pp. 321–328.

Grocholski A., Milewicz J., 1958 – Morfologia i rozwój doliny Bobru między Lwówkiem a Bolesławcem. Biuletyn Instytutu Geologicznego, vol. 129, pp. 111–145.

Grodzicki A., 1972 – Petrologia i mineralogia piasków złotonośnych Dolnego Śląska. Geologia Sudetica, vol. 6, pp. 233–288.

Grodzicki A., 1977 – Rozsypiskowe koncentracje minerałów ciężkich występujących na Dolnym Śląsku. Acta Universitatis Wratislaviensis, no. 378, Prace Geologiczno-Mineralogiczne, vol. 6, pp. 157–182.

Jęczmyk M., Wojciechowski A., 1994 – Zasoby złota i minerałów ciężkich w odpadach poeksploatacyjnych kopalń kruszywa naturalnego w Polsce. Przegląd Geologiczny, vol. 42, no.10, pp. 819–827.

Kaźmierczyk J., 1974 – Sprawozdanie z badań nad górnictwem złota koło Złotoryi w 1973 roku. Śląskie Sprawozdania Archeologiczne, vol. 16, pp. 72–80.

Kaźmierczyk J., 1976 – Wyniki badań wykopaliskowych na terenie zagłębia złota koło Lwówka Śląskiego. Śląskie Sprawozdania Archeologiczne, vol. 18, pp. 78–81.

Kaźmierczyk J., Grodzicki A., 1976 – Górnictwo złota koło Złotoryi na Dolnym Śląsku w XI–XIV w. w świetle badań archeologicznych. Acta Universtitatis Wratislaviensis, no. 253. Studia Archeologiczne, vol. 7, pp. 205–248.

Laplante A.R., Shu Y., Marois J., 1996 – Experimental characterisation of a laboratory centrifugal separator. Canadian Metallurgical Quarterly, vol. 35, no.1, pp. 23–29.

Łuszczkiewicz A., 1990 – Minerały ciężkie w żwirach i piaskach eksploatowanych na Dolnym Śląsku. Fizykochemiczne Problemy Mineralurgii, vol. 23, pp. 27–39.

Łuszczkiewicz A., 2000 – Occurrence of heavy minerals in sand and gravel mined from the Rakowice deposit near Lwówek Śląski, SW Poland (in Polish with English summary). Prace Naukowe Instytutu Górnictwa Politechniki Wrocławskiej nr 87. Studia i Materiały, vol. 28, pp. 27–38.

Łuszczkiewicz A. 2002 – Poznawcze i technologiczne aspekty występowania minerałów ciężkich w surowcach okruchowych. Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław.

Łuszczkiewicz A., 2005 – Tailings from sand and gravel operations as a source of valuable heavy minerals (in Polish with English summary), pp. 1–15. Kompleksowe i szczegółowe problemy inżynierii środowiska.VII Ogólnopolska Konferencja Naukowa, Ustronie Morskie.

Łuszczkiewicz A., Muszer A., 1999 – Gold from Rakowice placer deposit near Lwówek Slaski, SW Poland (in Polish with English summary). Physicochemical Problems of Mineral Processing, vol. 33, pp. 99–106.

Oberc J., 1972 – Sudety i obszary przyległe. Budowa Geologiczna Polski T. 4, Tektonika część 2. Wydawnictwo Geologiczne, Warszawa.

Quiring H., 1948 – Geschichte des Goldes, pp. 154–166. Ferdinand Enke Verlag, Stuttgart.

Radis U., 1989 – Sprawozdanie z inwentaryzacji reliktów górnictwa złota w rejonie Bolesławca w 1986 roku. Śląskie Sprawozdania Archeologiczne, vol. 29, pp. 104–108.

Rutkowski E., Wojciechowski A., 1988 – Wstępne wyniki badań nad złotonośnością dorzecza Oldzy i środkowego Pobobrza. Przegląd Geologiczny, vol. 7, pp. 421–422.

Shilo N.A., 2002 – Teaching on placer deposits: the placer forming ore associations and generation theory, 2nd ed., 576 p. Dalnauka Publication, Vladivostok [in Russian].

Silva M., 1986 – Placer gold recovery methods. Special publication no. 87. California Department of Conservation, Division of Mines and Geology, 31 p.

Speczik S., Wierchowiec J., 1991 – Evolution of placer gold occurences in the vicinity of Lwówek Śląski, SW of Poland. In: Source, transport and deposition of metals (eds. M. Pagel and J. L. Leroy), pp. 709–713. Balkema Publishers, Rotterdam.

Teisseyre H., Smulikowski K., Oberc J., 1957 – Geologia regionalna Polski, vol. 3, cz. 1. Kraków.

Turner J.F., 1991 – Gravity concentration, past, present and future. Minerals Engineering, vol. 4, no. 3–4, pp. 213–223.

Viladevall M., Pacheco J.A., Cadena J.L., 2006 – Sand and gravel plants as potential sources of gold production in the European Union. Applied Earth Science (Trans. Inst. Min. Metall. B), vol. 115, no. 3, pp. 94–101.

Walsh D., Kelly E.G., 1993 – Technical note nominal diameters of gold particles. Minerals Engineering, vol. 6, no. 2, pp. 193–198.

Wang W., Poling G.W., 1983 – Methods for recovering fine placer gold. Canadian Mining and Metallurgical Bulletin, vol. 76, no. 860: 47–56.

Wierchowiec J., 2002 – Morphology and chemistry of placer gold grains – indicators of the origin of the placers: an example from the East Sudetic Foreland, Poland. Acta Geologica Polonica, vol. 52, no. 4, pp. 563–576.

Wierchowiec J., 2007 – Placer gold and other economic minerals from the remnants of palaeofan deposits in the foreland of the East Sudetes, Poland. Acta Geologica Polonica, vol. 57, no. 4, pp. 523–537.

Woodcock F., Laplante A.R., 1993 – A Laboratory method for determining the amount of gravity recoverable gold, pp. 151–155. Randol Gold Forum, Beaver Creek.

Wojciechowski A., 1989a – Dokumentacja zasobów złota i innych minerałów użytecznych pola górniczego kopalni „Rakowice”. Centralne Archiwum Geologiczne PIG, Warszawa, nr arch. 512/91.

Wojciechowski A., 1989b – Zbadanie możliwości pozyskiwania złota w procesie eksploatacji kruszywa naturalnego w kopalni „Rakowice”. Centralne Archiwum Geologiczne PIG, Warszawa, nr arch. 498/91.

Wojciechowski A., 1993 – Okruchowe złoża złota w dorzeczu środkowego Bobru. Posiedzenia Naukowe Państwowego Instytutu Geologicznego, vol. 49, no. 1, pp. 13–14.

Wojciechowski A., 1994a – Okruchowe złoża złota na północnym przedpolu Gór Kaczawskich – stan obecny i perspektywy. Posiedzenia Naukowe Państwowego Instytutu Geologicznego, vol. 50, no. 2, pp. 16–18.

Wojciechowski A., 1994b – Recognizing and making evidence of gold reserves in arsenic sludges and mining wastes from natural aggregate mines (in Polish with English summary). Górnictwo Odkrywkowe, vol. 36, no. 6, pp. 99–111.

ODPADY Z PRZERÓBKI PIASKÓW I ŻWIRÓW JAKO POTENCJALNE ŹRÓDŁO ZŁOTA

Słowa kluczowe

Żwirownie, odpady mineralne, koncentrator Knelsona, minerały ciężkie, złoto okruchowe

Streszczenie

Górnictwo surowców okruchowych zlokalizowane w Sudetach wytwarza znaczne ilości odpadów mineralnych (piasków i mułków) deponowanych w wyeksploatowanej części złoża, a powstających najczęściej po operacji klasyfikacji ziarnowej urobku. W procesie przesiewania i przemywania powyższe odpady są wzbogacane w złoto i inne minerały ciężkie, które w złożu występują zazwyczaj w ilościach śladowych. W artykule, na przykładzie drobnoziarnistych odpadów z płukania żwirów i piasków w żwirowni Rakowice koło Lwówka Śląskiego na Dolnym Śląsku, przedstawiono możliwości ich wykorzystania jako źródło minerałów ciężkich i złota. Odpady z płukania kruszyw poddano wzbogacaniu grawitacyjnemu za pomocą koncentratora Knelsona wydzielając koncentrat minerałów ciężkich ze złotem.

Wzbogacanie grawitacyjne próbek tych odpadów wykazało, że możliwe jest otrzymywanie koncentratów zawierających średnio 27 g/t Au z uzyskami złota w zależności od typu osadów rzędu 85–98%. Do koncentratów tych przechodzą także minerały tytanu, cyrkonu i metali ziem rzadkich. Według szacunku autora w odpadach żwirowni Rakowice deponuje się rocznie około 6 kg złota oraz 1000 Mg minerałów ciężkich możliwych do pozyskania w postaci takiego koncentratu.

TAILINGS FROM SAND AND GRAVEL PROCESSING PLANTS AS THE POTENTIAL SOURCE OF GOLD

Key words

Sand and gravel plants, tailings, Knelson concentrator, heavy minerals, placer gold

Abstract

Tailings produced during the manufacture of aggregates in the Rakowice sand and gravel plant (Middle Bóbr River valley, SW Poland) were characterized in the paper. A 3.0 inches laboratory Knelson concentrator was used to evaluate the recovery of free gold from tailings collected from the sand and gravel processing plant. Gravity recoverable gold (GRG) was determined using the difference between the gold content in the Knelson feed and the tails. Analysis of several samples collected from different types of tailings revealed the average content of 0.27 ppm of gold and recoveries of gold between 85–98% in the concentrates. The sand and gravel deposits are thus potential sources of gold and other economic heavy minerals, mainly of ilmenite and titanomagnetite, as well as small amounts of zircon, monazite and rutile. The annual deposition of about 6 kg of Au and 1000 Mg of other heavy minerals in the tailing pond during the last 5 years of the Rakowice Mine operation has been assessed.