

Characterization and environmental risk assessment of potential mining waste from Detva – Biely vrch deposit

Peter Šottník¹, Bronislava Lalinská-Voleková², Jana Brčeková¹, Peter Koděra¹ & Ľubomír Jurkovič³

¹Department of Geology of Mineral Deposits, Faculty of Natural Sciences, Comenius University, Mlynská dolina, Ilkovičova 6, 842 15 Bratislava, Slovak Republic

²Slovak National Museum – Natural History Museum, Vajanského nábrežie 2, 810 06 Bratislava, Slovak Republic

³Department of Geochemistry, Faculty of Natural Sciences, Comenius University, Mlynská dolina, Ilkovičova 6, 842 15 Bratislava, Slovak Republic

AGEOS Charakterizácia a hodnotenie environmentálneho rizika potenciálneho ťažobného odpadu z ložiska Detva – Biely vrch

Abstract: In the year 2006 the company EMED Slovakia determined at the locality of Biely Vrch near Detva the presence of a new type of porphyry mineralisation with a relatively high Au/Cu ratio that in the literature is marked as Au-porphyry mineralisation. This type of mineralisation was not described in Western Carpathians yet. Low content of metals and big amount of ore in porphyric systems requires exploration by open pit methodology which produces a big volume of mining waste. Main goal of this research was a characterization and qualified categorization of mining waste, which will be potentially created by exploitation of the Biely vrch deposit. This will enable to predict and prevent environmental problems related to mining and processing of ore. The results of chemical analyses of water extracts showed extremely low content of Sb, Cd, and Mo (under detection limits). Also the content of other parameters monitored (As, Cu, Fe, Pb, Zn, S) were relatively low, especially in comparison with total chemical analyses. The total average value of Net Neutralisation Potential (NNP= NP-AP) was set as 43.06 kg of CaCO₃/1000 kg of material and was calculated for all the samples from the database. Acidification Potential (AP) was calculated for every sample, in case of Neutralization Potential (NP) average value (42.65 kg of CaCO₃/1000 kg) for selected 60 samples was used for calculation. Based on this assessment, we can say that 3.64 % of the samples are potentially able to produce acidity and 7.06 % of the samples are in the field of uncertainty. Most of the studied samples (89.3 %) does not produce any acidity.

Key words: Biely vrch deposit, mining waste, risk assessment, neutralization potential

1. INTRODUCTION

The magmatic-hydrothermal systems situated in central zone of the Javorie Stratovolcano is related to subvolcanic intrusions of andesite and diorite porphyry, diorite and monsdiorite of the Kráľová and Kalinka intrusive complexes. For a long time these complexes were regarded as barren or weakly mineralised in terms of the presence of the classic Cu-porphyry type of mineralisation (Štohl et al., 1981; Konečný et al., 2002). Lexa et al. (2002) assumed that the central zone of the Javorie Stratovolcano could be a potential host of economically interesting Au-porphyry mineralisation. Using advanced methods of geological exploration EMED Slovakia, Ltd. indeed discovered that several of the hydrothermal systems contain Au-porphyry mineralisation, but only the locality of Biely vrch is of economic value (Hanes et al., 2010). The Biely vrch deposit is the biggest and best explored system, reaching from surface down to depth > 450 m, with 42 Mt at 0.8 g/t Au (Fletcher & Bennett, 2010). The preliminary research (Koděra et al., 2010) showed, that the parental intrusion is intensively affected especially by intermediate argillic alteration that replaces K-silicate and in deeper parts cause Ca-Na alteration. In outer zone of the system propylitic alteration prevails, while ledges of advanced argillic alteration are the youngest. Several types of veinlets are associated with alteration among which quartz veinlets

of several generations predominate and spatially correspond with increased concentrations of Au. However, gold of microscopic and submicroscopic size was not found inside quartz veinlets, but in close vicinity of quartz veinlets in altered rocks. This fact has probably a significant impact at the economic value of the Biely vrch deposit, as gold from argillised rock is easier released during processing of ore compared to gold enclosed in form of microinclusions in quartz.

Open-pit mining is a surface mining technique employed to extract ores from large deposits that are relatively close to the surface. Therefore most porphyry Cu(Au) deposits are mined this way, less commonly, by underground methods (Berger et al., 2008). By design, open-pit mining can expose large surface areas of wall rock to atmospheric oxygen (Blowes et al., 2014). This mining method is accompanied by high volumes of various metal rich wastes that are the most important potential hazard to the environment (Dudka & Adriano, 1997; Herr & Gray, 1997; Gray, 1997; Lottermoser, 2003). Mining and mineral processing are the two principal sources of the solid wastes in the mining industry (Lottermoser, 2003). Volumes of waste rock will depend upon the depth and geometry of the deposit as well as the competency of the country rock as it relates to stripping ratios. On average, about 1.5 tons of waste rocks and overburden must be removed for every ton of ore grade mined in porphyry Cu deposits (Phillips & Niemuth, 1993).

1.1. The current legislative for management of the waste from extractive industry

Slovakia has signed the agreement about implementation of Directive 2006/21/ES of the European Parliament and of the Council valid from 15th March 2006 on the management of waste from extractive industries. The law No. 514/2008 (Anon, 2008) on management of waste produced by mining industry with related legislative changes is valid in the Slovak Republic at the moment.

According to this law the mining waste storages have to be categorised by kind, volume and properties of deposited mining waste, localisation of mining waste storage sites, local environmental conditions and risk of serious accidents on mining waste storage sites of A and B category. Responsible authority evaluates particular mining waste storage site into the category A if:

(i) failure or incorrect operation, e.g. the collapse of a heap or the bursting of a dam, could give rise to a major accident, on the basis of a risk assessment taking into account factors such as the present or future size, the location and the environmental impact of the waste facility; or

(ii) it contains waste classified as hazardous (under law about waste; Law No. 223/2001, Anon, 2001b) above a certain threshold (certain threshold constitute pronouncement of law No. 514/2008); or

(iii) it contains substances or preparations classified as dangerous under (Law No. 163/2001, Anon, 2001a) above a certain threshold (certain threshold constitute pronouncement of Law No. 514/2008).

It is necessary to characterize mining waste when the mining waste management plan is being created, especially if the information for mining waste site categorization is insufficient. Mining waste tests are focused on two groups of waste properties: (i) geotechnical properties; (ii) geochemical properties and waste behavior.

The definition of mining waste properties includes the determination of chemical and mineralogical properties of mining waste and all chemical substances and agents remained in mining waste. Main goal of environmental part of the project is the determination of composition and subsequent behaviour of "potential" mining waste after deposition on mining waste storage sites. These data will be used as a base for the determination of potential chemical

composition of drainage waters for each type of mining waste produced during the mine operation.

1.2. The current legislative for leaching tests

The leaching tests are classified according to their objectives and their domain of application. Following compliance tests and basic characterization tests are known: Regulatory compliance test (including that suitable one for our case – the STN EN 12457-2 test, December, 2002).

The compliance tests are used to compare concentrations or fluxes of emitted pollutants to the criteria of acceptance in landfill or criteria of valorisation - recycling as raw material or substitution material. These regulatory objectives correspond either to:

(i) the maximal leachable fraction for a given leachant (potentially leachable content in mg/kg);

(ii) the maximal concentration emitted in a given context (for example the Co concentration of the first eluate of the percolation test in column);

(iii) the released quantity in a given context (at a given L/S ratio for example).

1.3. Characterization test of the waste behaviour in scenario

Characterization test of waste and assessment of pollutants emission from waste based on materials which are defined in a given scenario (use of Municipal Solid Waste Incineration bottom ashes or MSWI bottom ashes in roadbase layer for example; Fig. 1).

The objectives can be then to identify the main mobilization mechanisms, to characterize the release dynamics of pollutants, and to determine the influence of some scenario factors on this release dynamics.

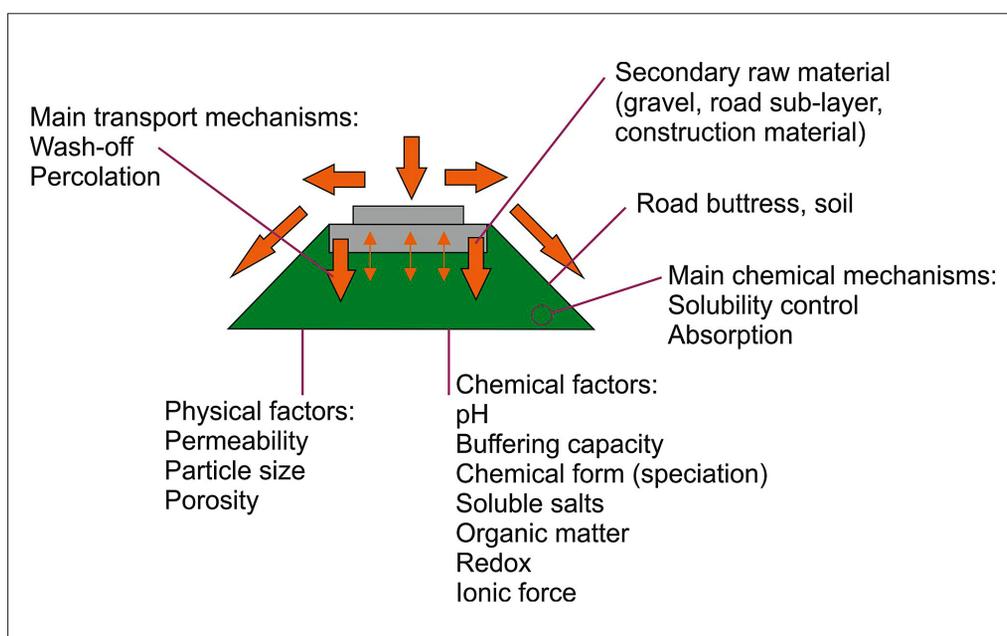


Fig. 1. Description of roadbase layer scenario in terms of influence factors (van der Sloot & Dijkstra, 2004).

These basic characterization tests can also be classified in two categories:

(i) the static tests aiming to reach the equilibrium for some of the parameters (such as pH). Both European tests aiming to study the influence of the pH on the elements solubilisation

are presented below: the standardized test XP CEN/TS 14429 and the standardized test XP CEN/TS 14997;

(ii) the dynamic tests in order to determine the release dynamics of the material in standard conditions. On granular material, the standardized percolation test is presented STN P

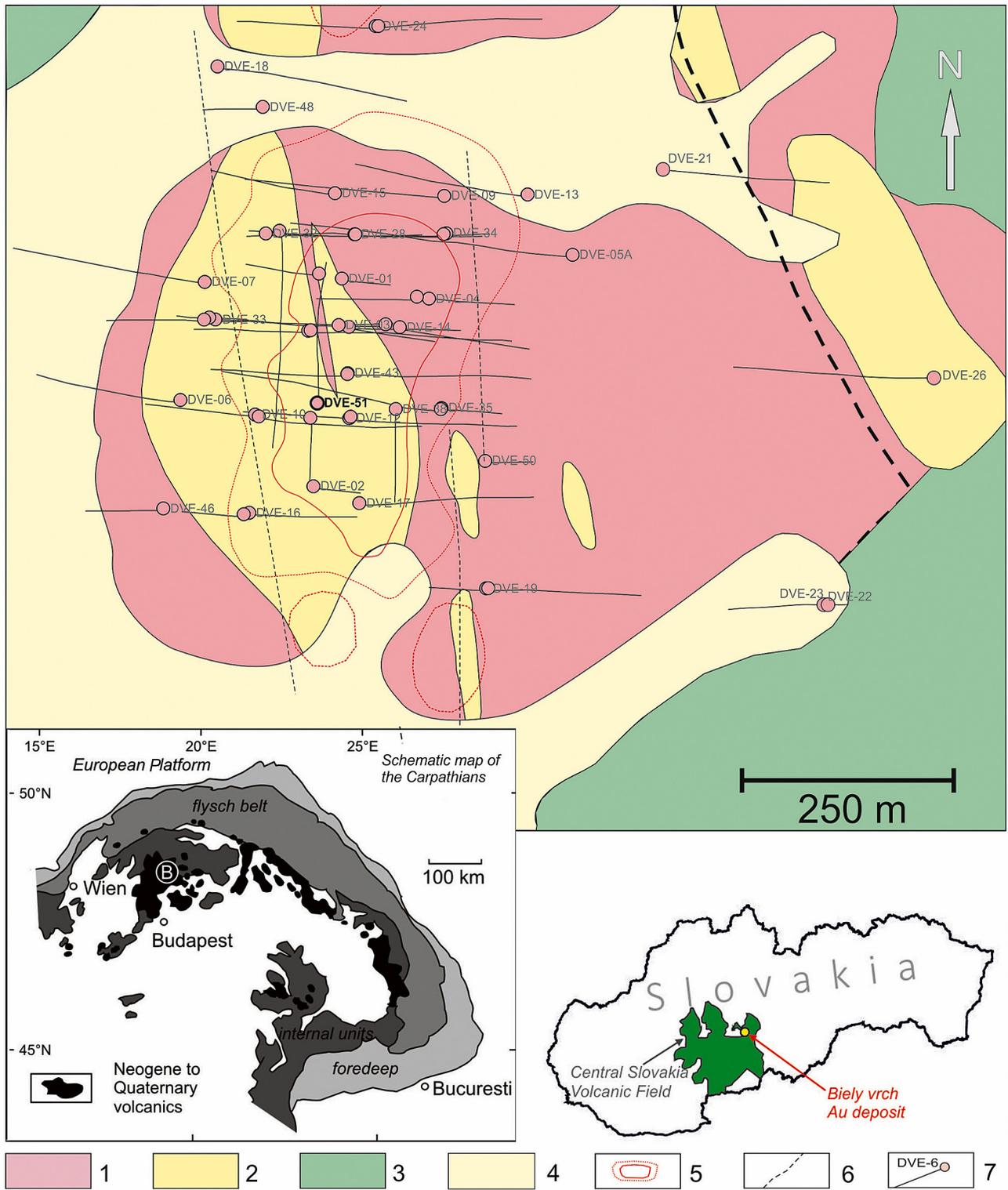


Fig. 2. Geology of studied area with drillhole plan. Legend: 1 – diorite porphyry; 2 – advanced argillic alteration zones of the diorite porphyry; 3 – andesite of the Stará Huta Formation; 4 – alluvial and deluvial deposits; 5 – quartz stockwork; 6 – faults; 7 – drill holes collar and drill hole lines.

CEN/TS 14405. On monolithic material, the future European standard STN P CEN/TS 15864 that distinguishes two manners to perform the test: in batch (liquid periodically renewed) and continuously (liquid continuously renewed).

2. GEOLOGICAL CHARACTERIZATION OF STUDIED AREA

Porphyry gold deposit of Biely vrch is situated in the northern part of the middle Miocene Javorie Stratovolcano in eastern part of the Central Slovakia Volcanic Field (Fig. 2). It represents new porphyry type of ore mineralization in Slovakia with economic accumulation of gold ore – 42 Mt at 0.8 ppm Au (Hanes et al., 2010). Parental intrusion of diorite to andesite porphyry is emplaced into andesite. Diorite intrusion is affected by hydrothermal alteration of various types. The dominant intermediate argillic alteration overprints earlier high-temperature K-silicate alteration and deeper Ca-Na silicate alteration. Ledges of advanced argillic alteration represent the youngest alteration stage. Alterations are accompanied by several generations of veinlets. The oldest biotite-magnetite, amphibole-pyroxene-apatite, and quartz-biotite-magnetite veinlets associated with K- and Ca-Na silicate alteration. Younger quartz veinlets with banded texture, pyrite (\pm chalcopyrite, sphalerite, galena, marcasite, and molybdenite) veinlets and intermediate argillic veinlets are related to intermediate argillic alteration. The youngest generations of veinlets are represented by calcite-zeolite and advanced argillic veinlets (Kodera et al., 2010).

Gold mineralization occurs in the vicinity of quartz veinlets (down up to about 750 m). K-silicate alteration located in the central part of porphyry intrusion is probably the primary source of gold (Bakoš et al., 2012). High Au grades occur in the vicinity of quartz veinlets, in altered rocks with clays, chlorite, and K-feldspar; sometimes attached to sulphides or Fe-Ti minerals (Kodera et al., 2010).

3. METHODS

3.1. Studied samples

Database received from EMED Company was used as the basic source of the total element concentrations of core samples from the Biely vrch deposit (elements analysed: Au, Ag, Al, As, Ba, Be, Bi, Ca, Cd, Co, Cr, Cu, Fe, Ga, K, La, Mg, Mn, Mo, Na, Ni, P, Pb, S, Sb, Sc, Sr, Th, Ti, Tl, U, V, W, Zn). These data were the

most important for the potential mine waste evaluation (total of 15276 analyses from 52 drill holes).

Analysed samples were collected from the boreholes; most often one sample per meter was taken. Only in case of the DVE-51 and DVE-52 boreholes, one sample per two meters was taken. All samples were analysed at Acme Laboratories Vancouver by ICP-MS (group AQ250 – Ultratrace).

For the laboratory experiments (leaching tests according to standard STN EN 12457-2, neutralization potential, acidification potential) 60 samples from the following boreholes were used: DVE-4 (4 samples), DVE-05A (9 samples), DVE-10 (8 samples), DVE-28 (1 sample), DVE-29 (9 samples), DVE-30 (2 samples), DVE-51 (15 samples), and DVE-52 (12 samples). The samples from the DVE-10, DVE-29, DVE-51, DVE-52, and DVE-05A boreholes have been collected systematically, to be representative for the whole length of the borehole (each rock type was sampled). Samples from the DVE-4, DVE-28, and DVE-30 boreholes were chosen based on sulphur content (important factor for the acid generation test).

3.2. The STN EN 12457-2 test – selected for this study

This part of the European Standard specifies a compliance test providing information on leaching of granular waste and sludge under the experimental conditions specified hereafter, and

Tab. 1. The selected limits for mine waste evaluation, classification as inert waste, not hazardous waste and hazardous waste (Council Decision, 2003/33/ES).

| Parameter | Inert waste | Not hazardous waste | Hazardous waste |
|-----------|------------------------|------------------------|------------------------|
| | mg.kg ⁻¹ DW | mg.kg ⁻¹ DW | mg.kg ⁻¹ DW |
| As | 0.5 | 2 | 25 |
| Cd | 0.04 | 1 | 5 |
| Cu | 2 | 50 | 100 |
| Hg | 0.01 | 0.2 | 2 |
| Mo | 0.5 | 10 | 30 |
| Ni | 0.4 | 10 | 40 |
| Pb | 0.5 | 10 | 50 |
| Sb | 0.06 | 0.7 | 5 |
| Zn | 4 | 50 | 200 |
| sulphates | 1 000 | 20 000 | 50 000 |
| TDS | 4 000 | 60 000* | 100 000* |

* The values for total dissolved solids (TDS) can alternatively be used as values for sulphates and chlorides

Tab. 2. The total content of selected elements in samples from boreholes from Biely Vrch locality (mg.kg⁻¹ DW; content of S and Fe are in %).

| | As | Cd | Cu | Fe | Mo | Pb | S | Sb | Zn |
|---------|--------|--------|---------|-------|---------|----------|------|-------|----------|
| mean | 20.82 | 1.08 | 112.84 | 4.35 | 10.27 | 96.17 | 0.42 | 0.53 | 115.94 |
| minimum | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| maximum | 940.00 | 387.00 | 3330.00 | 28.00 | 1680.00 | 10000.00 | 8.30 | 46.00 | 10000.00 |
| median | 11.00 | 0.50 | 65.00 | 4.55 | 6.00 | 62.00 | 0.12 | 0.00 | 67.00 |

particularly liquid to solid ratio of 10 l/kg¹/kg of dry matter. It applies to waste which has a particle size below 4 mm without or with size reduction. The test procedure specified in this Standard produces an eluate which shall subsequently be characterized physically and chemically according to appropriate standard methods.

Selected method consists of following steps:

(i) This leaching test uses deionized water (filtered under 0.4 µm) as the leachant at a liquid to solid ratio of 10;

(ii) The mixture is rotated end over end for 24 hours at – 10 rpm;

(iii) After extraction the leachate is centrifuged (3000 rpm. for 15 minutes) and filtered under 0,4 µm;

(iv) Leachate conductivity and pH are recorded by equipment WTW pH/Cond 340i and afterwards concentration of selected elements are analysed by atomic absorption spectrometry (AAS) in accredited laboratory EL Ltd. Spišská Nová Ves.

According to the results of this leaching test, the studied material – potential mining waste – can be classified as inert, not

dangerous according to valid European legislative 2003/33/ES (Tab. 1).

Static tests predict drainage quality by comparing the sample's maximum acid production potential (AP) with its maximum neutralization potential (NP). The AP is determined by multiplying the percent of total sulphur or sulphide sulphur (depending on the test) in the sample by a conversion factor ($AP = 31.25 \times \%S$). NP is a measure of the carbonate material available to neutralize the acid (Sobek et al., 1978; US EPA 1994).

The results visualization in the Geographic Information System (GIS)

The Leapfrog Geo software was used for visualization of the neutralization potential and S distribution. Software permits a 3D display of geochemical data using polyharmonic Radial Basis Functions to create smooth surfaces from scattered data points, such as isolated samples collected from drill holes. Radial basis functions are a family of interpolation functions (Carr et al., 2001; Cowan et al., 2003). RBF interpolation represents the function as a sum of so-called basic functions, with linear

weights in exactly the same way as the dual formulation of kriging (Chilès & Delfiner, 1999). RBF interpolation is a global interpolation method, requires all the data points to be used to calculate the coefficients (ie the weights assigned to each value; Cowan et al., 2003). Spherical interpoland and isotropic ratio 1.0 were used for interpolation method of NNP and S modelling.

Datasets for the visualization and modelling were obtained from the EMED Company and contain spatial and attribute data from 52 boreholes (the longest ranges to the depth of 782 m). The boreholes are situated in the area of approx. 700 × 900 m and the distance between them is from 50 to 100 m. Digital model of the relief created in Grass GIS software (GRASS Development Team, 2015) was used for the georelief of 3D model definition (at a scale of 1:10000). Digital model of the quarry pit was provided by EMED Slovakia.

4. RESULTS AND DISCUSSION

The results of the selected leaching tests (according to STN EN 12457-2) were compared with the limits on elements content according to actual norm and also with the total content of the selected elements in the studied samples.

In general, the total contents of potentially hazardous elements were not

Tab. 3. The average content of selected elements in solid samples (from database; average TA) and the average content of selected elements in water leachate (average LT; limit IO – limit for inert waste, limit NNO – limit for not hazardous waste).

| | As | Cu | Fe | Pb | Zn | S |
|------------|---------|---------|---------|---------|---------|---------|
| | mg.kg-1 | mg.kg-1 | mg.kg-1 | mg.kg-1 | mg.kg-1 | mg.kg-1 |
| DVE-04 | | | | | | |
| average LT | 0.01 | 0.03 | 1.22 | 0.06 | 0.30 | 258 |
| average TA | 17.68 | 275.03 | 49100 | 141.90 | 173.10 | 8200 |
| DVE-5A | | | | | | |
| average LT | 0.02 | 0.01 | 0.67 | 0.01 | 0.04 | 70 |
| average TA | 8.26 | 258.41 | 51040 | 79.60 | | 7300 |
| DVE-10 | | | | | | |
| average LT | 0.38 | 7.87 | 236.17 | 0.28 | 7.27 | 3147 |
| average TA | 47.60 | 97.90 | 46000 | 394.10 | 110.80 | 11600 |
| DVE-28 | | | | | | |
| average LT | 0.05 | 0.01 | 1.77 | 0.01 | 0.13 | 10 |
| average TA | 30.80 | 129.44 | 32700 | 85.80 | 57.90 | 4500 |
| DVE-29 | | | | | | |
| average LT | 0.02 | 0.05 | 2.61 | 0.10 | 0.47 | 167 |
| average TA | 20.51 | 156.12 | 57600 | 159.62 | 128.40 | 1800 |
| DVE-30 | | | | | | |
| average LT | 0.06 | 10.39 | 80.06 | 0.61 | 6.54 | 3253 |
| average TA | 9.57 | 118.31 | 54001 | 109.35 | 146.00 | 21500 |
| DVE-51 | | | | | | |
| average LT | 0.02 | 0.18 | 0.75 | | 0.13 | 36 |
| average TA | 18.40 | 91.07 | 40600 | | 58.93 | 8000 |
| DVE-52 | | | | | | |
| average LT | 0.02 | 0.15 | 0.27 | 0.01 | 0.24 | 42 |
| average TA | 12.61 | 140.00 | 39200 | 50.77 | 63.16 | 1400 |
| limit IO | 0.5 | 2 | | 0.5 | 4 | 1000 |
| limit NNO | 2 | 50 | | 10 | 50 | 20000 |

extremely high (Tab. 2). Just in few samples Pb and Zn content were enhanced, probably due to the presence of sulphides. In term of the evaluation of possible environmental impact of potential mining waste, the concentration of total sulphur (S) appears to be the most important. The average content of S is 0.42 wt % (median = 0.12 wt %). The “critical” content of S (according to majority of authors) seem to be those exceeding 1 wt%. Only 3 % of all samples exceeded this critical value (maximum content = 8.2 wt %), the sulphur content in the rest of the samples was lower.

The host rocks situated in the environment of the porphyry deposits are generally known for their low neutralization capacity (Blowes et al., 2014). Therefore more tests were necessary in case of studied locality to quantify the proportion of potentially hazardous materials.

4.1 Water extracts

The results of chemical analyses of water extracts showed extremely low content of Sb, Cd, and Mo (under detection limits). Also the content of other parameters monitored (As, Cu, Fe, Pb, Zn, S) were relatively low, especially in comparison with total chemical analyses (Tab. 3). Based on the average contents of decisive elements in individual boreholes, it is possible to conclude, that most of the studied boreholes (except DVE-10 and DVE-30) meet the threshold for inert waste. In case of the DVE-10 and DVE-30 boreholes, the content of Cu, Pb, Zn and S is higher and the material could be classified as “non-hazardous waste”. However since these two boreholes were sampled based on the increased content of S, the measured contents could be considered as maximal.

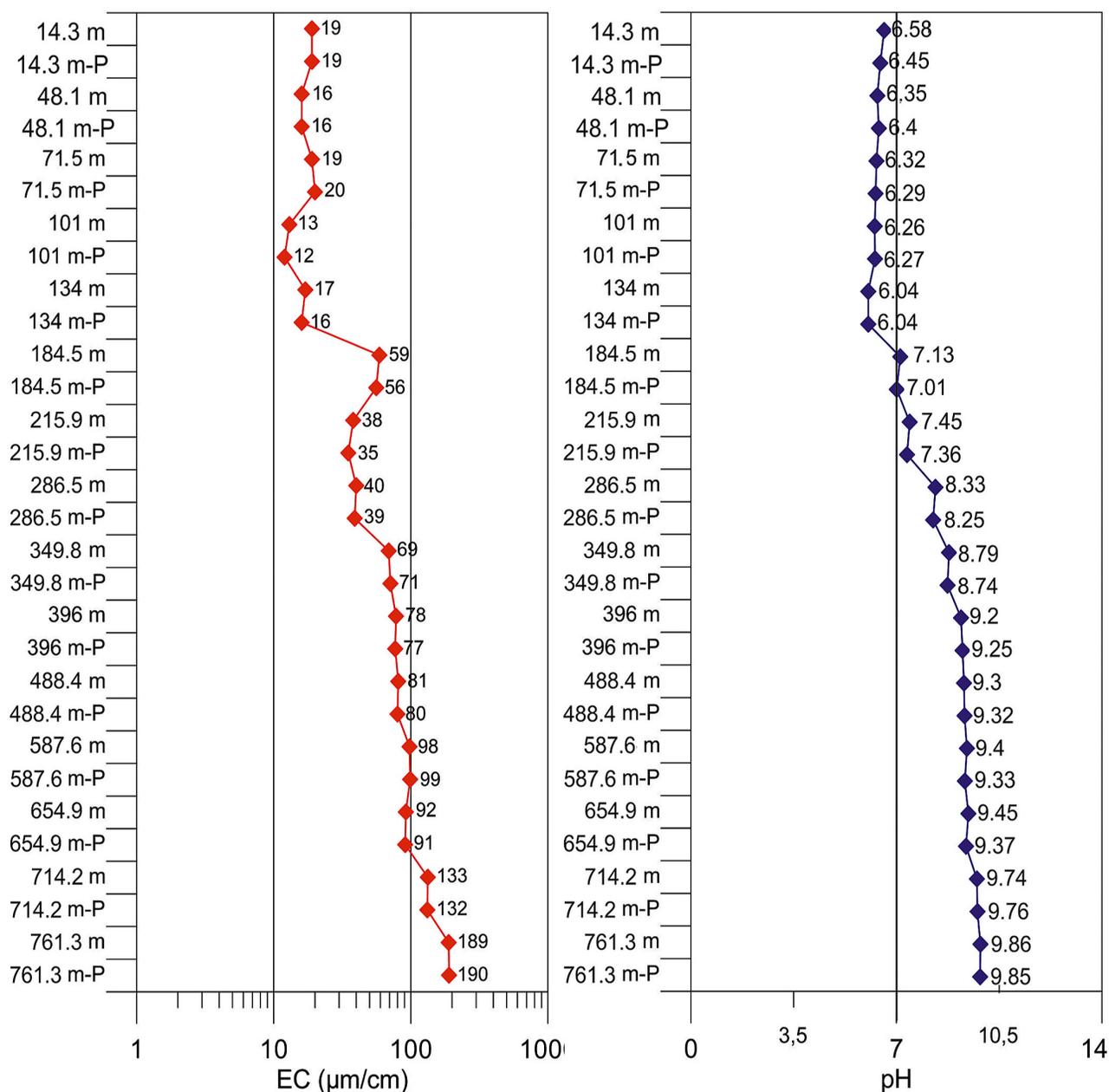


Fig. 3. The pH values and conductivity in the profile of the borehole DVE-51 (measured in water leachate).

Other fact that has to be considered is, that the selected leaching test STN EN 12457-2 (2002) represent the maximal level of leachability. In real conditions, the material is not going to be milled to as fine fraction and even washing the material on the waste dump will not be as intense as in the laboratory. Based on all of these facts we can state, that in term of leachability of potentially toxic elements, the studied material does not present any environmental risk and there is no presumption that significant amounts of contaminated waters would be released into the surrounding environment.

The values of pH and EC were measured in all leachates. The most consistent results were obtained in samples from the boreholes of DVE-51 and DVE-52, which were sampled continually in the whole profiles. The average pH in leachates

from the borehole DVE-51 is 7.99 (min. 6.04 – max. 9.86), in case of the DVE-52 borehole the average pH is 7.23 (min. 5.82 – max. 8.72). In both cases the pH presents neutral reaction. The average EC value is $63.8 \mu\text{S}\cdot\text{cm}^{-1}$ (min. $12 \mu\text{S}\cdot\text{cm}^{-1}$ – max. $190 \mu\text{S}\cdot\text{cm}^{-1}$) in case of the DVE-51 borehole and $75.5 \mu\text{S}\cdot\text{cm}^{-1}$ (min. $32 \mu\text{S}\cdot\text{cm}^{-1}$ – max. $125 \mu\text{S}\cdot\text{cm}^{-1}$) in case of the DVE-52. The significant increase of pH and EC values with depth is an interesting fact. It can be caused by the increasing amount of mineral phases which contain alkali metals and alkaline earth metals (e.g., feldspar, amphibole and calcite) in the host rocks (Fig. 3). This can also be seen in Fig. 4, where the total contents of Ca, Mg, and S are visualized in the profile of the DVE-51 borehole.

4.2. Acidification and neutralization potential

The values of AP (acidification potential) were determined by calculation on the basis of a standard methodology according to Sobek et al. (1978). The average AP was calculated from all 15 256 samples and was set as 13.17 kg of H_2SO_4 for each 1000 kg of studied material.

This value could be considered being most accurate and was used for further calculations. Generally the values of AP range from 0 to 259.38 kg $\text{H}_2\text{SO}_4/1000$ kg of material. The zero values represent samples, where sulphur content is under detection limit and no acidity can be produced (6.52% of all samples).

Slightly different values of AP were obtained in cases where NP was set in laboratory. The average value of AP (calculated from 60 samples) would be little higher in that case – 24.9 kg $\text{H}_2\text{SO}_4/1000$ kg of material, and ranges from 4.28 to 66.10 kg $\text{H}_2\text{SO}_4/1000$ kg of material, for individual wells. This higher average value of AP is caused by the sampling method and after excluding the extreme values we get the number which is very similar to that counted for all samples by previous methodology – 14.90 kg $\text{H}_2\text{SO}_4/1000$ kg of material. This fact can be considered as adequate verification of correct determination of average AP value for whole site.

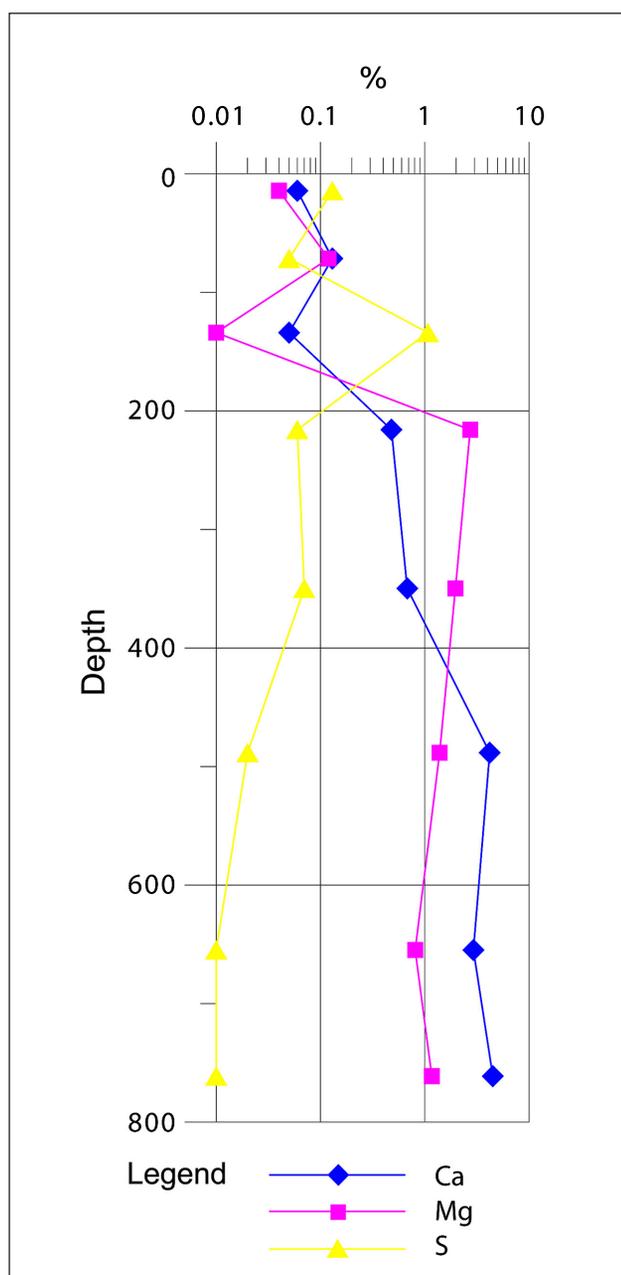


Fig. 4. Total content of Ca, Mg and S in the profile of the borehole DVE-51.

Tab. 4. The average values of total sulphur content, acidification potential, neutralization potential and net neutralizing potential for individual boreholes. The value corresponding to “mean” is calculated from all samples except of the samples from the boreholes DVE-4, DVE-28 a DVE-30; the other one (mean*) is calculated from all studied samples.

| borehole | S (%) | AP | NP | NNP |
|----------|-------|-------|--------|--------|
| DVE 04 | 0.82 | 25.54 | 16.68 | -8.49 |
| DVE 05 | 0.73 | 22.81 | 190.91 | 168.10 |
| DVE 10 | 1.16 | 36.25 | 18.58 | -17.66 |
| DVE 28 | 1.06 | 33.12 | 28.40 | -4.68 |
| DVE 29 | 0.19 | 5.97 | 23.77 | 17.80 |
| DVE 30 | 2.12 | 66.10 | 14.97 | -51.14 |
| DVE 51 | 0.66 | 5.18 | 32.84 | 27.66 |
| DVE 52 | 0.14 | 4.28 | 15.06 | 10.78 |
| mean | 0.57 | 14.90 | 56.23 | 41.34 |
| mean* | 0.86 | 24.90 | 42.65 | 17.80 |

Neutralization potential (NP) was set by laboratory method according to Sobek et al. (1978) for selected 60 samples. The average NP values for each borehole ranged from 14.97 to 190.91 kg of CaCO₃/1000 kg of material, total average NP value was than 42.65 kg of CaCO₃/1000 kg of material. However this value can be considered underestimated due to the inclusion of samples from boreholes DVE–4, DVE–28 and DVE–30 that have been chosen for the increased sulphur content. More precise would be average value of 56.23 kg of CaCO₃/1000 kg of material – calculated after removal of 7 extreme samples. This value was used for further calculations and also for visualization proposes in GIS.

In Tab. 6, values obtained using the lower value of NP (42.65 kg CaCO₃/1000 kg of material) are presented for illustration.

On the bases of AP and NP, net neutralization potential was calculated (NNP = NP-AP), what is the most commonly used expression for the potential acidity production (Sobek et al., 1978; Tab. 4).

The total average value of NNP was set as 43.06 kg of CaCO₃/1000 kg of material and was calculated for all samples from the database (AP was calculated for every sample, in case of NP average value was used for calculation, Tab. 5).

Afterwards, the results were evaluated according to methodology after Lapakko (1993), who has established three categories:

(i) the area of potential acidity formation (the values under -20 kg of CaCO₃/1000 kg of material);

(ii) the area of uncertainty (the values in-between -20 and 20 kg of CaCO₃/1000 kg of material);

(iii) the area where no acidity is produced (the values over 20 kg of CaCO₃/1000 kg of material).

Based on this assessment, we can say that 3.64 % of the samples are potentially able to produce acidity and 7.06 % of the samples are in the field of uncertainty. Most of the studied samples (89.3 %) does not produce any acidity (Tab. 6).

The Slovak Laws No. 514/2008 (Anon, 2008) on management of waste produced by mining industry and on amendments to certain Acts in the Annex. III, Article 7 states that, if the ratio of the total waste classified as hazardous and the total waste whose presence is expected in the equipment at the end of the operation is lower than 5 %, than the equipment will not be included in category A (and will be included to category B).

As it was already stated, according to our results, only 3.64 % of the total potentially excavated material is potentially acid producing. Of course, material falling into the field of uncertainty, also represents some risk. This risk can be easily eliminated by the proper waste and mining management (the appropriate mixing of material from different parts of the deposit).

Very similar were the results of Moddaberi et al. (2013), who have studied the possibility of acid mine drainage (AMD) generation in active and derelict mine waste piles in Sarcheshmeh Copper Mine produced in several decades, using static tests including acid-base accounting (ABA) and net acid-generating pH (NAGpH). The analysis of data indicates that eight waste piles (out of 51) are potentially acid generating with net neutralization potentials (NNPs) of -56.18 to -199.3, net acid generating of 2.19 to 3.31, and NPRs from 0.18 to 0.44. Other waste piles exhibited either a very low

Tab. 5. The mean, maximum, minimum and median of total sulphur content (S), Acidification Potential (AP), Net Neutralizing Potential (NNP) and Neutralizing Potential Ratio (NPR) calculated for the whole deposit. NNP* and NPR* were calculated from the lower value of Neutralization Potentials (42.65 kg CaCO₃/1000 kg of material).

| | S (%) | AP | NNP | NPR | NNP * | NPR * |
|---------|-------|--------|---------|--------|---------|--------|
| Mean | 0.42 | 13.17 | 43.06 | 45.13 | 29.45 | 34.23 |
| Minimum | 0.00 | 0.00 | -203.14 | 0.22 | -216.72 | 0.16 |
| Maximum | 8.30 | 259.38 | 56.23 | 179.94 | 42.34 | 136.48 |
| Median | 0.12 | 3.75 | 52.48 | 15.00 | 38.90 | 11.37 |

Tab. 6. Quantification of the amount of potentially hazardous waste on the bases of NNP (Net Neutralization Potentials) and NPR (Neutralizing Potential Ratio). NNP* and NPR* were calculated from the lower value of Neutralization Potentials (42.65 kg CaCO₃/1000 kg of material).

n - number of samples, % - percentage of these samples within the whole database

| | | below -20 | from -20 to +20 | over +20 |
|-------|---|-----------|-----------------|----------|
| NNP | n | 555 | 1077 | 13624 |
| | % | 3.64 | 7.06 | 89.30 |
| NNP * | n | 802 | 1604 | 12850 |
| | % | 5.26 | 10.51 | 84.23 |
| | | below 1 | from 1 to 3 | over 3 |
| NPR | n | 2015 | 1494 | 11747 |
| | % | 13.21 | 9.79 | 77.00 |
| NPR * | n | 1348 | 2100 | 11808 |
| | % | 8.84 | 13.77 | 77.40 |

sulphur, high carbonate content or excess carbonate over sulphur; hence, they are not capable of acid production or they can be considered as weak acid producers. Barnes et al. (2009) studied ARD potential for a “Climax” type porphyry molybdenum deposit in arctic environment. They found out, that the majority of waste rock to be extracted (approximately 79 %) does not appear to have potential for acid generation and that the most acidic sulfate rich water are the pyritized sandstone, pyrite-bearing granite and greisens zone units. The acid-generating potential of Pebble (Bristol Bay Watershed, Alaska) is also similar to that found at other porphyry copper deposits: waste rock and tailings span the range from potentially acidic drainage generating to non-potentially acidic drainage generating due to the low contents of pyrite and other sulfide minerals as potential sources of acid, and the presence of silicate minerals such as feldspars and trace amounts of carbonate minerals to neutralize acid (Seal, 2012).

4.3. Visualization in GIS

This was the reason for further data visualization in GIS. The 3D model of the planned quarry, its location and the material with sulphur content over 1 % is visualized in Fig. 5. In Fig. 6,

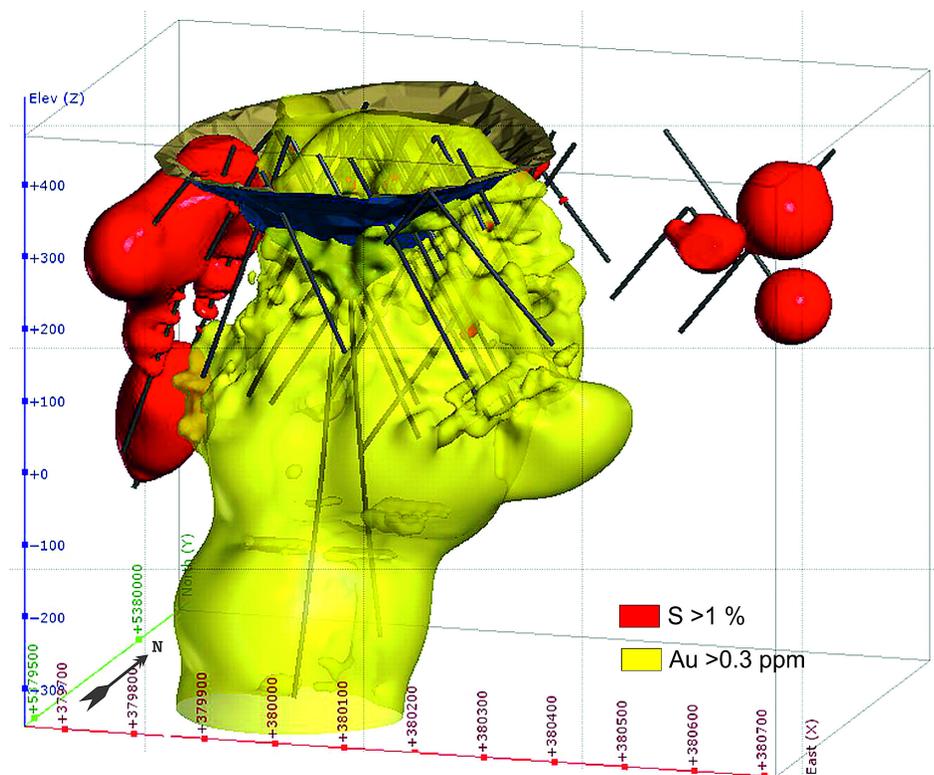


Fig. 5. 3D model (in coordinate system UTM-34U/WGS84 ellipsoid) of the planned quarry and its surrounding, showing the parts with sulphur content over 1% and Au content over 0.3 mg.kg⁻¹. Note: shades of yellow colour represented shading to highlight the 3D effect.

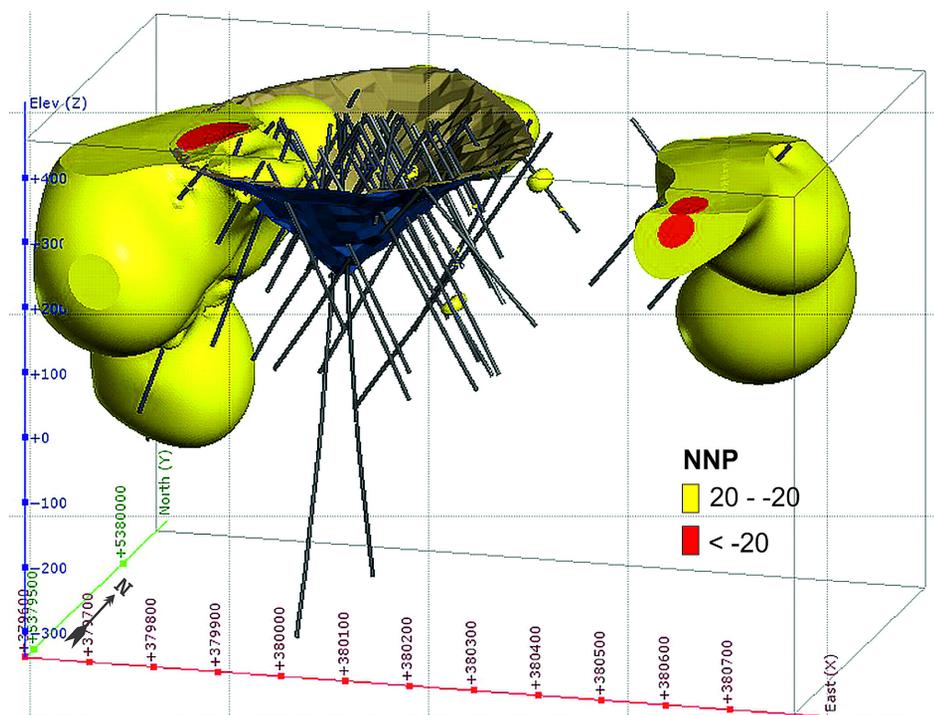


Fig. 6. 3D model (in coordinate system UTM-34U/WGS84 ellipsoid) of the planned quarry and its surrounding, showing the parts with NPR in the area of uncertainty (yellow colour, in the range from -20 to 20) and parts in the area of potential acidity formation (red colour, below -20). Note: shades of yellow colour represented shading to highlight the 3D effect.

also rocks with NNP in the field of uncertainty and the areas of potential acidity formation are shown. The areas where the content of total sulphur is lower than 1% and NNP is higher than 20 kg CaCO₃/1000 kg of material are not included. As can be easily seen in both pictures, there is an area in the eastern part of the planed quarry with elevated content of sulphur hosted by pyrite. This zone significantly corresponds with the area with relatively low NNP (since calculated AP is a function of the total sulphur content). Identification of this zone can be very helpful to eliminate possible environmental risks of future mining. Potential mine operator can actively prevent the accumulation of risk material in one place and mix it with suitable rock material from the other parts of the deposit.

Besides NNP also NP:AP ratio can be used for characterization of neutralization potential and it is called NPR (Neutralizing Potential Ratio). NNP = 0 is equivalent to NPR = 1 (Ferguson & Morin, 1991).

According to published data, NPR values of 3 and higher indicate very low risk of acid water formation (Brodie et al., 1991). When the ratio is higher than 4, no additional tests are required. The values between 1 and 3 are in the field of uncertainty and additional kinetic tests are necessary. If the NPR value of sample is 1 or lower, the risk of potential acid is quite likely to be produced (Lapackko, 1992).

Based on calculated NPR values, 86.79% of the samples from the Biely vrch deposit represent no risk of acidity formation (77% of samples represent no risk and 9.79% are in the field of uncertainty). The NPR value is lower

than 1 in the rest 13.21 % samples (the same zone as mentioned above).

Price & Kwong (1997) have used the combination of the total sulphur content, pH reaction, and NPR for the potential acid mine waters formation. They do not expect any possibility of acid drainage formation, when the content of total sulphur is less than 0.3 % and pH reaction is over 5.5. In case of higher sulphur content and lower pH reaction authors have allocated 4 categories:

- (i) probable (NRP is lower than 1);
- (ii) possible (NRP is in between 1 and 2);
- (iii) low (NRP is in between 2 and 4);
- (iv) no (NRP is higher than 4).

The values of pH reaction of samples from the Biely vrch site were higher than 5.5, so from this point of view the potential waste from the deposit does not produce any acidity. Pierce et al. (2008) do not consider the option where pH reaction is higher than 5.5 and sulphur content is higher than 0.3 (68.97 % of our samples are within this field) and therefore this methodology is not suitable for the Biely vrch deposit.

The values of NP, NNP and NPR of samples from the Biely vrch locality are significantly higher compared to other porphyry deposits. This can be explained by the fact, that total sulphur content is higher compared to other porphyry deposits (especially compared to Cu porphyry deposits). For example at Aitik deposit in Sweden, average total content of sulphur is 2.64 % and NNP = 74.3 kg CaCO₃/t. The samples at other porphyry deposit Pebble Mine in Alaska contain even lower amount of sulphur (0.5 %), AP is in the range from 1.26 to 128.8 kg H₂SO₄/t and average NNP is 0.5 kg CaCO₃/t. In case of the deposits Cauquenes Teniente and Piquenes Andina in Chile the NNP values are in the range from -101.8 to -18.2 kg CaCO₃/t (Seal, 2012). At Huckleberry Mines deposit in Canada, the average content of total sulphur in samples from boreholes is 4.15 %, from which 2.98 % is sulfidic. The rest is sulphur hosted by anhydrite and gypsum. The AP value represents 93 kg H₂SO₄/t, NP 72 kg CaCO₃/t and NPR 0.77 (Perkins et al., 1995).

5. CONCLUSION

According to obtained results following conclusions can be stated:

- (i) the leachability of potentially toxic elements is very low (even under detection limit in case of several elements);
- (ii) the pH values and conductivity rise in dependence on the depth in correlation with amount of mineral phases containing alkali metals and alkaline earth metals (e.g., feldspar, amphibole, and calcite);
- (iii) the average value of acidification potential is 13.17 kg H₂SO₄/1000 kg, what is significantly higher compared to other porphyry deposits – especially if the average neutralisation potential values was determined at 42.65 kg of CaCO₃/1000 kg of material;
- (iv) the studied samples don't have potential for acid mine drainage formation, as long as the concentration of S does not exceed 1 %.

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