EMPOWERING UNDERGROUND LABORATORIES NETWORK USAGE

Activity Report of WP3.3 **12|2021**

Scheme of Polkowice-Sieroszowice mine (CUPRUM) devoted to natural background radiation (NBR) characterization

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Interreg Baltic Sea Region
EUROPEAN UNION
EUROPEAN REGIONAL DEVELOPMENT FUND

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1. General information

Name of Underground Laboratory:

Conceptual Lab development co-ordinated by KGHM Cuprum R&D centre Polkowice-Sieroszowice mine
(http://www.cuprum.wroc.pl)

Localization (country/city):
Poland/Polkowice-Sieroszowice

Coordinates to the facility:
51° 27’ 54.36” North
16° 6’ 7.2” East

The altitude of the facility:
about 150 m

Name of the responsible scientist/measurer:
University of Silesia, Poland:
Jan Kisiel
Kinga Polaczek-Grelik
Agata Walencik-Łata
Katarzyna Szkliniarz

National Centre for Nuclear Research, Poland:
Karol Jędrzejczak
Jacek Szabelski

Place where the data is stored (e.g., file in a drawer X, internal data cloud, etc.):
Pendrive, external memory,

2. Measurements of the NBR in Underground Laboratory

Description of the sites where the in-situ measurements were performed:

Tab. 1 Description of the site where the in-situ measurements were performed.

Hall ID	**Dimension of the cavern** [height x length x width] (m)	**Air volume exchange rate / Ventilation** [m^3/s]	**Depth below surface** [m w.e.]	**Environmental condition** (average temperature /average humidity)
excavation No 3 near SW-1 shaft	3.62 x 85 x 4.52	1162	2941.8	18.8 - 25.6 °C / 52%

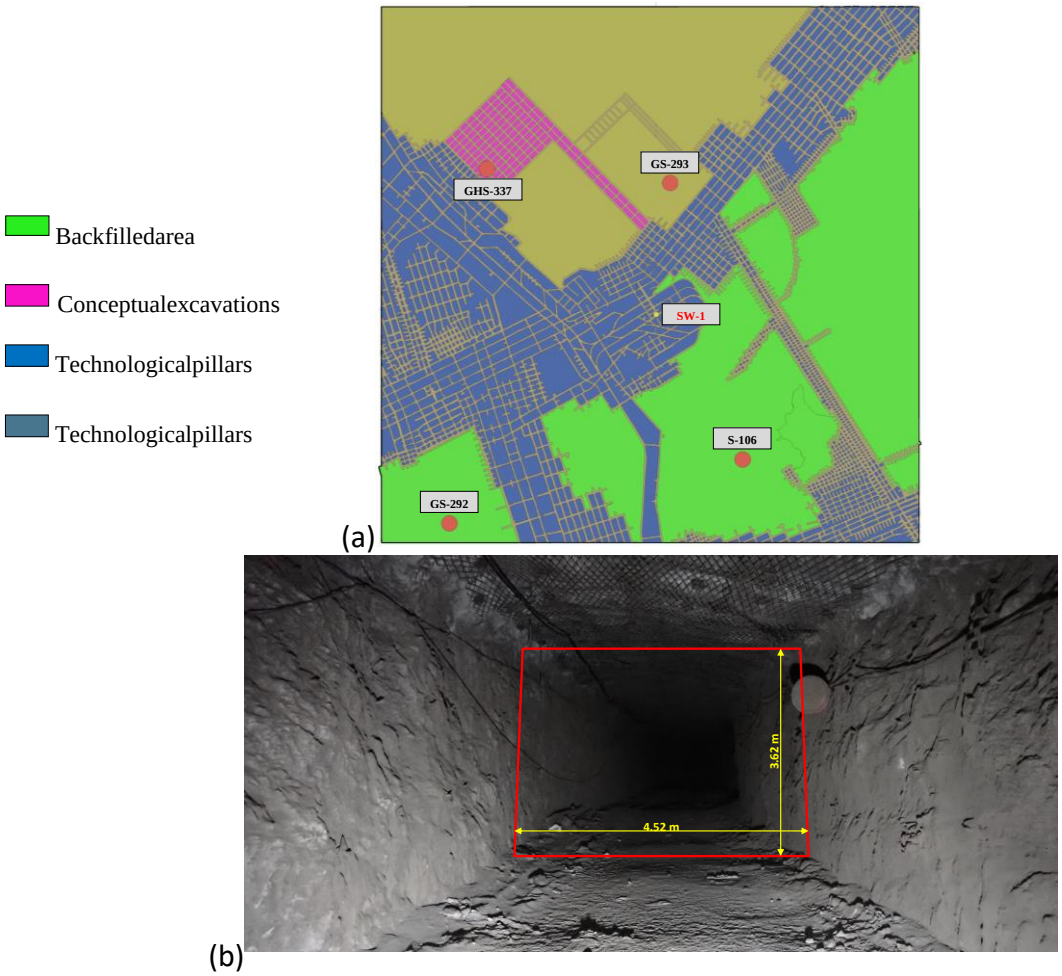

Fig. 1 (a) the view of the surroundings of measurement point location (by Krzysztof Fuławka, KGHM) in dolomite formation, about 1000 m below the ground in Polkowice-Sieroszowice copper mine, (b) The view of 85-m long excavation No 3 with cross sectional dimensions.

a. In-situ gamma-ray measurement

- Information about measurement

The in-situ measurement of the natural background radiation (NBR) was performed by using portable gamma-ray spectroscopy and HPGe (high-purity germanium) detector. Multichannel analyzer and special software packages were applied for spectra registration and analysis. Energy calibration (covering the range of 14 – 2506 keV) was performed using a set of sealed radioactive sources (1 cm in diameter and about 40 kBq activity): ^{133}Ba, ^{137}Cs, ^{54}Mn, ^{57}Co, ^{109}Cd, ^{22}Na, and ^{60}Co. Efficiency calibration was performed using the geometry of room/box with internal surface contamination, modeled in Geometry Composer software applying ISOCSTM software and monoenergetic photons covering the energy range of 10 – 3300 keV (an adequate measuring range). The monoenergetic photon flux density was estimated from the photopeak areas employing detection efficiency curve ε(E), Ge crystal surface area, and lifetime of spectrum acquisition. An effective dose was calculated using photon flux-to-dose conversion coefficients for isotropic irradiation with monoenergetic photons, interpolated based on data provided by the International Commission on Radiological Protection (ICRP) in report 116 using a third-degree Lagrange formula. Identification of in-situ registered radioisotopes was based on the photopeaks' energies.

Measurements performed in free space

Efficiency modeling

The horizontal orientation of spectrometer

Geometry for efficiency calibration was based on room/box with internal surface contamination (software template) with dimensions of investigated localization. Radioactivity was assumed to be distributed equally between 5 out of 6 walls.

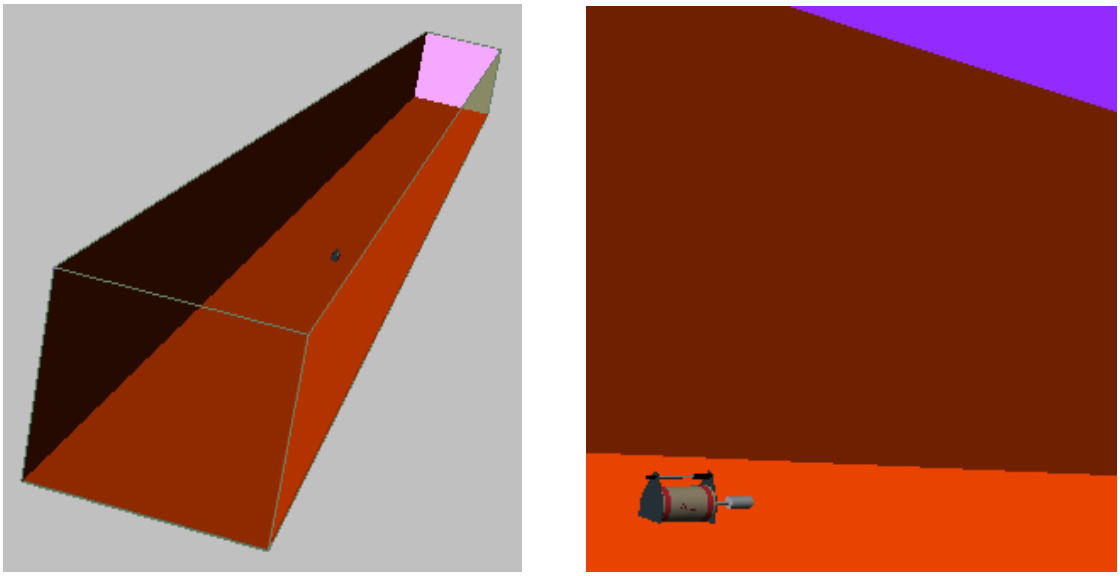

Fig. 2 Geometry modelled for efficiency calibration in ISOCS software.

Description of detector settings during measurement (where the detector was placed (near wall, floor….):

detector position (horizontal, vertical): **horizontal position, on the floor**
distance from the walls: **about 2 m**
measurement of the gamma-ray spectrum from the wall, floor, concrete, other: **2m in front of the nearest wall (the center of the germanium crystal was 13 cm above the floor)**
use of a collimator during the measurement (if yes, what): **no**

- Results

Tab. 2 Results of in-situ gamma-ray measurements.

Hall ID (and place)	**Measurement method**	**Equipment type**	**Detection relative efficiency** [%]	**Energy range** [keV]	**Results** (integrated counts per second) [cps]
excavation No 3 near SW-1 shaft	Gamma spectroscopy	-GR4020 portable spectrometer, -HPGe coaxial detector, -InSpector™ 2000 multichannel - analyser (for data collecting), -Genie™ 2000 v.3.2.1 software package (for spectra analysing)	40	7-3150	216.12 ± 0.07*

*data are presented in K.Szkliniarz et al., Characteristics of Natural Background Radiation in the Polkowice - Sieroszowice Mine, Poland Energies (2021) 14, 4261.

Schematic plan of the Hall with marked site where the measurements were performed.

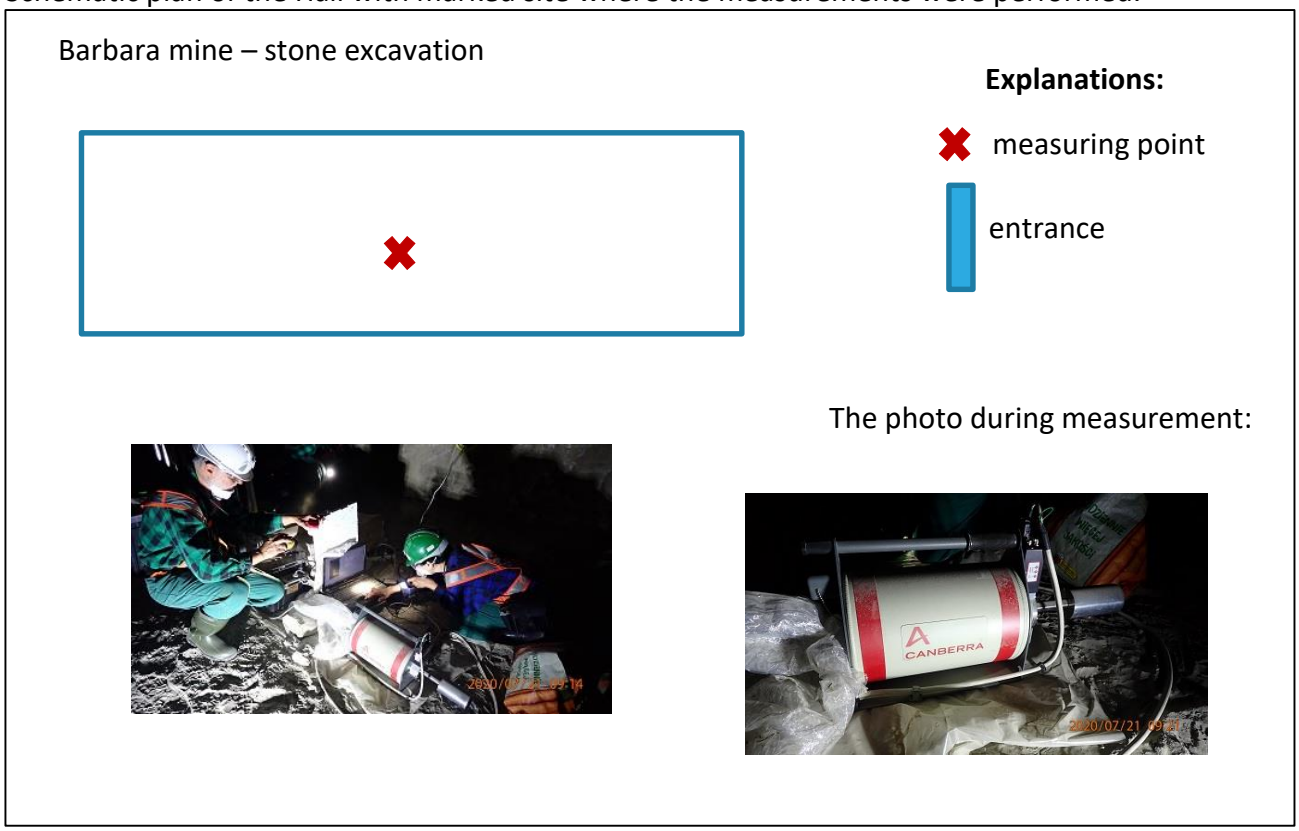

Fig. 3 Schematic plan of excavation No 3 near SW-1 shaft with marked site where the in-situ gamma-ray measurement was performed.

Gamma-ray spectrum:

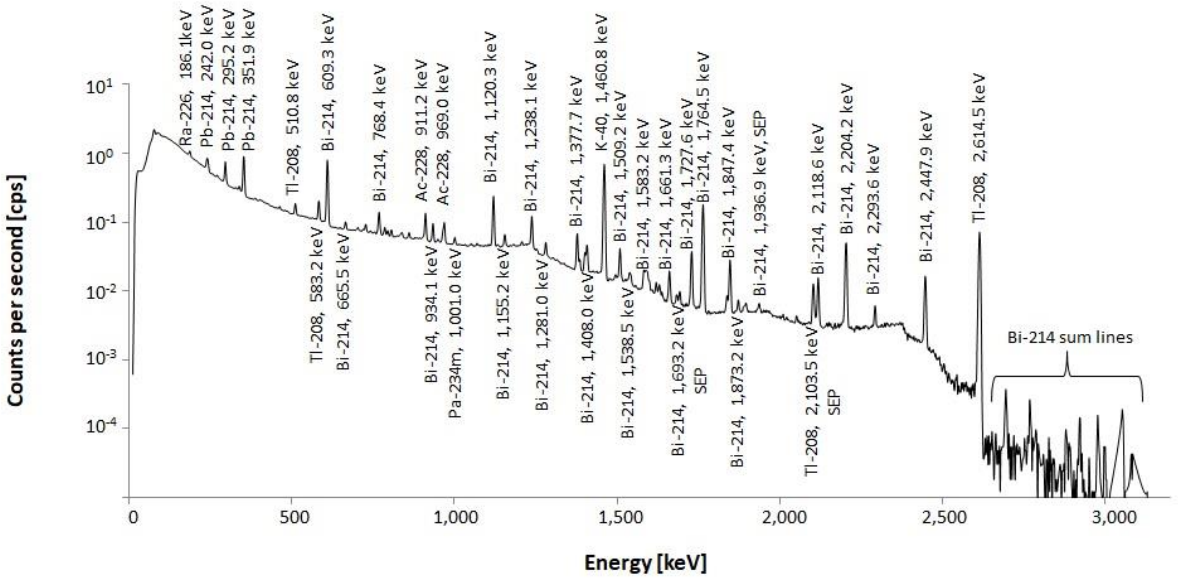

Fig. 4 Gamma-ray spectrum from excavation No 3 near SW-1 shaft.

Other relevant information:

Tab. 3 Results of gamma flux, gamma-ray dose and contribution of the radioisotopes for the investigated localizations.

Hall ID (and place)	**Gamma flux** [$cm^{-2}s^{-1}$]	**Gamma-ray dose** [µSv/h]	**Radioisotopes that have the main contributions ineffective dose**		
			Decay chain	**Isotope**	**Concentration** [%]
excavation No 3 near SW-1 shaft	0.64 ± 0.20*	0.008 ± 0.001*	Uranium - Thorium Uranium Thorium	^{214}Bi ^{40}K ^{208}Tl ^{214}Pb ^{228}Ac	49.2 29.9 12.0 4.1 4.0

*data are presented in K.Szkliniarz et al., Characteristics of Natural Background Radiation in the Polkowice - Sieroszowice Mine, Poland Energies (2021) 14, 4261.

Qualitative analysis of gamma-ray spectra registered in underground laboratory.

Qualitative analysis of gamma-ray spectra registered in the underground laboratory (LT - live time, measuring time; Area – net area of the photopeak on the spectrum gamma-ray)
(SEP – single escape peak, DEP – double escape peak)

Tab. 4 Qualitative analysis of gamma-ray spectra registered in Polkowice-Sieroszowice mine – excavation No 3 near SW-1 shaft.

True Energy [keV]	**Isotope**	**CPS = Area/LT**	**Δ CPS [%]**
63.29	^{234}Th	0,1005	9.7
77.12	Bi - K_{a1}	0.935	1.3
87.343	Bi - K_{b1}	0.3855	2.1
92.59	^{234}Th	0.319	2.6
186.1	^{226}Ra	0.3769	2.2
241.98	^{214}Pb	0.9756	0.8
270.24	^{228}Ac	0.0639	8.6
295.21	^{214}Pb	0.987	0.7
327.6	^{228}Ac	0.0274	9.4
338.32	^{228}Ac	0.1116	2.8
351.92	^{214}Pb	1.7785	0.4
463.01	^{228}Ac	0.0356	9.6
478.3	^{228}Ac	0.0075	29
510.77	^{208}Tl	0.1478	3.5

583.19	^{208}Tl	0.272	1.1
609.31	^{214}Bi	1.8521	0.3
665.45	^{214}Bi	0.0602	4.7
703.11	^{214}Bi	0.0208	13.6
719.86	^{214}Bi	0.0133	10
727.2	^{214}Bi	0.0569	2.9
768.36	^{214}Bi	0.2165	1.4
785.91	^{214}Pb	0.0531	2.7
794.95	^{228}Ac	0.0356	3.8
806.17	^{214}Bi	0.0459	3.1
840.377	^{228}Ac	0.0282	8.7
860.56	^{208}Tl	0.0319	7.7
911.21	^{228}Ac	0.1963	1.3
934.06	^{214}Bi	0.1125	2.2
949.83	^{40}K (SEP)	0.0135	16.4
968.97	^{228}Ac	0.1722	1.6
1001.03	^{234m}Pa	0.0352	6.5
1051.96	^{214}Bi	0.0052	30.3
1069.96	^{214}Bi	0.006	32.8
1120.29	^{214}Bi	0.5198	0.5
1155.19	^{214}Bi	0.0578	4
1207.68	^{214}Bi	0.0171	12.3
1238.11	^{214}Bi	0.2042	1.3
1280.96	^{214}Bi	0.0484	4.2
1377.67	^{214}Bi	0.132	0.9
1385.31	^{214}Bi	0.026	3.1
1401.5	^{214}Bi	0.0458	2
1407.98	^{214}Bi	0.0778	1.4
1460.83	^{40}K	1.8681	0.2
1495.91	^{228}Ac	0.0084	7.7
1509.23	^{214}Bi	0.0734	1.3
1538.5	^{214}Bi	0.0291	3.5
1583.22	^{214}Bi	0.0357	2.7
1592.53	^{208}Tl (DEP)	0.0369	2.6
1599.31	^{214}Bi	0.0115	7

1620.5	^{214}Bi	0.0118	4.9
1630.63	^{228}Ac	0.012	4.8
1638.281	^{228}Ac	0.0046	10.6
1661.28	^{214}Bi	0.0364	2.8
1683.99	^{214}Bi	0.0072	6.6
1693.21	^{214}Bi (SEP)	0.0101	5
1729.6	^{214}Bi	0.0899	1.3
1764.5	^{214}Bi	0.4892	0.4
1838.36	^{214}Bi	0.0115	3.9
1847.42	^{214}Bi	0.0646	1.2
1873.16	^{214}Bi	0.007	11.9
1896.3	^{214}Bi	0.0028	26.9
1936.86	^{214}Bi (SEP)	0.0049	15.4
2052.94	^{214}Bi	0.0014	37.4
2103.53	^{208}Tl (SEP)	0.0293	1.8
2118.55	^{214}Bi	0.0345	1.6
2204.21	^{214}Bi	0.1449	0.8
2293.36	^{214}Bi	0.0077	8.2
2447.86	^{214}Bi	0.0446	1.6
2614.53	^{208}Tl	0.2131	0.5
2694.63	^{214}Bi sum	0.0008	12.2
2775.35	^{214}Bi sum	0.0003	22.7
2884.79	^{214}Bi sum	0.0003	18.4
2919.69	^{214}Bi sum	0.0002	21.7
2984.62	^{214}Bi sum	0.0004	14.8
3002.61	^{214}Bi sum	0.0002	23.7
3057.17	^{214}Bi sum	0.0005	11.8

Apparent radioactivity and effective dose rate calculated on the base of the gamma-ray spectrum.

Tab. 5 Effective dose rate and apparent radioactivity results calculated based on the gamma-ray spectrum for excavation No 3 near SW-1 shaft.*

Decay chain	Radionuclide	Effective dose rate [pSv/s]	% contribution	Apparent activity in measuring point [Bq/cm^2]
Uranium	^{234}Th	0.0020 ± 0.0002	0.1	0.095 ± 0.087
	^{234m}Pa	0.007 ± 0.001	0.3	0.255 ± 0.017
	^{226}Ra	0.0030 ± 0.0005	0.2	0.177 ± 0.004
	^{214}Bi	1.109 ± 0.160	49.2	0.239 ± 0.083
	^{214}Pb	0.093 ± 0.013	4.1	0.205 ± 0.096
Thorium	^{228}Ac	0.091 ± 0.013	4.0	0.063 ± 0.041
	^{208}Tl	0.271 ± 0.039	12.0	0.019 ± 0.007
none	^{40}K	29.910 ± 0.675	29.9	1.339 ± 0.003
	X rays	0.005 ± 0.001	0.2	-

*data are presented in K.Szkliniarz et al., Characteristics of Natural Background Radiation in the Polkowice - Sieroszowice Mine, Poland Energies (2021) 14, 4261.

b. *Measurements of the radon concentration in air*

- Information about measurement

Measurements of the radon concentration in the air were performed using the RAD7 radon detector. The measurements were made in cycles.

Description of detector settings during measurement (where the detector was placed (near the wall, floor…,):
Place of the measurement: **detector was placed next to the gamma spectrometer**
Ventilation (on/off): **ventilation was on**
Other relevant information (use a drying unit, humidity, temperature, pressure, other):
measurement was performed with the use of a drying unit, humidity 8.5 %, temperature *29.7°C*

- Results

Tab. 6 The results of radon concentration in the air at the Polkowice-Sieroszowice mine – excavation No 3 near SW-1 shaft.

Hall ID	**Measurement method**	**Equipment type**	**Collection period**	**Average result** [Bq/m^3]
excavation No 3 near SW-1 shaft	Alpha spectroscopy	RAD7 electronic radon detector (Durridge)	48 h (2-day protocol with 1-hour measurement cycle)	6.6 (median: 4.8)*

*data are presented in K.Szkliniarz et al., Characteristics of Natural Background Radiation in the Polkowice-Sieroszowice Mine, Poland Energies (2021) 14, 4261.

Schematic plan of the Hall with marked site where the measurements were performed.

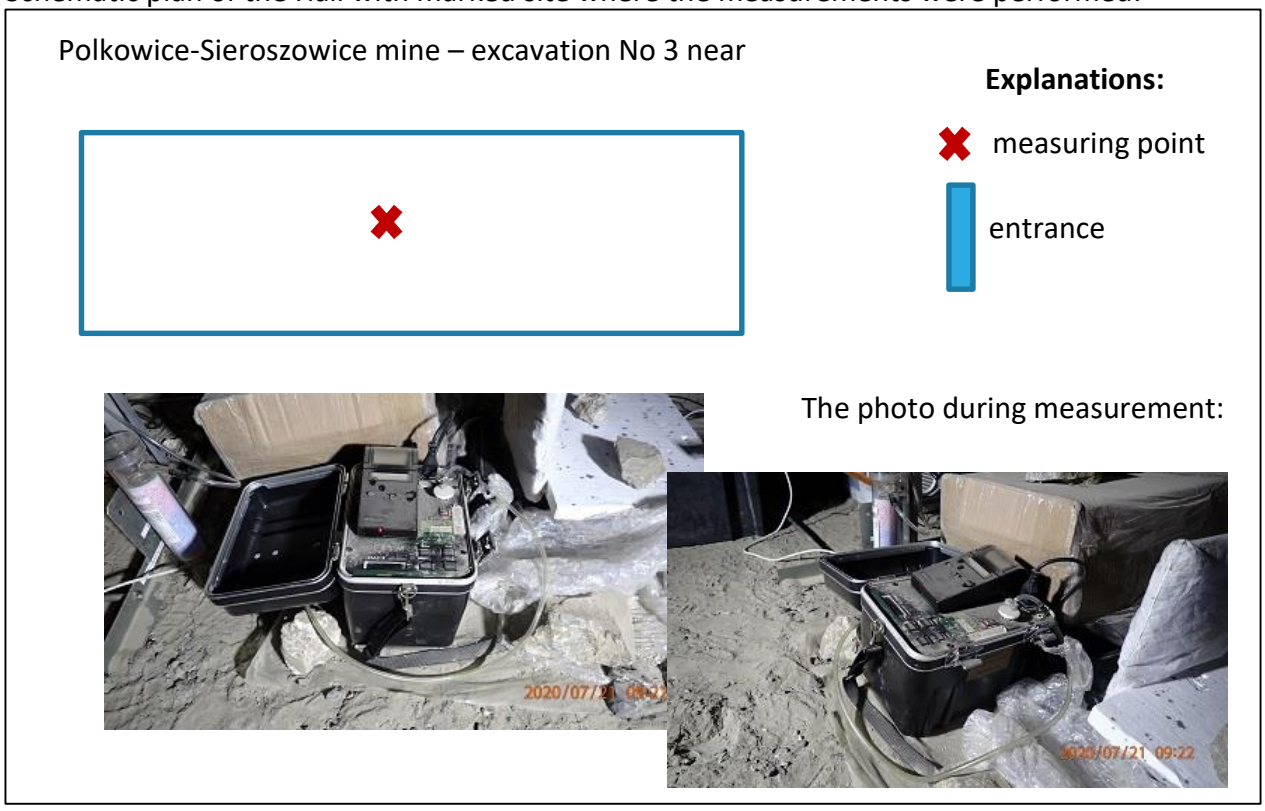

Fig. 5 Schematic plan of the excavation No 3 near SW-1 shaft with marked sites where the measurements of the radon concentration in air were performed.

The plot of radon activity concentration in excavation.

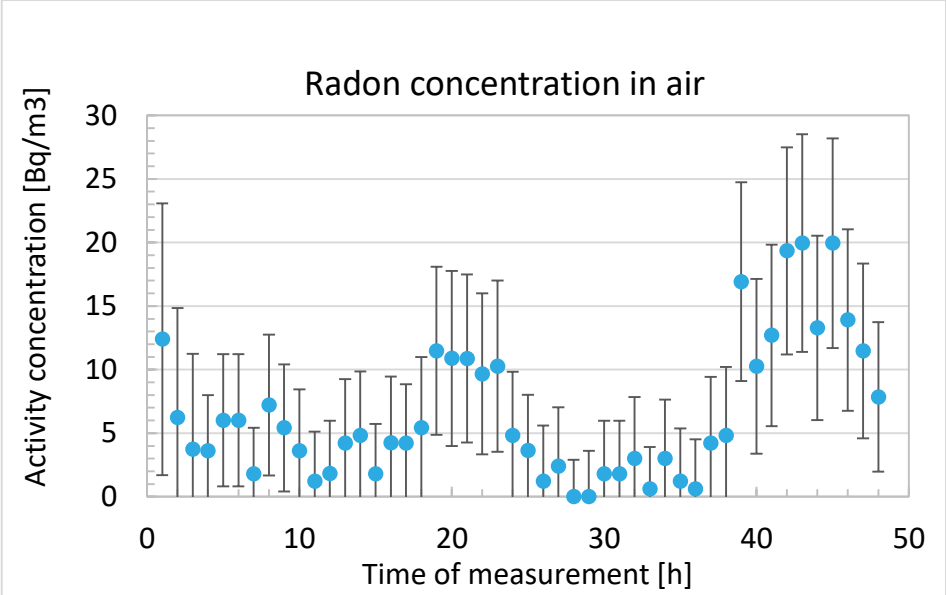

Fig. 6 Plot of radon concentration in the air in Polkowice-Sieroszowice mine – excavation No 3 near SW-1 shaft.

c. Measurements *of the neutron flux*

- Information about measurement

The thermal neutron flux was measured with eight proportional gas counters. The data acquisition system (DAQ) was designed and made in National Center for Nuclear Research in Poland. DAQ is built in the form of a cassette with eight measurement cards. Each card contains four independent measurement channels; together, it gives 32 channels. Each measurement channel is sampled with a frequency of 10 MHZ by an ADC with a dynamic of 10 bits. To determination of the neutron flux, the Monte Carlo simulation was used. The simulations were carried out using the Geant4 package version 10.04 using the physical package QGSP_BERT_HP and NeutronHPThermalScattering, which is essential for low-energy neutron interactions with nucleons bound in nuclei.

Standard method:

a) Type of counters (helium/boron) and name of the manufacturer, counter's dimensions: **two kinds of helium detectors: 2 inches in diameter, 50 cm long tubes with 2 atm of ^{3}He, 0.5 atm of Argon, some CO gas, and 25 - micrometer wires made by Centronic in 2008, and old thinner (1 inch), 50 cm long tubes with 4 atm of ^{3}He and Krypton stopping gas produced**

by ZDAJ in 60ties.
b) Setup description: number of counters, their distances in a tray, etc.:
8 helium counters, A flat tray of helium counters was positioned vertically in a rack. The tray was divided into two parts: first, there were four Centronic counters (Centronic 50He3 / 190 / 50MS), a 30 cm empty space, and again four ZDAJ counters (ZDAJ NEM425A50). There were 5 cm gaps between the individual counters to limit a shadowing effect.
c) Place of measurement: chamber name, distance from walls, large objects nearby, and what they are made of (water, polyethylene, graphite, etc.): **detection setup for the neutron measurements was placed in the center of excavation No 3 near SW-1 shaft, a distance 2 m from walls**
d) Humidity: normal / low / high

- Results

Tab. 7 Results of the neutron flux measurements.

Hall ID	Collection period	Average neutron counting rate	Dispersion of neutron counting rate	Calculated neutron flux witch error
excavation No 3 near SW-1 shaft	20–23 July 2020	2.8±0.2 counts/h for Centronic; 1.9±0.2 counts/h for ZDAJ counters		$1.9\pm0.2\times10^{-6}$ [$cm^{-2}s^{-1}$] for Centronic counters, $2.2\pm0.4\times10^{-6}$ [$cm^{-2}s^{-1}$] for ZDAJ counters Average: $2.0\pm0.2\times10^{-6}$ [$cm^{-2}s^{-1}$]*

*data are presented in K.Szkliniarz et al., Characteristics of Natural Background Radiation in the Polkowice-Sieroszowice Mine, Poland Energies (2021) 14, 4261.

Schematic plan of detector location in the chamber.

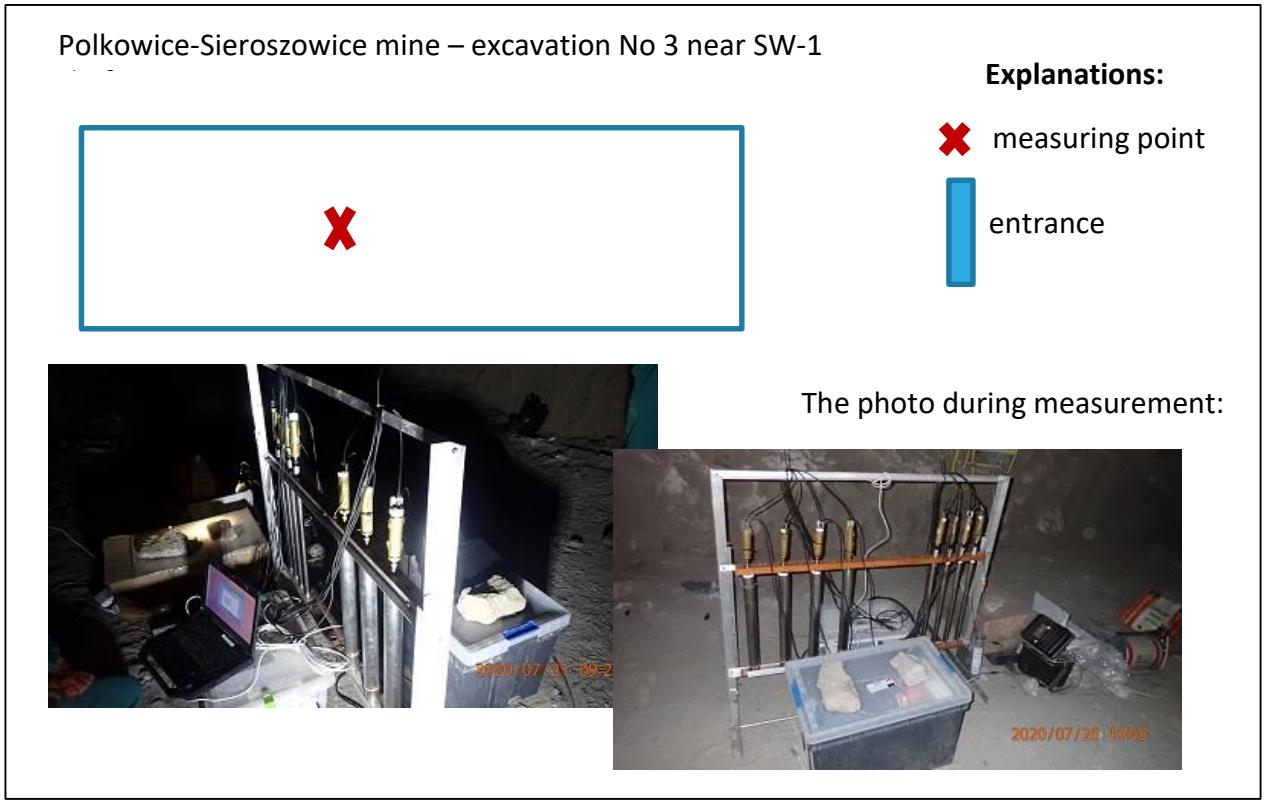

Fig. 7 Schematic plan of neutron detector location in the excavation No 3 near SW-1 shaft.

Distribution of amplitude of signals from ^{3}He counter:

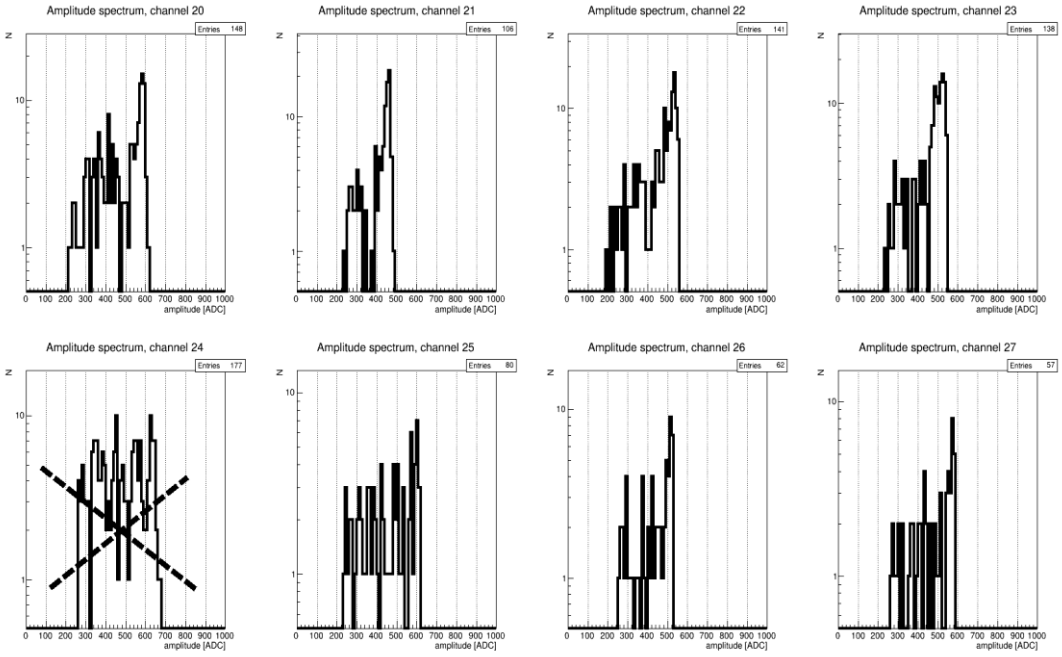

Fig. 8 Amplitude spectra for neutron signals in individual counters. Top row: Centronic counters, bottom row: ZDAJ counters. The ZDAJ counter connected to the 24 DAQ channel was excluded from the analysis due to high noise.

3. Laboratory analyses of the water samples

There is no water in the Polkowice-Sieroszowice mine.

4. Laboratory analyses of the rock samples

Measurements of the concentration of uranium, radium, and potassium radioisotopes in the rock samples (***Fig. 9***) were performed in an external laboratory - "Low-level Activity Research Laboratory", Institute of Physics, the University of Silesia in Katowice, Poland.

Description of the sites where rock samples were taken:

Tab. 8 Description of the sites where rock samples were collected.

Hall ID	**Depth below surface** [m w.e.]	**Sites** (wall, floor, brick, concrete, other)	**Method of the sampling**	**Name of the sample**
excavation No 3 near SW-1 shaft	2941.8	Centre of the corridor	newly blasted excavation	rock sample 1
		Behind the bend of corridor 1		rock sample 2
		The excavation hall		rock sample 3
		The end of the corridor		rock sample 4
		Behind the bend of the corridor, near the floor		rock sample 5
		Behind the bend of the corridor, slightly above the floor		rock sample 6
		Behind the bend of corridor 2		rock sample 7

Fig. 9 Rock samples from Polkowice-Sieroszowice mine.

a. Radium and potassium concentration in rock samples

- Information about measurement

The concentration of radium and potassium isotopes in the rock samples was determined by gamma spectroscopy with the HPGe detector in a lead shield (Fig. *10*a). The activity of ^{40}K was calculated directly from a single 1460 keV line. The activity of ^{226}Ra was calculated as the weighted mean of the values obtained from the ^{214}Pb (295.2, 351.9 keV) and ^{214}Bi (609.3, 1120.3 keV) isotopes, while ^{228}Ra activity was calculated from the gamma lines 338.3 keV and 911.1 keV originating from ^{228}Ac decay. The total duration of a single measurement depended on the sample activity.

Description of the procedure performed before measurements and conditions during measurements (e.g., use of a Marinelli beaker; shielding of the detector; drying, crushing, grinding, mixing of rock; other relevant information): **Before the measurements, the rock sample was dried, crushed, ground, mixed and placed in a Marinelli container (Fig. 10b,c), which was then sealed and left for one month to achieve secular equilibrium in the thorium and uranium series. The grains diameter after crushing the rock sample was less than 1 mm. Measurements were made in a shielded cover made of lead and copper (Fig. 10a).**

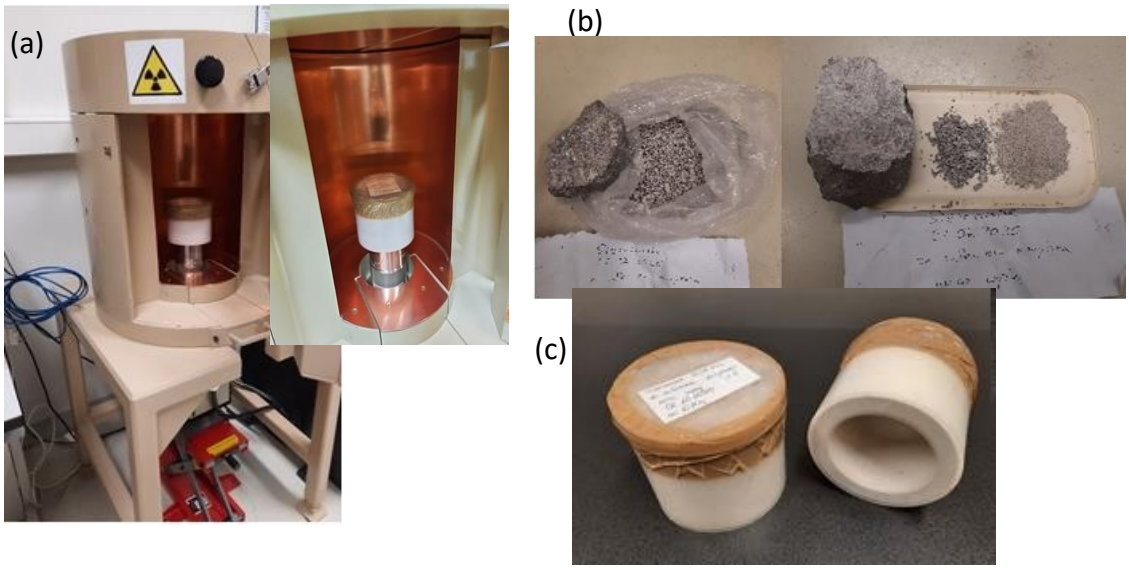

Fig. 10 (a) rock sample placed in the Marinelli container during measurement with the HPGe detector, (b) crushed rock samples, (c) rock samples in Marinelli containers.

Tab. 9 Results of radium and potassium concentration in rock samples.

Hall ID (name of sample)	Measu-rement method	Equipment type	Detection relative efficiency [%]	Collection period	Average results* [Bq/kg]		
					^{226}Ra	^{228}Ra	^{40}K
Rock sample 1	Gamma spectro-metry	HPGe detector	20	4.9 days	6.2±0.2	0.19±0.02	15.4±0.3
Rock sample 2				9.9 days	0.94±0.04	0.20±0.02	7.6±0.2
Rock sample 3				4.2 days	1.0 ±0.1	0.27±0.05	9.2±0.4
Rock sample 4				3.0 days	1.1 ±0.1	0.20±0.04	7.2±0.4
Rock sample 5				6.0 days	19.3±0.7	0.46±0.08	8.6±0.3
Rock sample 6				6.0 days	0.63±0.03	0.19±0.03	6.1±0.2
Rock sample 7				3.9 days	21.1±0.7	0.60±0.10	11.4±0.5

*data are presented in K.Szkliniarz et al., Characteristics of Natural Background Radiation in the Polkowice - Sieroszowice Mine, Poland Energies (2021) 14, 4261.

Gamma-ray spectra:

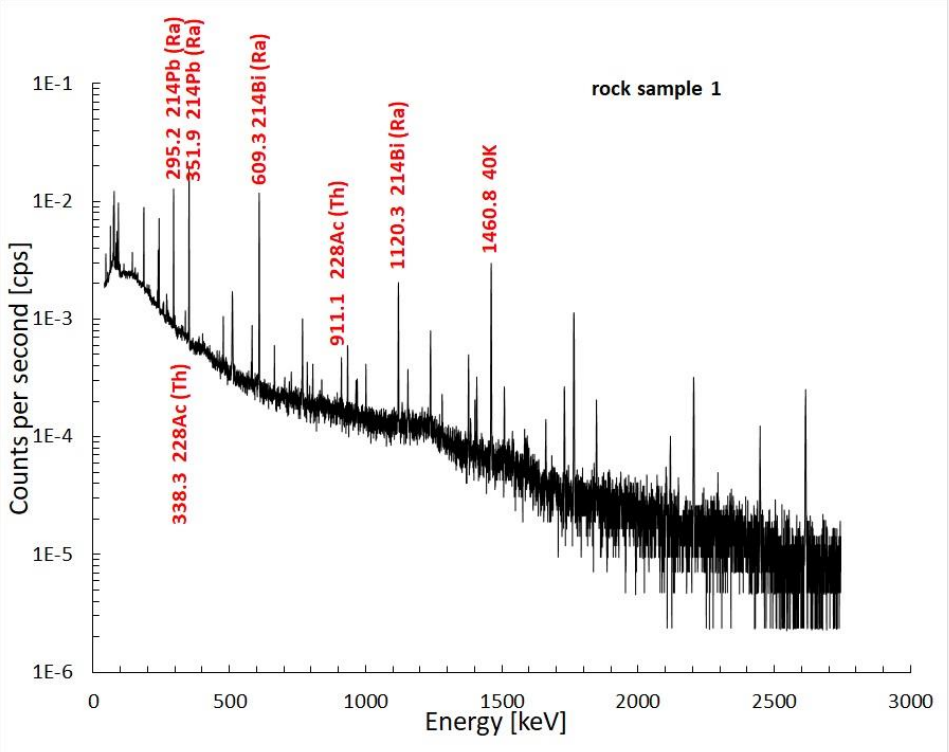

Fig. 11 Gamma-ray spectrum of a rock sample 1.

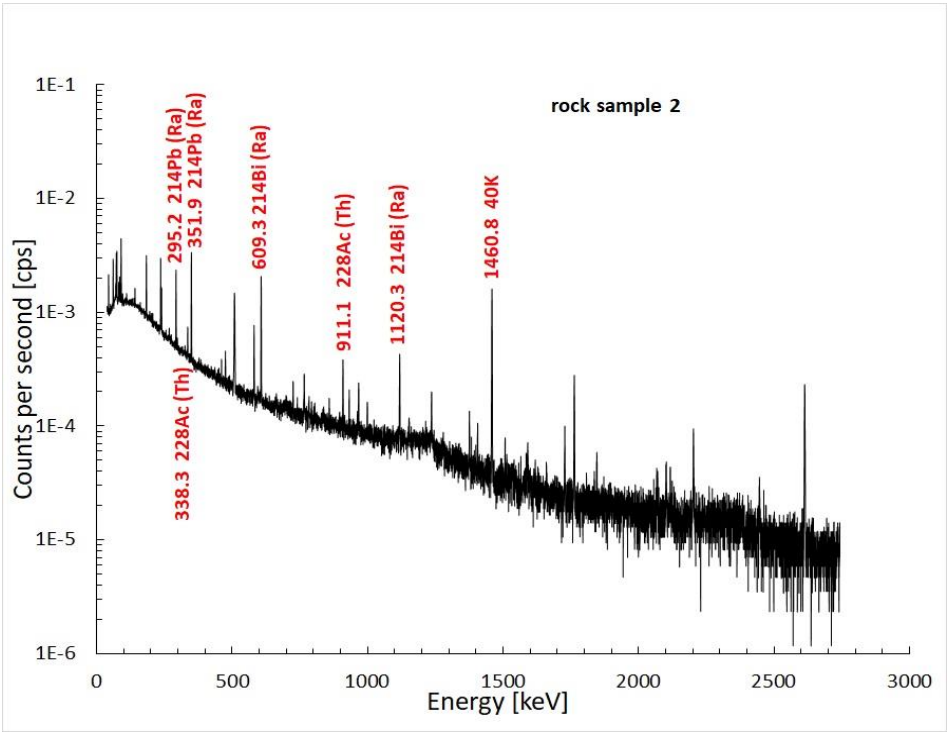

Fig. 12 Gamma-ray spectrum of a rock sample 2.

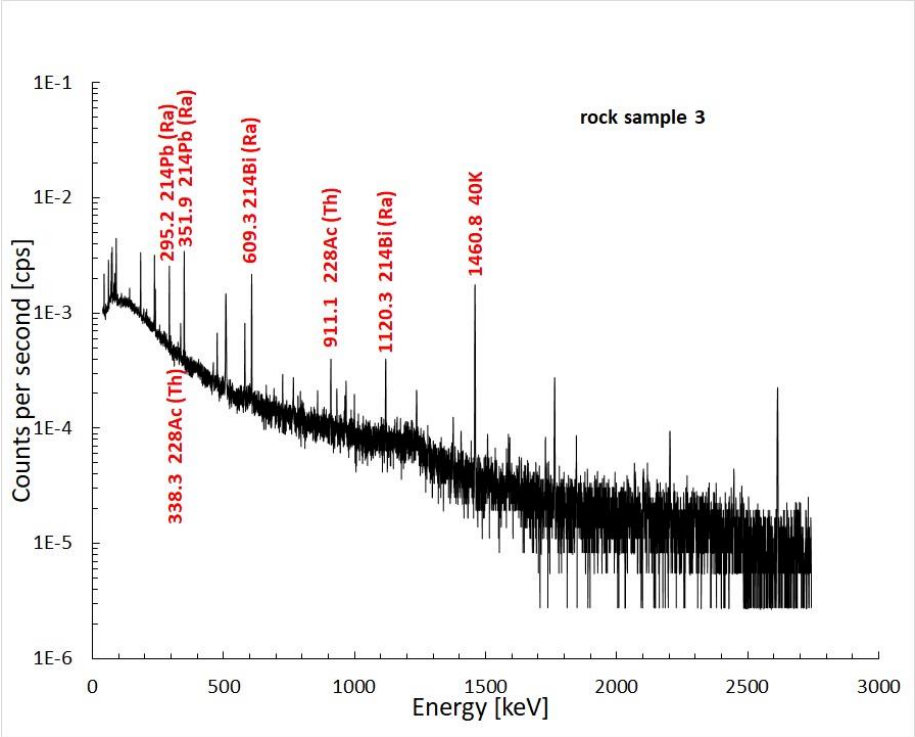

Fig. 13 Gamma-ray spectrum of a rock sample 3.

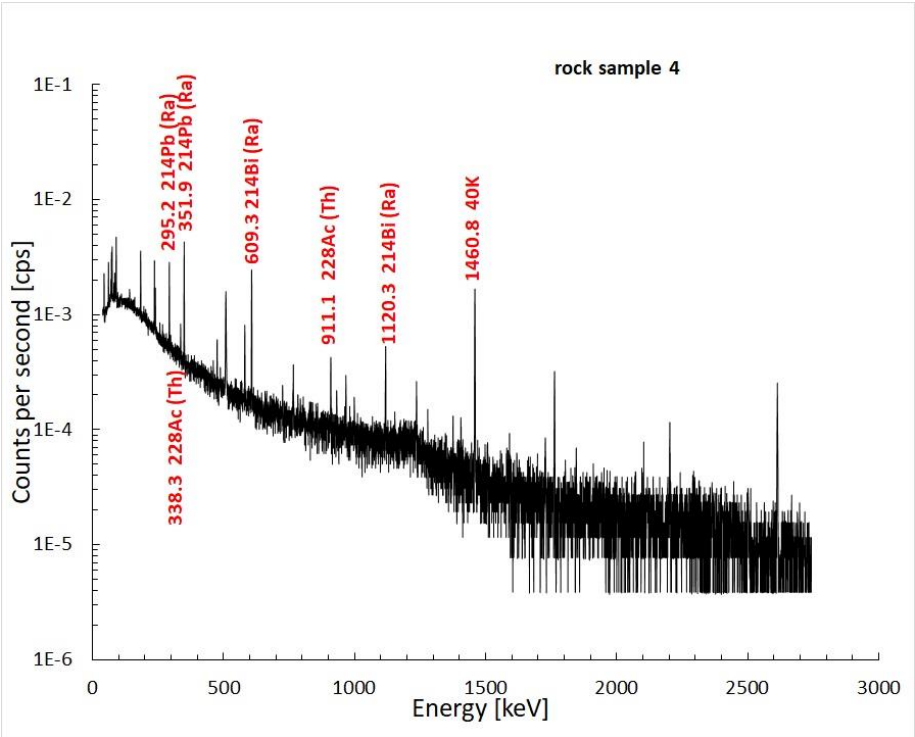

Fig. 14 Gamma-ray spectrum of a rock sample 4.

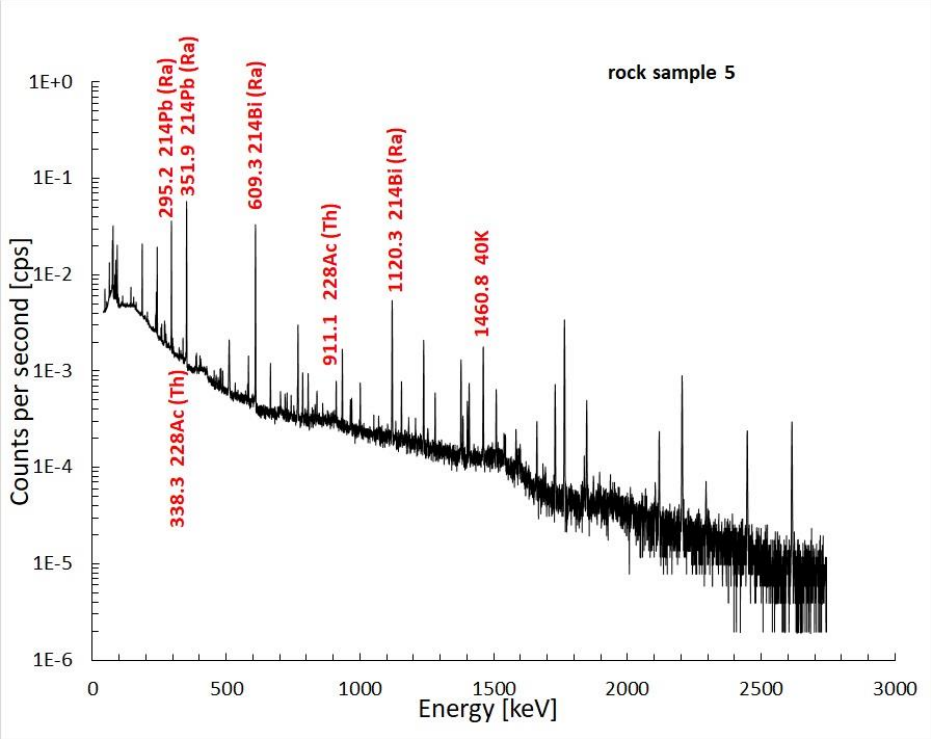

Fig. 15 Gamma-ray spectrum of a rock sample 5.

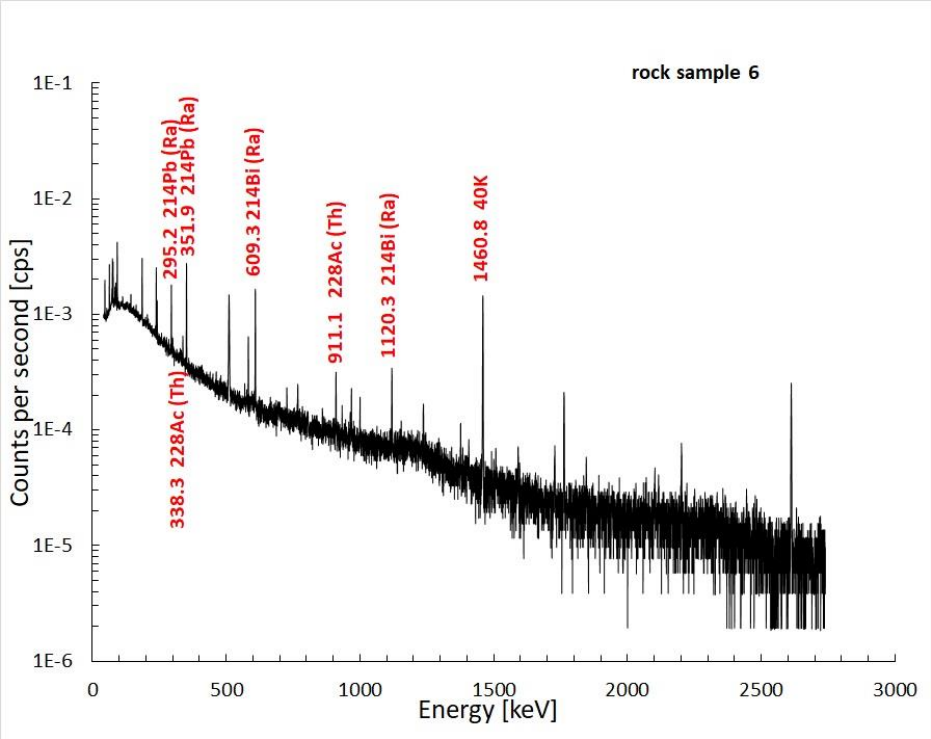

Fig. 16 Gamma-ray spectrum of a rock sample 6.

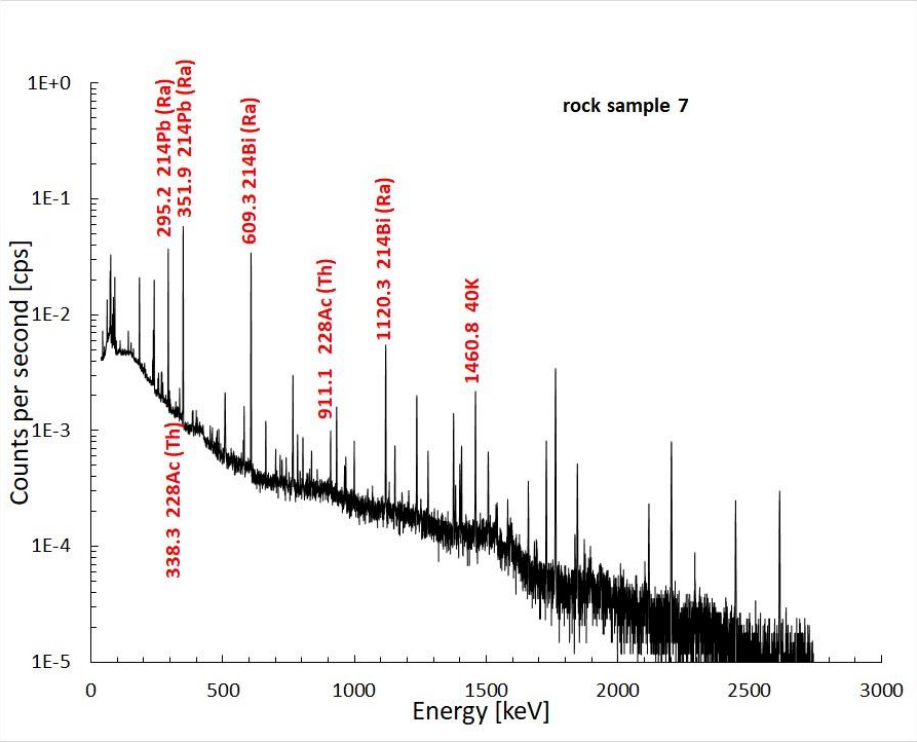

Fig. 17 Gamma-ray spectrum of a rock sample 7.

b. *Uranium concentration in rock samples*

- Description of the performed chemical procedure

The concentration of uranium ^{234}U and ^{238}U isotopes in the rock samples were determined by semiconductor alpha spectrometry and 7401VR (Canberra, USA) (Fig. *18*a) and Alpha Analyst™ (Mirion Technologies (Canberra), Inc., USA) spectrometers (Fig. *18*b). A radiochemical procedure was applied to prepare an alpha spectrometric source before measurement. For this purpose, wet mineralization of the rock sample was performed using hot acids: HF, HNO_3, HCl with H_3BO_3. Uranium was pre-concentrated with iron and co-precipitated at pH 9. The separation of U was performed using the anion exchange resin Dowex 1×8 (Cl- type, 200-400 mesh) based on a procedure worked out by Suomela (1993). The spectrometric source was prepared by co-precipitation of U with NdF_3 and deposition on polypropylene disks (0,1 µm) (Pall Corporation).

References:

J, Suomela, Method for determination of U-isotopes in water, Swedish Radiation Institute, Stockholm, SSI-rapport, 0282-4434, 93:14 (1993),

(a)  (b) 

Fig. 18 (a) The alpha spectrometer 7401VR (Canberra, USA), (b) The alpha spectrometer Alpha Analyst™ (Mirion Technologies (Canberra), Inc., USA).

- Information about measurement and results

Tab. 10 Results of uranium radioisotopes concentration in rock samples.

Hall ID (name of the sample)	Measu-rement method	Equipment type	Collection period	Limit of detection	Average results* [Bq/kg]		ratio $^{234}U/^{238}U$	U [ppm]
					^{234}U	^{238}U		
rock sample 1	Alpha spectro-scopy	spectrometer 7401VR (Canberra, USA)	2 days	0.4 mBq/l for both $^{234,238}U$ isotopes and 0,5 l initial sample volume	8.99±0.36	9.14±0.36	0.98±0.06	0.74±0.03
rock sample 2					1.27±0.12	1.24±0.12	1.03±0.14	0.10±0.01
rock sample 3					1.22±0.12	1.30±0.13	0.94±0.13	0.11±0.01
rock sample 4					1.54±0.12	1.55±0.12	0.99±0.11	0.13±0.01
rock sample 5					22.48±0.64	23.29±0.66	0.96±0.04	1.89±0.05
rock sample 6					0.84±0.08	0.82±0.08	1.02±0.14	0.07±0.01
rock sample 7					24.75±0.74	24.37±0.73	1.02±0.04	1.97±0.06

*data are presented in K.Szkliniarz et al., Characteristics of Natural Background Radiation in the Polkowice - Sieroszowice Mine, Poland Energies (2021) 14, 4261.

Alpha spectrum:

Polkowice-Sieroszowice mine – rock sample 1

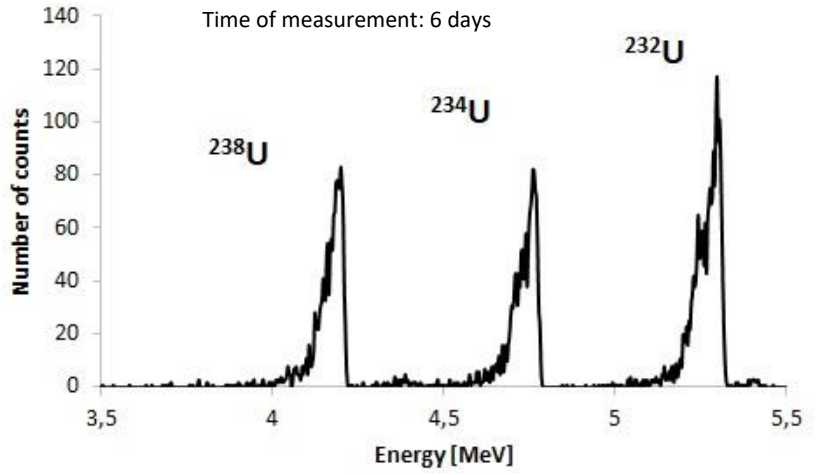

Fig. 19 The alpha spectrum of a rock sample 1 – Polkowice-Sieroszowice mine.

Polkowice-Sieroszowice mine – rock sample 2

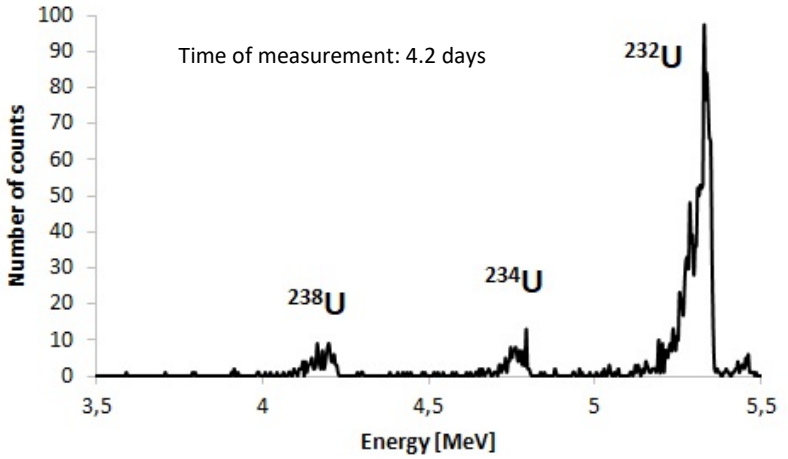

Fig. 20 The alpha spectrum of a rock sample 2 – Polkowice-Sieroszowice mine.

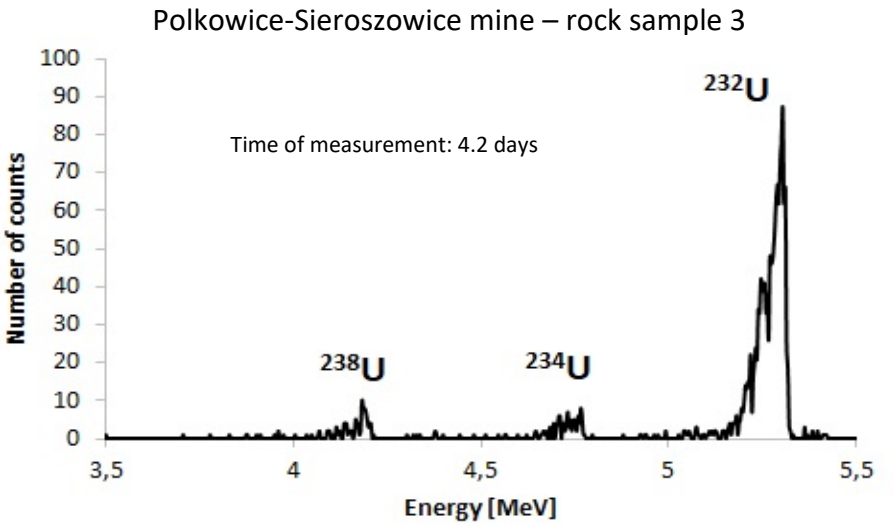

Fig. 21 The alpha spectrum of a rock sample 3 – Polkowice-Sieroszowice mine.

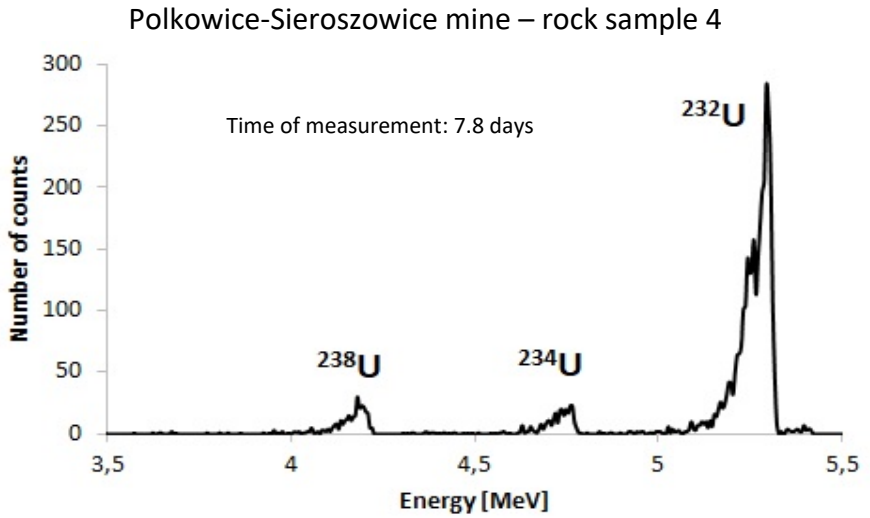

Fig. 22 The alpha spectrum of a rock sample 4 – Polkowice-Sieroszowice mine.

Polkowice-Sieroszowice mine – rock sample 5

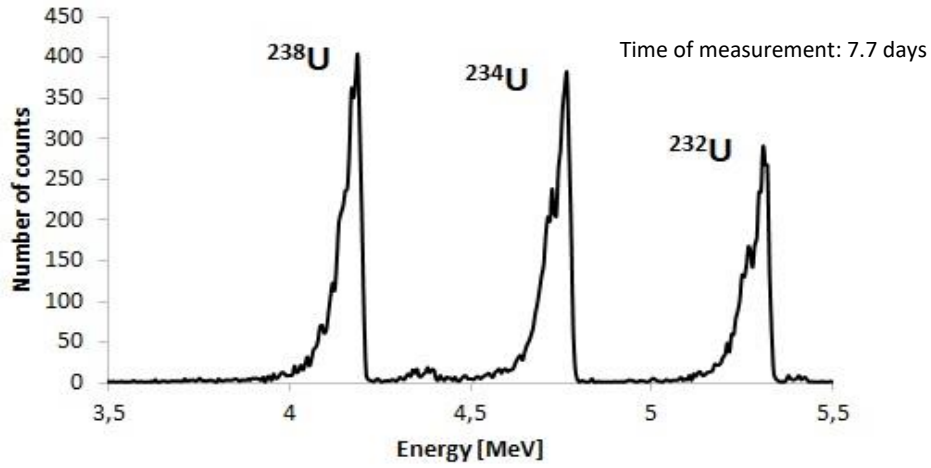

Fig. 23 The alpha spectrum of a rock sample 5 – Polkowice-Sieroszowice mine.

Polkowice-Sieroszowice mine – rock sample 6

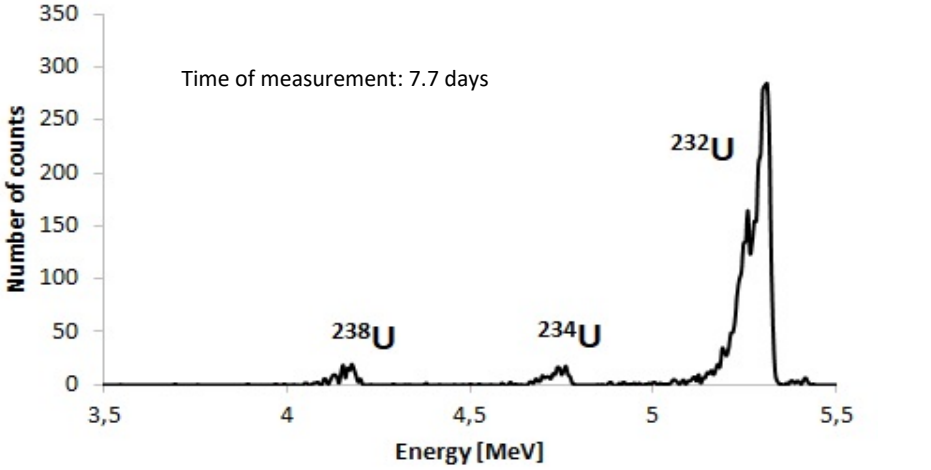

Fig. 24 The alpha spectrum of a rock sample 6 – Polkowice-Sieroszowice mine.

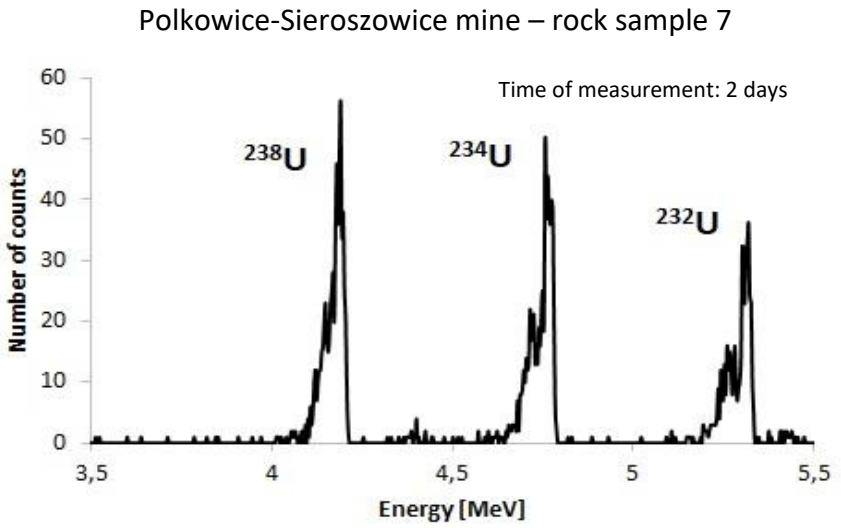

Fig. 25 The alpha spectrum of a rock sample 7 – Polkowice-Sieroszowice mine.

c. *Neutron activation of the rock sample*

- Information about measurement and results

Before the measurements, the rock samples were dried, crushed, and mixed. The grain diameter of the crushed rock sample was less than 1 mm. Then the sample was placed in a plastic bag and activated by neutron flux from a ^{252}Cf source (**Fig. *26***a,c) for a period of 45 days. Immediately after activation, the gamma-ray spectrum was measured by gamma spectroscopy with a lead-shielded HPGe detector (**Fig. *26***b). Measurements were carried out in several cycles, in short cycles to determine the short-lived isotopes produced during the activation of the sample by neutrons, and in long cycles to determine the long-lived isotopes.

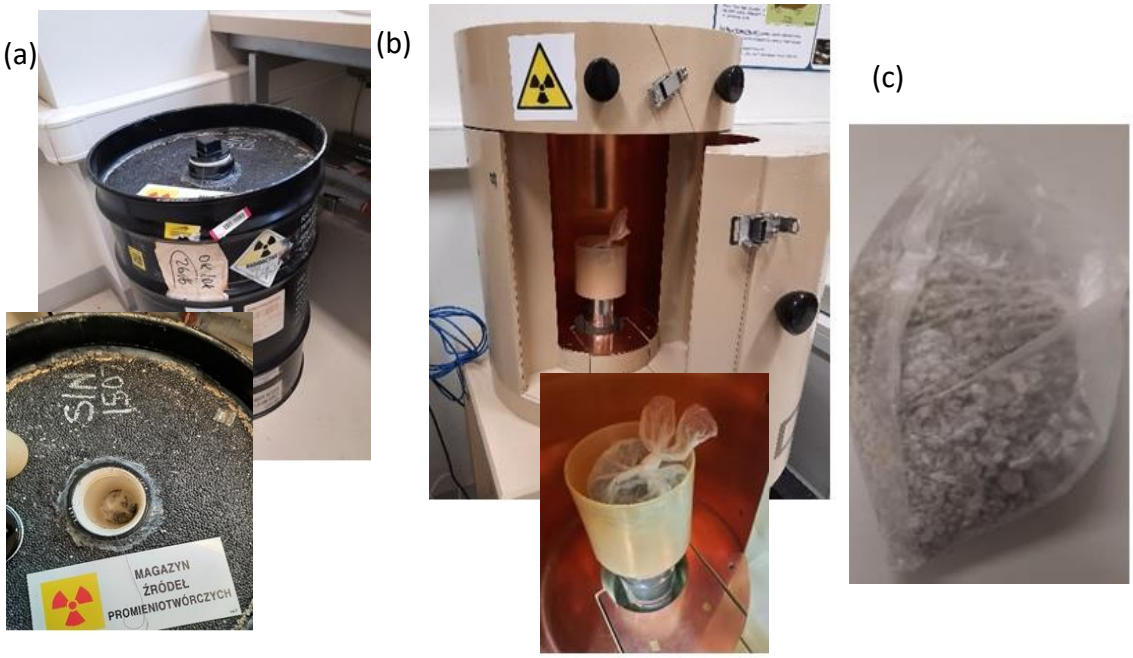

Fig. 26 (a) source (^{252}Cf) of neutron activation, (b) crushed rock sample after neutron activation placed on the HPGe detector, (c) crushed rock sample after neutron activation.

- Information about measurement and results

Tab. 11 Neutron activation results of the rock sample from Polkowice-Sieroszowice mine.

Hall ID (name of the sample)	**Measure-ment method**	**Equipment type**	**Detection relative efficiency** [%]	**Collection period**	**Source of neutron activation**	**Neutron flux of the source**	**Activated isotopes**
rock sample 6	Gamma spectrometry	HPGe detector	20	Short measurements and long measurements by a few days	californium (^{252}Cf),	10^5 n/cm^2/s	^{24}Na ^{56}Mn

Analysis of rock sample, which underwent neutron activation.

Tab. 12 Comparison of counts per second for a rock sample before and after neutron activation of a rock sample.

Isotope	Energy [keV]	Counts per second		
		Rock sample before neutron activation	Rock sample 5.3 h after neutron activation	Rock sample 94.2 h after neutron activation
^{210}Pb	46.5	0.0025	-	0.0034

^{234}Th	63.3	0.0045	0.0134	0.0047
X Pb Kα2	72.8	0.0011	-	0.0016
X:Pb Kα1	74.97	0.0049	0.0208	0.0068
X:Bi Kα1	77.12	0.0047	0.0266	0.0085
X: Pb Kβ3	84.45	-	-	0.0025
X:Bi Kβ1	87.34	0.0018	0.0098	0.0033
X Bi Kβ2	89.8	0.0006	0.0040	0.0017
^{234}Th	92.59	0.0091	0.0387	0.0128
^{235}U	143.8	0.0013	-	0.0014
^{235}U	185.7	0.0075	0.0349	0.0100
^{227}Th	236	0.0002	-	-
^{212}Pb	238.63	0.0054	0.0129	0.0037
^{214}Pb	241.98	0.0020	0.0186	0.0048
^{208}Tl	277.4	0.0001	-	-
^{214}Pb	295.21	0.0044	0.0371	0.0098
^{212}Pb	300.1	0.0002	-	-
^{233}Pa	**312.2**	**-**	0.0014	-
^{228}Ac	332.4	0.0001	-	-
^{228}Ac	338.3	0.0008	-	0.0009
^{214}Pb	351.92	0.0084	0.0611	0.0169
^{214}Bi	387	-	0.0051	-
^{228}Ac	463	0.0001	-	-
^{208}Tl	510.77	0.0085	0.0335	0.0098
^{208}Tl	583.2	0.0019	-	0.0010
^{214}Bi	609.31	0.0063	0.0424	0.0121
^{214}Bi	665.5	-	-	0.0002
^{212}Bi	727.2	0.0004	-	-
^{214}Bi	768.36	0.0007	0.0047	0.0012
^{212}Bi	785.4	0.0001	-	-
^{228}Ac	795	-	-	0.0001
^{55}Mn(n,γ)^{56}Mn	846.8	-	0.0013	-
^{228}Ac	911.2	0.0013	-	0.0006
^{214}Bi	934.1	0.0002	-	0.0006
^{228}Ac	964.8	0.0002	-	-
^{228}Ac	969	0.0005	-	0.0004
^{234m}Pa	1001.03	0.0003	0.0015	0.0004
^{228}Ac	1033.2	-	-	0.00003
^{214}Bi	1120.29	0.0014	0.0088	0.0025
^{214}Bi	1155.2	-	-	0.0002
^{214}Bi	1238.11	0.0005	0.0046	0.0010

^{23}Na(n,γ)Na	1368.6	-	0.0273	0.0026
^{214}Bi	1377.67	0.0004	0.0028	0.0006
^{214}Bi	1408	0.0002	-	0.0003
^{40}K	1460.83	0.0080	0.0164	0.0053
^{214}Bi	1509.2	0.0002	-	0.0002
^{228}Ac	1588.2	-	-	0.0001
^{208}Tl (DEP)	1592.5	0.0002	-	-
^{214}Bi	1661.3	-	-	0.0002
^{214}Bi	1729.6	0.0003	-	0.0005
^{214}Bi	1764.5	0.0013	0.0077	0.0021
^{214}Bi	1847.4	-	-	0.0003
^{208}Tl (DEP)	2103.5	0.0002	-	-
^{214}Bi	2118.6	-	-	0.0001
^{214}Bi	2204.21	0.0004	0.0017	0.0005
^{214}Bi	2447.9	0.0000	-	0.0001
^{208}Tl	2614.7	0.0016	0.0040	0.0012

Gamma-ray spectrum:

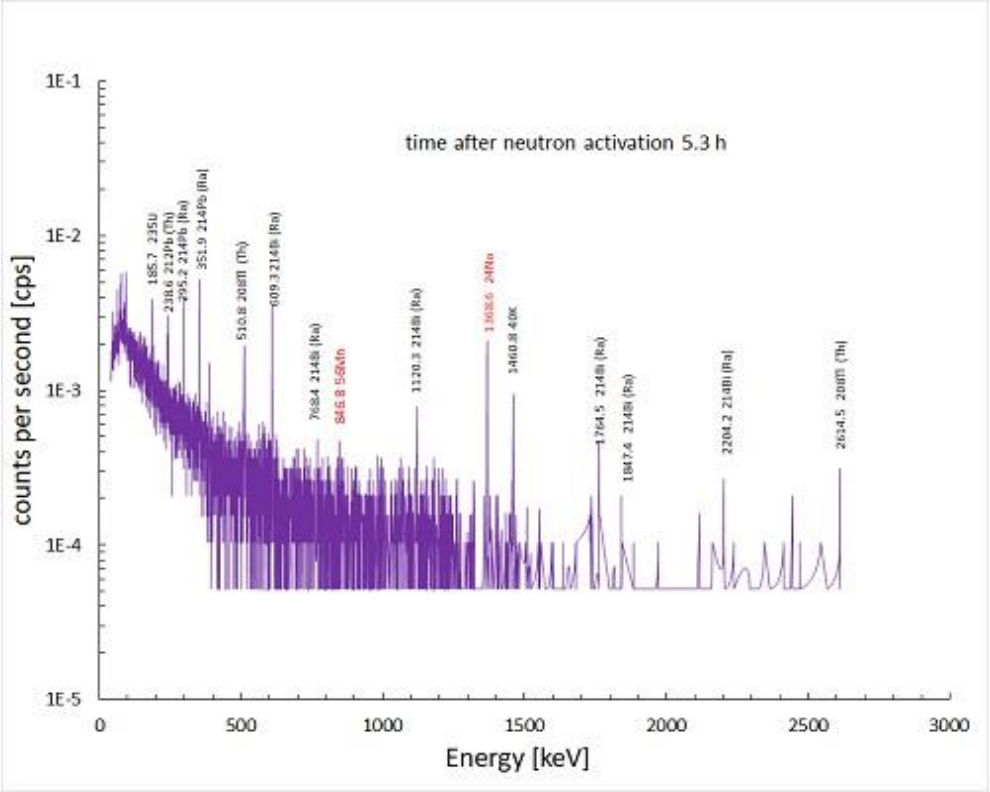

Fig. 27 Gamma-ray spectrum of the rock sample measured 5.3 h after neutron activation.

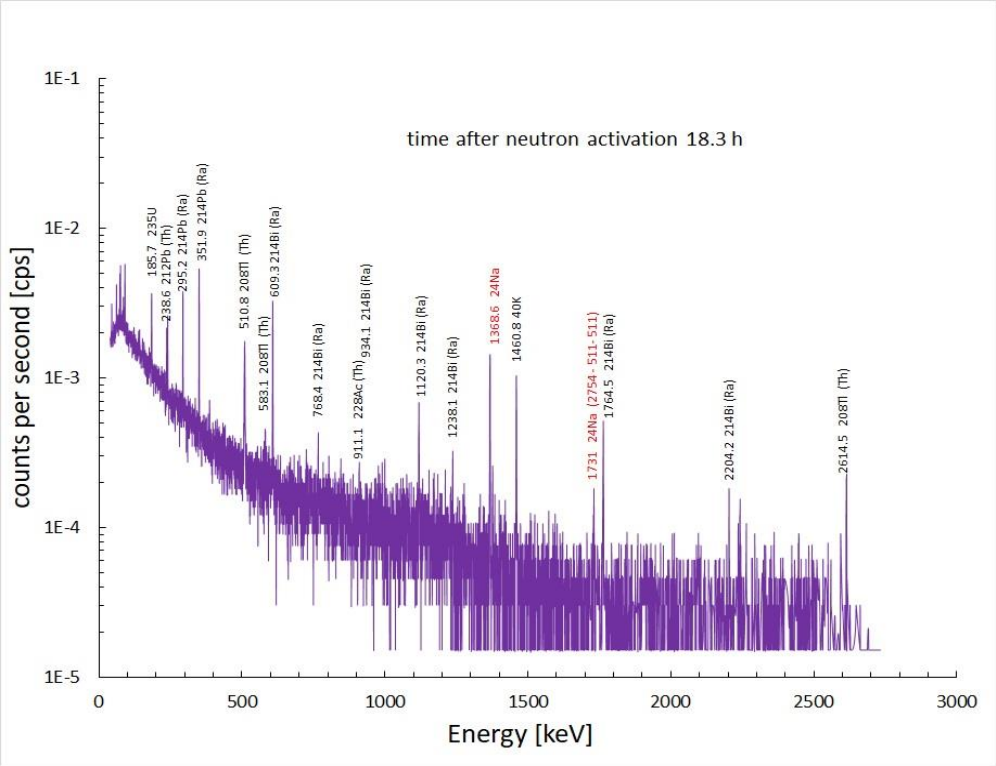

Fig. 28 Gamma-ray spectrum of the rock sample measured 18.3 h after neutron activation.

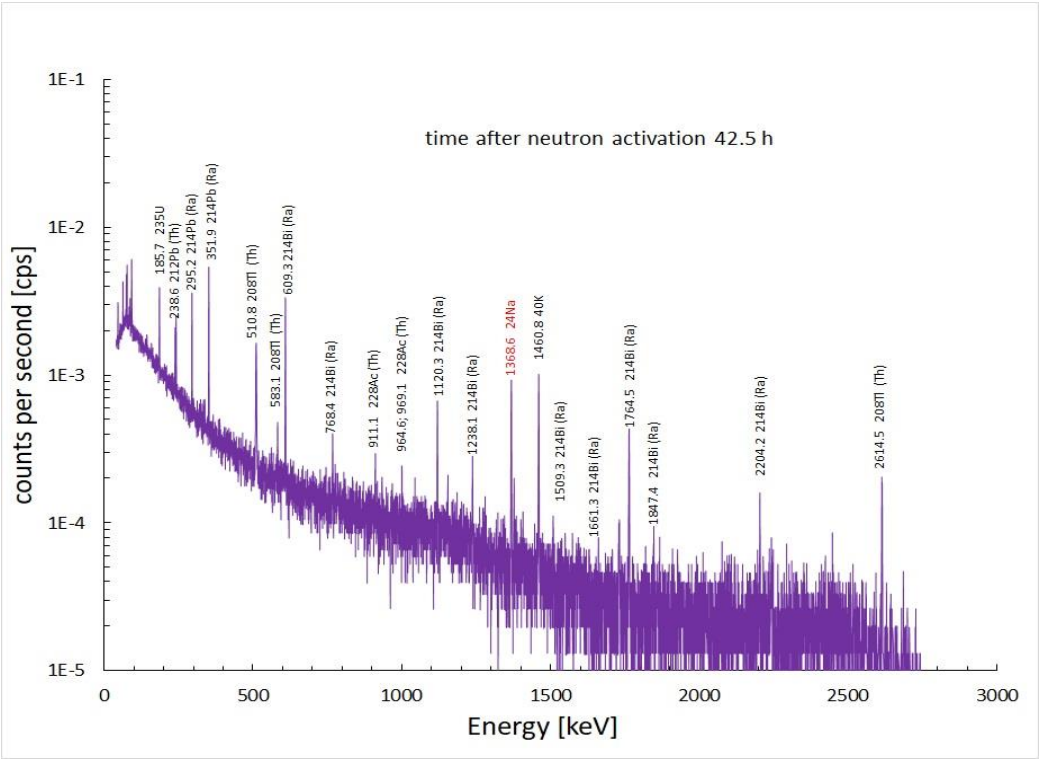

Fig. 29 Gamma-ray spectrum of the rock sample measured 42.5 h after neutron activation.

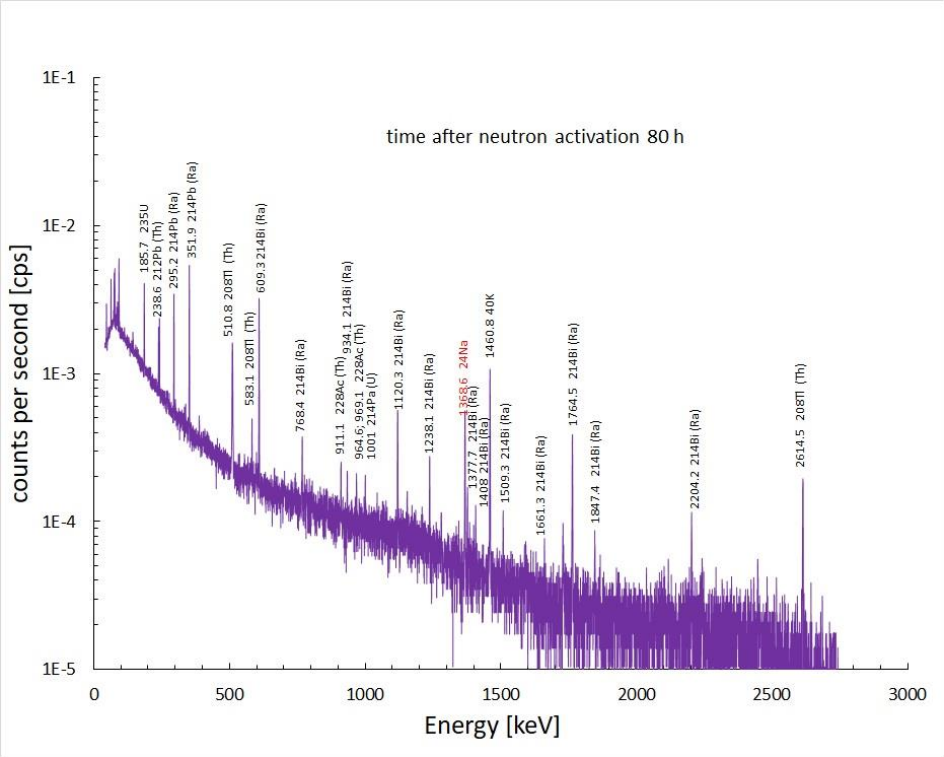

Fig. 30 Gamma-ray spectrum of the rock sample measured 80 h after neutron activation.

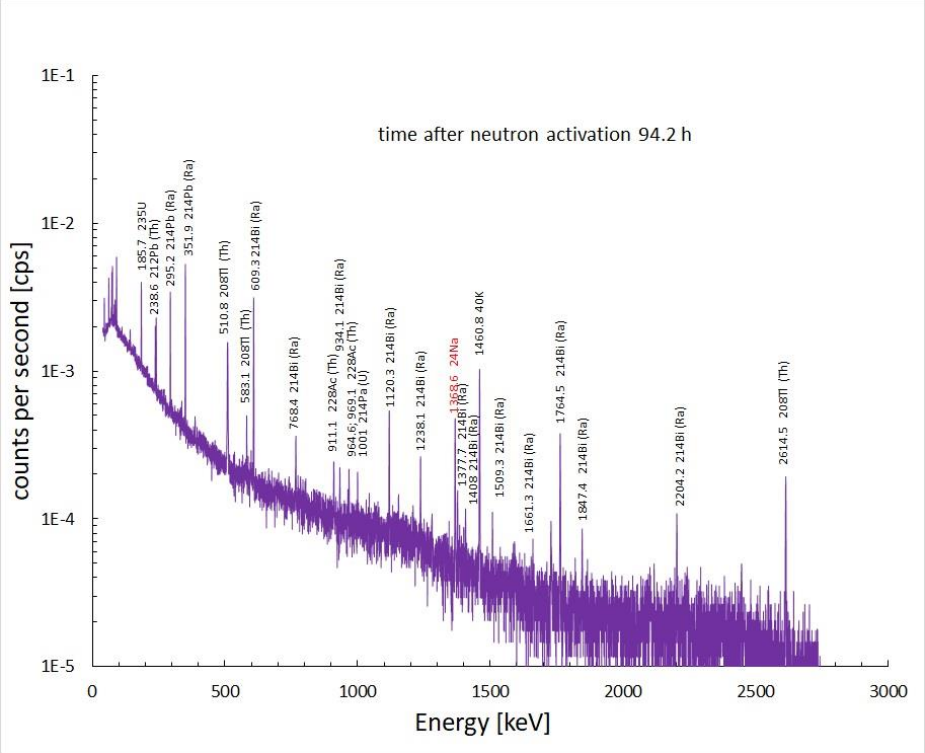

Fig. 31 Gamma-ray spectrum of the rock sample measured 94.2 h after neutron activation.