Technical report No. 464/2020

DATA ACQUISITION FROM THE DEEP HORIZONS OF THE ROŽNÁ MINE

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FINAL SUMMARY

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Prague, 2020

SÚRAO

Report name: Data acquisition from the deep horizons of the Rožná mine – final summary

Project name: Data acquisition from the deep horizons of the Rožná mine

Identification:

Final Summary

Number of contract: *SO 2017/023*

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Obsah

List of abbreviations:

AS CR – Academy of Sciences of Czech Republic

CAI – Cerchar abrasivity index

CERCHAR – abrasivity test

DGR – deep geological repository

DIAMO – DIAMO s. p., o. z. GEAM

Dm – mineralogical density

Do – bulk density

EDZ – excavation damaged zone

eU – equivalent of Uranium

FDZ – fault damage zone

HiRAT-ABI – High Resolution Acoustic Televiewer

LV – large volume

MIP – mercury intrusion porosimetry

OPTV – Optical TeleViewer

PDB – Pee Dee Belemnite

PhMP physical and mechanical properties

REE – rare earth elements

RM – rock mass

RQD – Rock Quality Designation

SMOW – *Standard* Mean Ocean Water

SUSC – susceptibility

URF – underground research facility

UW – ultrasonic wawes

Abstrakt

Cílem projektu bylo získat informace o prostorovém rozložení geologických, geotechnických, geochemických a transportních vlastností horninového prostředí v různých hloubkách dolu Rožná v rozmezí 12. až 24. patra. Dále zahrnoval pochopení vlivu tektonické zóny na vlastnosti horninového prostředí, sledování vývoje geotechnických a geochemických parametrů s hloubkou, vymezení homogennějších skalních bloků v rozsahu přístupných oblastí, popis zóny EDZ a revalidci ložiska. Toto anglické shrnutí obsahuje nejdůležitější výstupy z projektu a jeho závěrečné zprávy (Bukovská et al. 2020).

Klíčová slova

Hluboké horizonty, důl Rožná, zlom, porucha, ovlivnění horninového masivu, seismická tomografie, transportní experimenty, DFN model, 3D model, migmatitizovaný vulkanosedimentární komplex, difuze, sorpce, radionuklidy, pórová voda, prognóza zdrojů uranu, vývoj uranové mineralizace s hloubkou, fyzikální a mechanické vlastnosti hornin, vlastnosti horninového masivu, anizotropie horninového masivu, kvalita horninového masivu, napěťově-deformační stav horninového masivu, měření napětí in situ, zóna poškození ražbou (EDZ), pórový prostor horniny, rentgenová počítačová mikrotomografie, vrtný georadar, seismokarotáž, seismická refrakční tomografie

Abstract

The aim of this project was to obtain information on the spatial distribution of geological, geotechnical, geochemical and transport properties of the rock environment at various depth levels of the Rožná mine in the range of 12th to 24th floors. Moreover, it included understanding the influence of the tectonic zone on the properties of the rock environment, monitoring of the development of geotechnical and geochemical parameters with depth, definition of more homogeneous rock blocks in the range of accessible areas, description of the EDZ zone and deposit revalidation. This English summary includes the most important outcomes from the project and its final report (Bukovská et al. 2020).

Keywords

Deep horizons, Rožná mine, fault, migmatitised volcano-sedimentary complex, diffusion, sorption, radionuclides, pore water, uranium resources assessment, evolution of uranium mineralization with depth, physical and mechanical properties of rocks, rock mass properties, rock mass anisotropy, rock mass quality, stress-strain state of the rock mass, in situ stress measurements, Excavation Damaged Zone (EDZ), rock pore space, X-ray computed microtomography, Borehole Georadar, Vertical Seismic Profie, Seismic Refraction Tomography

1 Introduction

The aim of the project was to obtain unique spatial geological data from the Rožná uranium mine, which is now in a phase of decline, in an environement and depth close to the future underground depth repository. The main aim was to collect spatial information on distribution of geological, geochemical, geotechnical and transport properties on different depth levels and on different distance to a regional scale fault structure. From these data were defined more homogeneous (less fractured) rock blocks. The works also included study of deformation zones (EDZ and eDZ) which allowed setting a deformation envelope for large regional scale fault zone. Moreover, classical structural analysis led to preparation of a 3D model of fracture network in selected parts of the mine area. Furthermore, the data enabled the determination of the damage envelope of the selected tectonic failure zone (first zone) and the description of the damage zone (EDZ), in an environment close to the potential location of the repository in the Kraví hora locality. At the same time, the works also included a revalidation of the Rožná uranium deposit as well as a summary of available archival materials, descriptions of accessible underground areas around the first zone on the 12th–24th mine level, laboratory work on the collected rock samples and underground work.

The works were carried out in the former deep uranium mine at Rožná, within its controlled zone. The Rožná mine is located in the Vysočina region near the village of Dolní Rožínka and is owned by DIAMO, s.p., o.z. GEAM. Performed scientific activities focused on the area between shaft R-7S and R-3 at 12th–24th mine levels (Figure 1), approx. 600–1200 m below the earth's surface. As part of the work, archival data were also processed from the Zlatkov and Habří deposits.

The main part of the work included study of rock properties and rock mass characteristics from several geotechnical stations, which have been built at different depth levels and different distance from the R1 zone, in order to understand changes of rock properties across the depth profile and with respect to the tectonic zone.

Location of performed works

Localization of individual studied sites and observation points was planned during the reconnaissance works. Emphasis was placed on the selection of sites with as uniform a lithology as possible for good comparability of analysis results across deep horizons, in order to explore differences, which may be related to the depth level and distance from large fault zone. It was unfortunately very complicated to fill, given the varied lithological structure of the area.

Understanding of the influence of rock mass by the tectonic zone formation and presence was studied mainly on a selected rock block; this was complemented by detailed documentation of fracturing at any reachable rock wall in the mine.

On the 20th floor (Figure 2), a well accessible rock block was selected, in which the zone R1, whose influence was assessed in the project, extends. This block is delimited by the Z3-XX, PŠ1-203 and RV4 20-101 galleries. Within this block, two geotechnical stations in the hanging wall of the zone R1 (GS20/1, GS20/2) were located in the area of the pit R-7S on the Z3-XX gallery. Furthermore, the geotechnical stations were located in the footwall of the zone R1 near the B-2 pit on the 12th floor (GS12), on the 18th floor near the R-7S pit on the Z3-XVIII gallery (GS18), on the 24th floor in the footwall of the zone R1 near the pit R-7S on the Z3-XXIV gallery (GS).

Large-volume samples (VO) were then taken usually on the walls opposite the geotechnical stations.

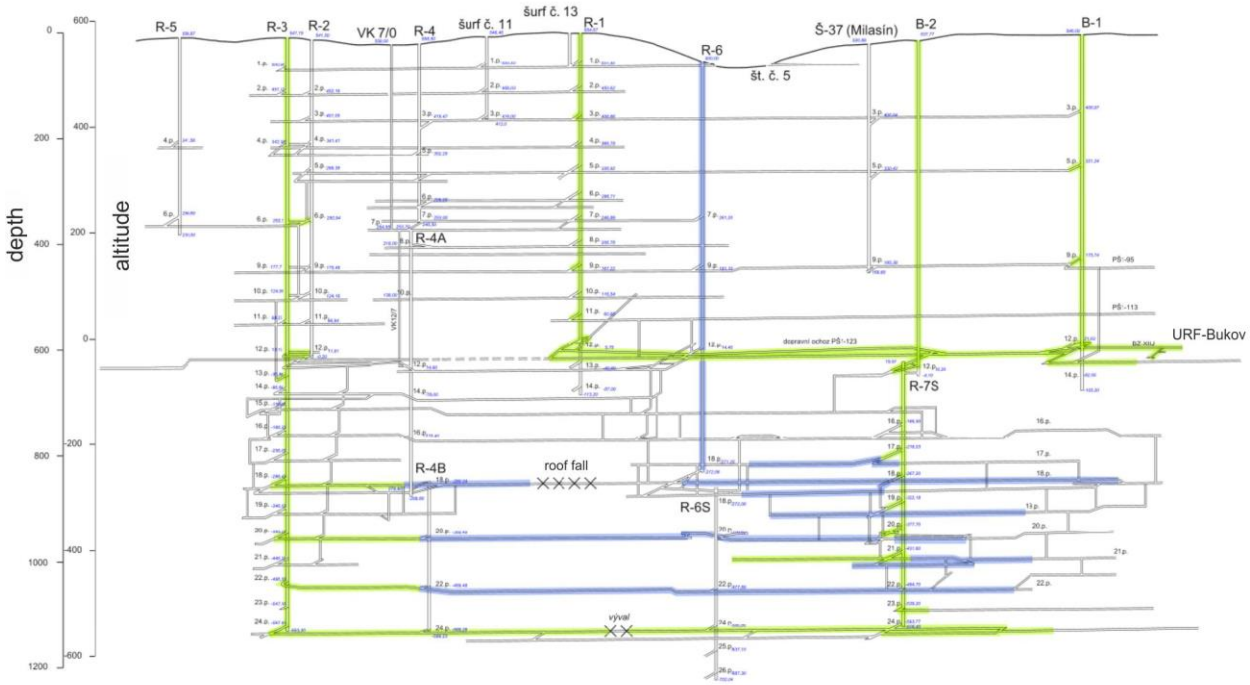

Figure 1 Rožná mine scheme with accessible galleries: axonometric plan (source DIAMO s. p.); accessible galleries in the winding part of the wind network are marked in green galleries accessible in the exhaust part of the wind network in blue (only for documentation purposes), in red location of works for this project

For a detailed study of the rock influence by the zone R1, an accessible “quasi-homogeneous” rock block limited by the Z3-XX gallery from the north, the RV4 20-101 gallery from the southeast and the PŠ1-203 gallery from the east was selected (Figure 1). In this block, mainly migmatized biotitic paragneiss to amphibole-biotitic paragneiss is found. In this area, the first zone is located approximately 30–40 m from the crossing of the Z3-XX gallery with the PŠ1-203 gallery and about 20–30 m from the RV4 20-101 gallery from the crossing with PŠ1-203 gallery. The zone is characterized by strong graphitization and in most of its intersection with individual galleries is covered with reveal. In connection with the description of the block on the 20th floor, a seismic cut through this block was performed between the galleries (PŠ1-203, RV4 20-101, Z3-XX) and also an oblique cut between Z3-XX and Z3-XXI through the chimney R-1-21/20-95P between the 20th and 21st mine level.

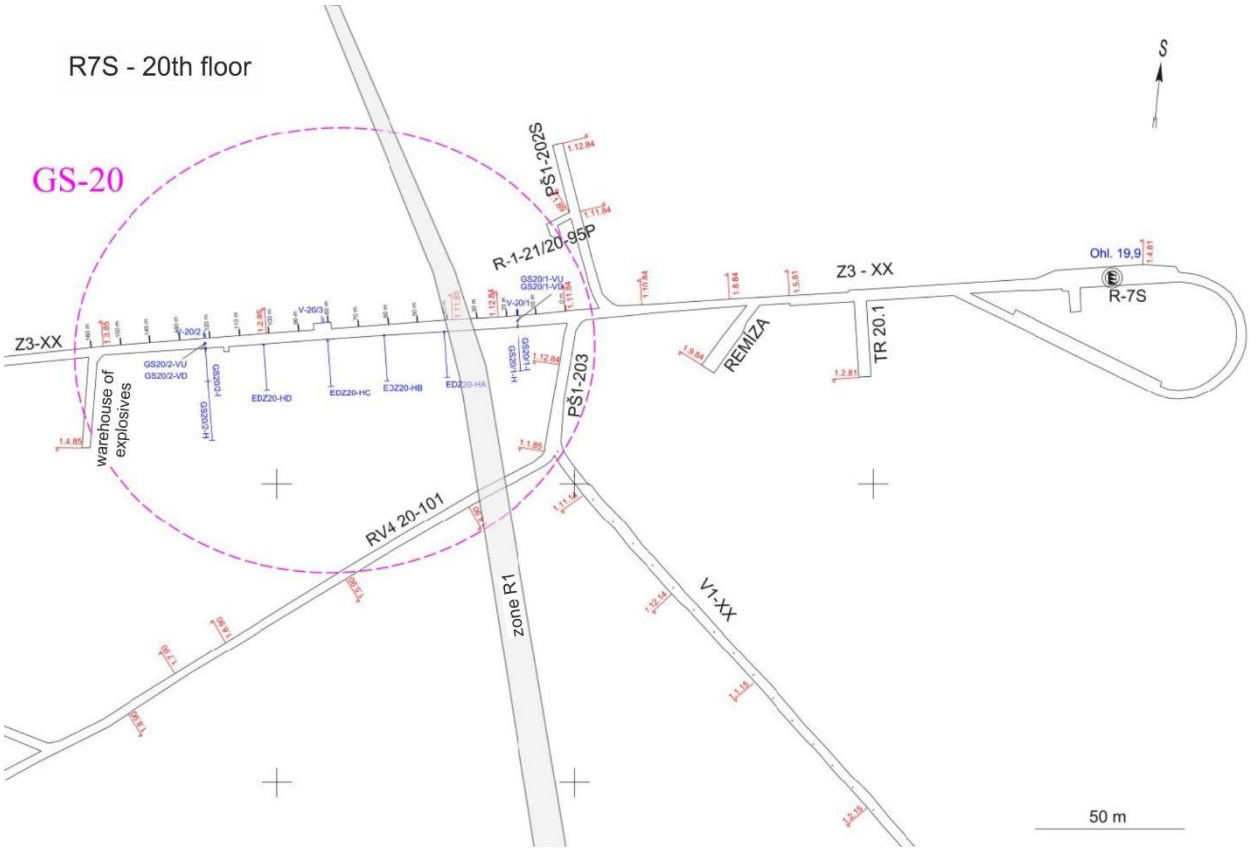

Figure 2 Localization of works on the 20th floor of the Rožná mine near the pit R-7S

All the results have been described in the final report Bukovská et al. (2020; in Czech) on more than 700 pages and 156 electronic attachments. Any results commented in this summary report, can be found there.

Studied fault zone description

The study was located in highly metamorphoused rocks, which belong to the moldanubian zone of Bohemian massif and are mainly represented by migmatised paragneisses, amphibolites and migmatites. The area is intensively faulted by NNW – SSE faults (extending for kilometres long) which contain uranium-rich mineralisation. From these, the tectonic zone R1 (the so-called first zone) was chosen for this study. It represents one of the directional cataclazite zones of the direction N – S to NNW – SSE with an inclination of 45–70° to W – WSW. These zones have a thickness ranging from millimeters to several meters (maximum 30 m) and are filled with graphitic, coherent and incoherent cataclazites and tectonic breccia. The length of these zones, to which the major part of the dispersed uranium mineralization is bound, reaches up to 15 km (Kříbek and Hájek 2005). In terms of mineralization, zone R1 is one of the main ore structures of the Rožná deposit. The mineralization here consists mainly of the minerals uraninite and coffinite, which are dispersed in strongly chloritized, hematitized, limonized, argilitized, graphitized and pyritized rocks. The average thickness of ore bodies in the R1 zone is around 3.5 m, which are most often tied to places where the slope changes and / or to the intersection points of zones with diagonal structures. In terms of the amount of carbonates on this structure, the range is 5–10% by volume.

These carbonates can be found scattered in the fine-grained matrix of cataclazites, or they are exposures with thickness of up to several cm. In the footwall of the zone R1 there is a markedly developed system of cracks and small dislocations with inclination of 66-80° to NW and SE. Their range is mostly within a few tens of meters and is often terminated just on the structure R1. Typical fillings of these structures are carbonate minerals and at the same time, there is frequent presence of older (pre-uranium) sulfide mineralization and sericization of rocks in their surroundings. Between zones R1 and R4, there are systems of spherical structures with a thickness of less than 3 m (Kříbek and Hájek 2005) running in the directions of 320–340° and with the inclination of 55–90°. Hereinafter, the studied zone is usually called either the R1 zone or first zone.

2 Influence of the fault zone and depth on the host rock and host rock characteristics

2.1 Mineralogy and geochemistry of fault and fracture fillings

The products of multiple giant hydrothermal activities along shear zones, faults and fractures are preserved in the Rožná U deposit. Several generations of carbonate and quartz-carbonate and sulphidic mineralization formed during tectonic and geological processes. They are supposedly a good tool for palaeohydrogeological studies (Tullborg et al. 2008).

Both stratiform and vein mineralizations can be found in the Rožná U deposit. Stratiform mineralization is formed by barite-hyalophane sulphidic ores, probably metamorphosed ores of submarine exhalative type (Kříbek and Hájek 2005).

Vein-type mineralization can be divided into pre-uranium quartz-sulphidic and carbonate-sulphidic mineralization, uranium-bearing mineralization accompanied by carbonate veins, and post-uranium quartz-carbonate-sulphidic mineralization with barite (Kříbek et al. 2009).

The samples of hydrothermal vein and fracture minerals were collected from the open galleries and edits of the 18th, 20th, 21th, 22th, and 24th levels of the R7S and R3 mines, and from the adjacent boreholes. The veins and fractures developed predominantly with NNW-SSE or NNE-SSW strike, and N-W and E-W orientation.

The samples were divided into several groups: probably late metamorphic quartz and quartz-feldspar veins, ore-bearing and post-ore carbonate and quartz-carbonate veins, post-uranium quartz-carbonate veins with barite and sulphides, sulphidic mineralization, and products of alteration processes. The prevailing minerals within the altered zones are quartz, calcite, chlorite, micas, palygorskite, smectites, hematite, kaolinite and pyrite.

The carbonate and quartz-carbonate hydrothermal veins are formed by calcite, and, rarely, by carbonates of dolomite-ankerite composition. The content of MgO in calcite ranges from 0.01 to 0.25 wt. %, FeO from 0.02 to 1.19 wt. %, and MnO from 0.08 to 1.05 wt. %. The content of CaO in dolomite-ankerite ranges in the interval 25.19–29.22 wt. %. The contents of MgO and FeO in dolomite-ankerite are variable, the content of MgO varies from 10.53 to 19.82 wt. %, the content of FeO ranges from 0.07 to 16.55 wt. %. The content of MnO in dolomite-ankerite is between 0.03 and 2.33 wt. %.

Trace elements and REE were analyzed in the set of 42 samples of carbonates. The high content of Sr in carbonates (47–813 ppm) gives evidence of their hydrothermal origin. On the other hand, the contents of U and Th are low, mostly less than 1 ppm. Only four samples revealed higher U contens, from 15.1 to 74.9 ppm. In addition, the contents of the elements of HFS group are low, Zr = 2.2–34.6 ppm, the contents of Nb and Ta are mostly below the detection limit, the content of Y ranges between 2.4 and 93.6 ppm. These values, together with bulk content of REE (ΣREE = 7.2–347.2 ppm), are lower than the contents of these elements in surrounding rocks (René 2002).

Quartz and quartz-feldspar veins probably represent the products of pre-uranium retrograde-metamorphic fluids. The veins contain two or three-phase primary and secondary inclusions of H_2O-CO_2 type, with homogenization temperatures from 260 to 360 °C and low salinity of the aqueous solution from 0.8 to 3.6 wt. % NaCl equiv.

The inclusions of H_2O type were observed in app. 60 samples of calcite, quartz and dolomite-ankerite of carbonate and quartz-carbonate veins of ore-bearing and post-ore stages. Temperatures of homogenization of two-phase primary inclusions were measured in the range from 40 to 180 °C. Homogenization temperatures higher than 150 °C were measured only in four samples of carbonates. The salinity of aqueous solution is highly variable, from 0.1 to 22 wt. % NaCl equiv. Temperature of the first melting ranges from –43.4 to –56.5 °C, it indicates the mixing of hydrothermal solutions of variable composition (Ca±Mg±Fe±Na chlorides).

In barite from late post-uranium quartz-carbonate veins with sulphides single-phase and two-phase inclusions of aqueous solution were found. Homogenization temperatures of two-phase primary inclusions were measured in the range from 64 to 128 °C, the salinity of aqueous fluid varied from 1.1 to 14.2 wt. % NaCl equiv. Temperature of the first melting (Tfm = –35.5 °C) indicates Mg-Fe-Na chlorides in solution.

The isotopic composition of carbon and oxygen in vein carbonates is variable and indicates the inconstant conditions of the vein formation. The values of $\delta^{13}C$ in calcite are between –2.7 and –8.4 ‰ (PDB), in dolomite-ankerite between –3.3 and –4.9 ‰ (PDB). These values probably correspond to carbon from the deep resource, alternatively multiple carbon sources. The values of $\delta^{18}O$ in calcite are in the range from +6.8 to +21.11 ‰ (SMOW), in dolomite-ankerite from +8.5 to +17.4 ‰ (SMOW). The recalculated values of $\delta^{18}O$ of fluid of calcites with temperature of homogenization higher than 120 °C range from +2.1 to +6.3 ‰ (SMOW). It shows that the source solutions were probably brines of sedimentary basins and partly metamorphic fluids. The values of $\delta^{18}O$ of fluid of calcites with lower temperature of homogenization are in the interval from –11.3 to +2.5 ‰ (SMOW). It seems that the source solutions of low-temperature veins were mostly meteoric waters. The values of $\delta^{18}O$ of fluid in dolomite-ankerite reach –9.7 up to +7.2 ‰ (SMOW), as in calcite more generations of dolomite-ankerite veins can be distinguished.

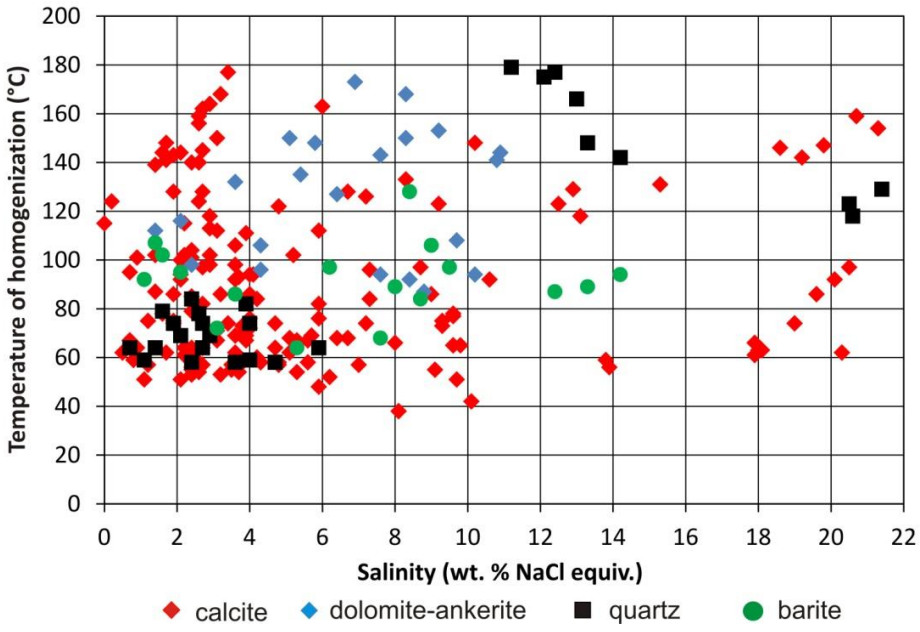

Figure 3 Temperature of homogenization vs. salinity of fluid inclusions of aqueous solution from carbonate and quartz-carbonate veins and barite from the Rožná U deposit

The analyses of the $^{87}Sr/^{86}Sr$ in vein carbonates yielded values from 0.708690 to 0.714530. Similar data were recorded in carbonates from the URF Bukov (Bukovská et al. 2019). It is suggested that the isotopic composition of Sr in carbonates was derived from the mixture of several sources from various rock types extracted by the brines of a deep circulation. The correlation of $^{87}Sr/^{86}Sr$ vs. $\delta^{18}O$ or $\delta^{13}C$ values in carbonates show a gradual drop in the values. This drop can indicate changes in the source solutions. It is probable therefore, that the source solutions of the low-temperature carbonates were predominantly meteoric waters.

Sulphidic mineralization is formed mainly by post-uranium crystallized pyrite along fractures and pyrite coatings on fracture walls. The isotopic composition of sulphur in pyrite provided $\delta^{34}S$ values between –7.1 and +7.0 ‰ (CDT). These values correspond to the values of $\delta^{34}S$ in sulphides from the post-uranium quartz-carbonate-sulphidic mineralization from the Rožná U deposit and sulphides from the URF Bukov (Bukovská et al. 2019).

The isotopic composition of sulphur in barite from the post-uranium quartz-carbonate-barite veins provided $\delta^{34}S$ values between +16.8 and +13.8 ‰ (CDT). These values are lower than $\delta^{34}S$ values in stratiform barites (Kříbek and Hájek 2005) and correspond to the $\delta^{34}S$ values of barites from post-uranium quartz-carbonate-sulphidic mineralization.

The interpretation of the data, based on the structural position and mineralogy of veins, geochemical data, correlation with the geochronological U–Pb and K–Ar data (Kříbek et al. 2009) and results of the fission track analyses in apatites from paragneisses, indicates several stages of crystallization of the studied veins. Quartz-carbonate and carbonate veins with temperature of origin of about 150 °C probably crystallized during ore-bearing to post-ore stages of the Rožná U deposit at c. 280 to 260 Ma. Carbonate and quartz-carbonate veins with barite and sulphides probably crystallized at post-uranium stage at c. 260 to 200 Ma.

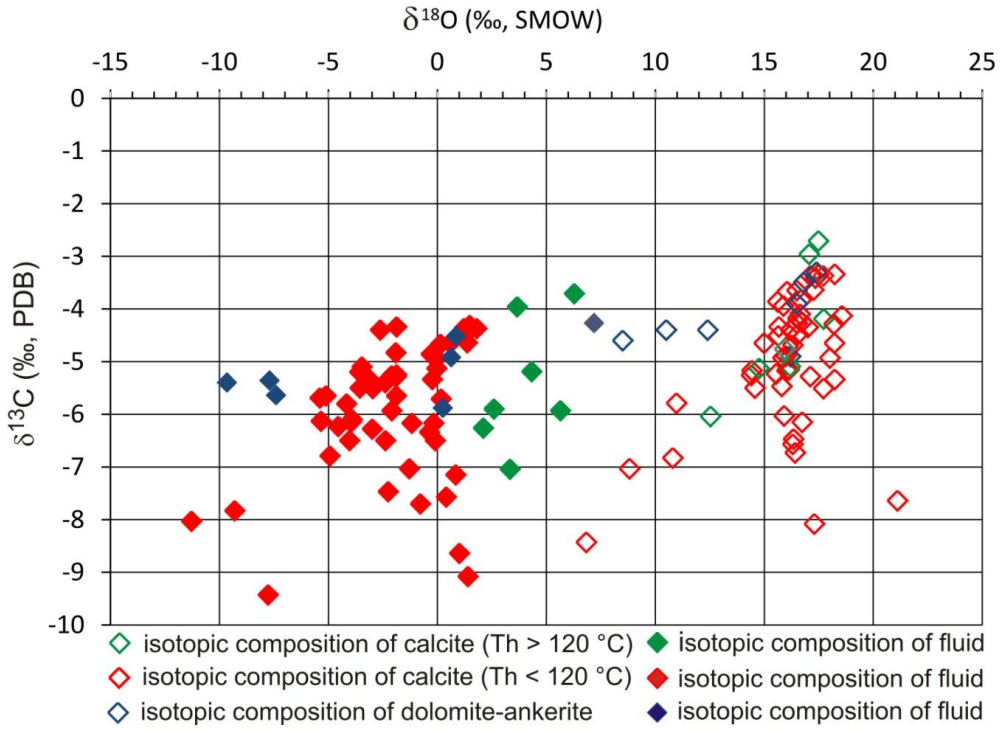

Figure 4 Isotopic composition of carbon and oxygen of calcite and dolomite-ankerite from carbonate and quartz-carbonate veins from the Rožná U deposit

2.2 Transport characteristics of host rock

Rock samples at different depth levels were selected for the study of transport characteristics. Moreover, the scope of the research was suposed to observe the effect of EDZ on the transport parameters. The study of transport parameters was mainly focused on diffusion experiments with ^{3}H, representing conservative non-absorbing tracers, further with d radionuclides in anionic form (^{125}I, ^{36}Cl). The sorption experiments were carried out on the samples collected from various depth levels (12th, 18th, 20th, 22nd and 24th floor) and from the subsurface drainage gallery (DG) with selected isotopes (^{137}Cs, ^{85}Sr, Se, U). The rock samples from the large-format boreholes with a diameter of 48 mm, designated for the study of transport parametres and comparison with the results of physico-mechanical properties (PMP), were sampled in different directions with respect to the metamorphic foliation (perpendicular and parallel direction).

The rock samples for the study of the pore water composition were collected at the 12th and 24th floor. At the same time, in-situ pore water was sampled and water pressure tests (WPT) were performed at selected borehole intervals in order to both test the WPT instrumentation at low permeability and verify the integrity of the rock matrix.

2.2.1.1 Sorption

Sorption experiments were conducted on the rock material from the large-volume boreholes of a total weight about 2 000–3 500 g. The rock samples were crushed and sieved in order to produce defined grain size samples (5 grain size fractions A – E). Subsequently, fraction C (0,63−0,125 mm) and D (0,8−0,63 mm) were used for the experiments. All the fractions were sampled, ground and subsequently analyzed by means of X-ray diffraction on a Bruker D8 Advance X-ray powder diffractometer.

The work was focused on the study of sorption of Cs (I), Sr (II), Se (IV) and U (VI). The concentration (activity) decrease over the time was monitored using several species:

- ^{137}Cs; CsCl (c = $2 \cdot 10^{-5}$ mol l^{-1}) labeled by $^{137}CsCl$ v 0,1 mol l^{-1} HCl (A_0 ~ 800 Bq ml^{-1})
- ^{85}Sr; $SrCl_2$ (c = $2 \cdot 10^{-5}$ mol l^{-1}) labeled by $^{85}SrCl_2$ v 0,5 mol l^{-1} HCl (A_0 ~ 800 Bq ml^{-1})
- SeO_3^{2-} in form Na_2SeO_3 (c = $2 \cdot 10^{-5}$ mol l^{-1})
- UO_2^{2+} in form $UO_2(NO_3)_2$ (c = $2{,}6 \cdot 10^{-4}$ mol l^{-1})

The solid phase m (g) to liquid phase V (l) ratio chosen for the experiments was 1:10, whereas the weight of solid phase was 0,5 g. The sorption experiment spanned over the six independent time intervals (0,04; 0,31; 1; 2; 4 and 7 days). Throughout the experiment, the samples were continuously mixed on a shaker. The synthetic granitic water SGW2 (Červinka and Gondolli 2016) was used for the experimental work.

Table 1 The final Rd values (ml.g^{-1}) of the selected radionuclides on the fractions C and D from the rock samples representing potential sites, phase ratio 1:10, 7 days, fraction C: 0,63−0,125 mm, fraction D: 0,8−0,63 mm

Sample	Cs		Sr		Se		U	
	Fractions C	Fractions D	Fractions C	Fractions D	Fractions C	Fractions D	Fractions C	Fractions D
OS_1025	35,6 ± 4,2	96,3 ± 9,1	2,3 ± 0,9	1,1 ± 0,9	1,0 ± 0,9	1,1 ± 0,9	<1,6	<1,6
V12	52,7 ± 4,7	51,4 ± 4,6	3,6 ± 0,9	4,7 ± 1,0	7,8 ± 1,3	12,1 ± 1,6	2,9 ± 1,9	2,0 ± 1,8
V18	89,5 ± 6,3	134,3 ±	3,1 ± 1,0	2,5 ± 0,9	< 0,8	< 0,8	<1,6	<1,6
V20	40,1 ± 6,2	38,8 ± 3,6	2,4 ± 0,9	0,9 ± 0,9	0,8 ± 0,9	< 0,8	<1,6	<1,6
V22	8,6 ± 1,5	24,3 ± 2,6	2,4 ± 0,9	2,0 ± 0,9	1,2 ± 0,9	1,3 ± 0,9	<1,6	<1,6
V24 (1)	14,7 ± 1,8	16,8 ± 1,9	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
V24 (2)	35,8 ± 3,5	45,6 ± 4,5	5,7 ± 1,1	4,4 ± 1,0	1,5 ± 0,9	0,9 ± 0,9	<1,6	<1,6

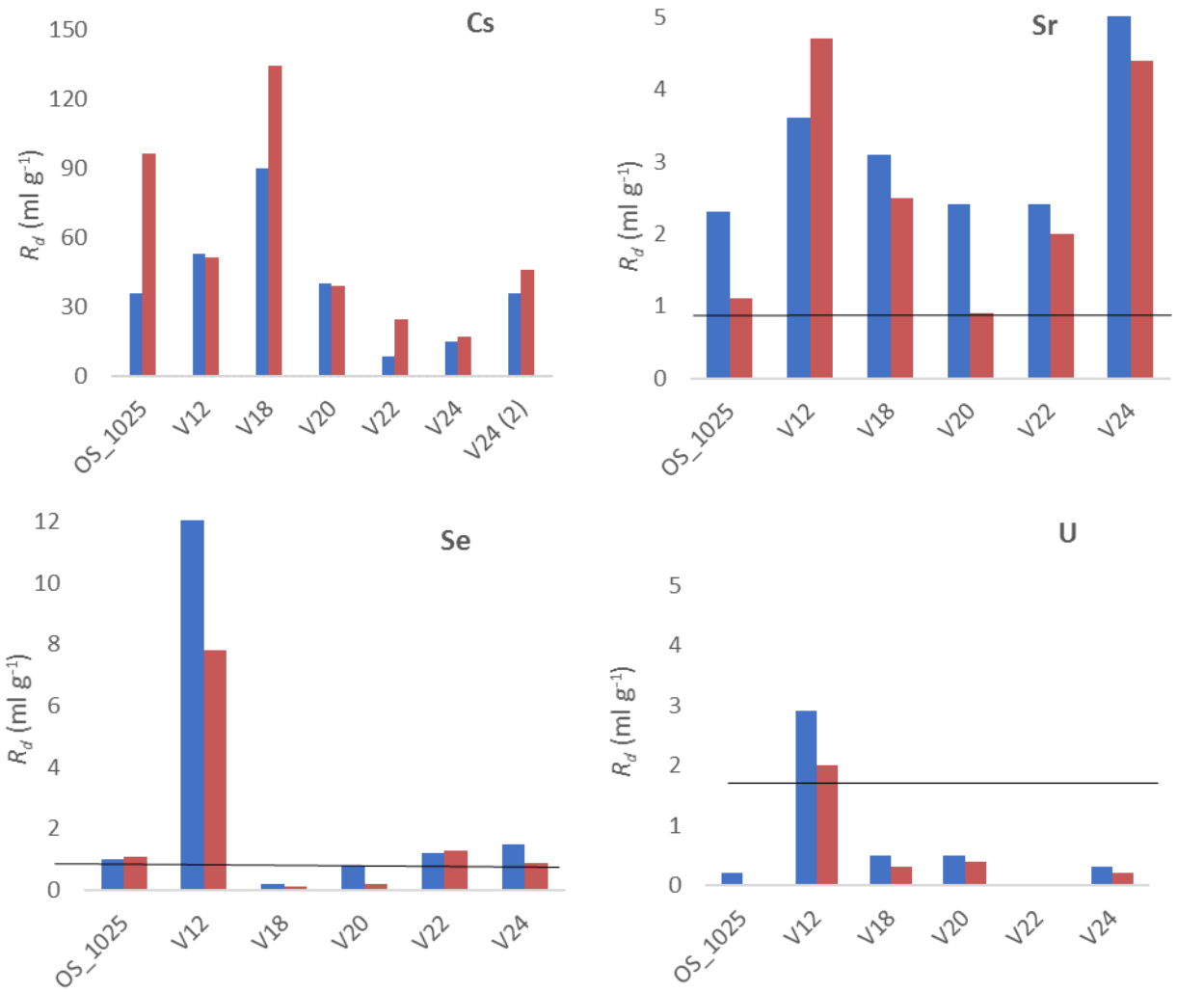

Figure 5 The sorption of selected radionuclides on rock samples, fraction C: 0,63−0,125 mm, fraction D: 0,8−0,63 mm

The results of sorption experiments on selected rock materials with two fractions from the Rožná locality are summarized in Table 1 and Figure 5. The differences in the values of the distribution coefficient R_d for individual species indicate different sorption patterns with respect to individual radionuclides. The highest sorption on the rock material was measured in the case of cesium on the sample from 18th floor (R_d ~ 134 ml g^{-1}). On the other hand, strontium exhibits lower sorption tendendy. Se and U (VI) can be classified as non-sorbing radionuclides since, with one exception (rock sample from the 12th floor), there was no significant sorption in the rock samples. The mineralogical composition of rock samples has a significant effect on the behavior of radionuclides and their sorption rate. Cationic radionuclides such as Cs (I) and Sr (II) are sorbed on layered minerals (e.g. mica). Anionic radionuclides such as Se and U are non-sorbing. If Fe-minerals and complexes of selected cations are present in the rock, these anions are also sorbed (rock sample from the 12th floor).

2.2.1.2 Diffusion experiments with tritium (HTO), chloride ($^{36}Cl^-$) and jodide ($^{125}I^-$) on the floor horizons

The drill cores were taken from the bulk rock samples and formatted into 10 mm segments, used for porosity and rock density measurements. The values for both parameters were determined on prepared discs with a diameter of 48–50 mm and a height of 10 mm, by means of the Melnyk and Skeet (1986) methodology. The selected samples were subsequently used for diffusion experiments.

The porosity values measured on the samples from the bulk samples ranged from 0.15 to 1.63 % (mean 0.43 %; n = 75). The highest porosities was measured on the samples from the large volume borehole on the 12th floor (V12), where the porosity was measured between 0.56 – 1.63 % (median 1.08 %). On the contrary, the lowest values of around 0.17 – 0.28 % were measured on samples from the 18th floor (V18).

The determination of the diffusion coefficient for non-sorbing or weakly sorbing tracers (^{3}H in the form of tritiated water, ^{36}Cl in the form of chloride, ^{125}I in the form of iodide) in the equilibrium usually uses the so-called through diffusion methodology (input reservoir - rock sample - output reservoir) (Havlová et al. 2018)

It is clear that no evident conclusions can be found, concerning interdependence between total porosity and the ^{3}H effective diffusion coefficient or D_e (m^2 s$^{-1,}$) based on the results of the studied samples from the 18th to the 22nd floor and the drainage gallery. The value of D_e is most probably influenced by the geometrical arrangement, connectivity and the shape of the pores. The results show significant influence of individual rock types.

The significance of the geometric factor G can also be demonstrated in the case evaluation of the potential influence of sample foliation (see samples parallel to foliation - “P” and samples perpendicular to foliation - “K”). The difference in the foliation direction and its influence are most evident on the rock samples from the 22nd floor where, at the same porosity, D_e is twice as high in a sample drilled perpendicular to foliation than in the samples parallel to the foliation.

Generally, the results show rather low D_e values. There is no significant difference in diffusion coefficient values and all are less than $2 \cdot 10^{-12}$ m^2 s^{-1}.

Comparing the values of the effective diffusion coefficients: HTO (median 8.3 10^{-13}) and anion: chloride $^{36}Cl^-$ (median 4.7 10^{-13}) or iodide ^{125}I (Figure 6), it is apparent that the anions exhibit lower

diffusion than tritium, which can be attributed to the anion exclusion due to repulsive electrostatic forces between negatively charged anionic tracer and the surface of the transport pores of rock samples. The presence of fractures may diminish this effect and D_e ratio (anion/^{3}H) may, in extreme cases, be greater than 1, but the effect of anion exclusion has been significantly suppressed in some samples (e.g. 18th floor). In the case of the 12th floor (amphibolites), D_e (HTO) values are similar to the other floors despite the multiple higher porosity of samples (perpendicular to the foliation up to 0.66 %, in parallel with the foliation up to 1.36 %). Comparing rock (from the 12th floor) with the rocks (from the 18th floor and below) a significant difference in the level of D_e ratio (anion/^{3}H) can be observed, which can be explained by the lithotype of the rock, but also possibly by different geometric arrangement.

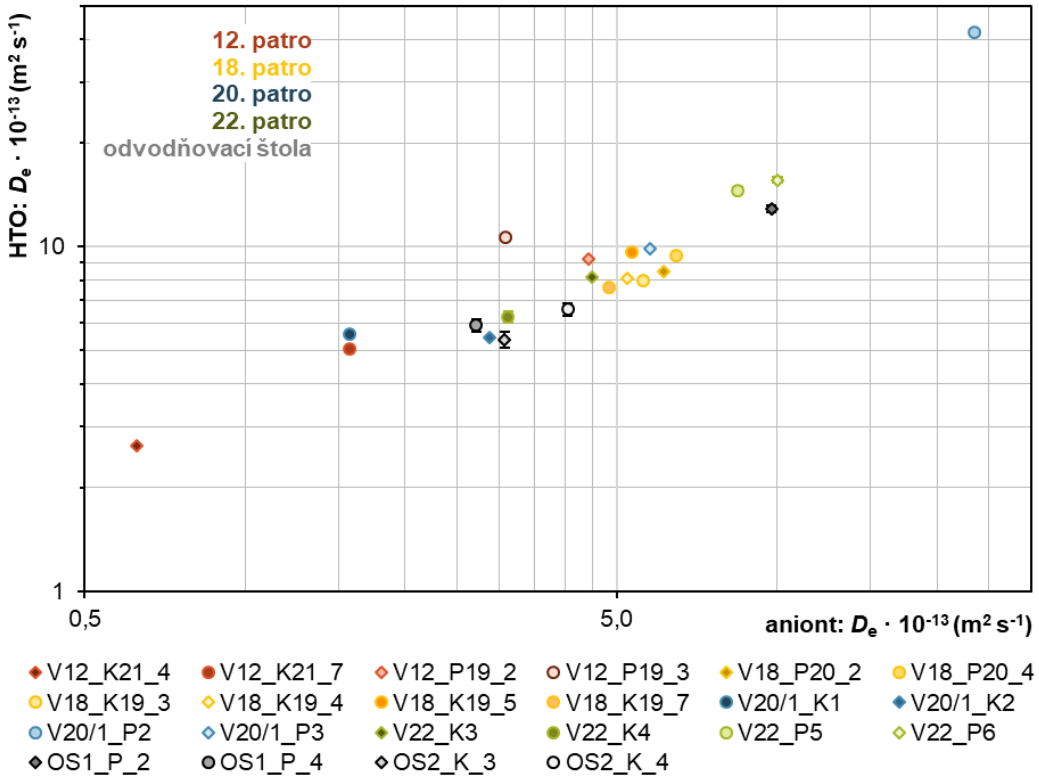

Figure 6 The values of De (analytical solution) of anions (chloride $^{36}Cl^-$, jodide $^{125}I^-$) vs. tritium (^3H)

2.2.2 Porewater chemistry

Only few information about the composition of the pore water in relation to the connected porosity from low permeable parts of the rock massive is available. Term “porewater“ refers to the water in the connected pore space of the rock matrix that is accessible for diffusion-dominated interaction with groundwater circulating in nearby (micro)fractures. The question whether a diffusion in a rock matrix can act as a retardation factor for the transport of radionuclides is related to the presence of an interconnected pore system that contains a solution, ie pore water, in which solutes can be transported. From the point of view of safety assessment, it is therefore important to know the composition of pore water and its development in recent geological periods during the last thousands to hundreds of thousands of years in accordance with the expected lifetime of the repository.

With regard to the expected differences in the hydrochemical composition, rock sampling for the study of pore water was carried out from the 12th and 24th levels of the Rožná mine.

The research of the porewater chemistry was focused on these experiments:

- determination of the chemical composition of the pore water from drill cores in the laboratory;
- determination of the chemical composition of the pore water obtained in-situ by installing a packer in an intact borehole;
- testing of high pressure extraction technique.

Rock samples from the borehole BGS12-H (amphibole-biotite gneiss with garnet) and BGS24-I (biotitic amphibolite) were collected and characterized for conducting of pore water experiments. Gravimetric water content (%), porosity, bulk density, specific density, silicate analyzes and petrological description of rocks were determined on the collected parts of the cores. Prepared samples (200 x 60 mm) were installed in diffusion cells with approx. 90 ml of ultrapure water (DW). In the surrounding reservoir concentrations of several species were regularly monitored, especially chlorides (representing conservative anions), sulphates, fluorides, nitrites and nitrates. At the end of the experiment, all major anions and cations were analyzed by means of AAS and ICP-OES.

Figure 7 The rock samples of drill cores were kept under the vakuum

Figure 8 Diffusion cells 1 – 4, strirring of the surrounding solutions before sampling

In – situ water sampling

A double packer with a sampling interval (-20 cm, +20 cm) was manufactured for in-situ pore water sampling with two sampling inlets for either suction or pressurisation of the sampling interval (PEEK; Figure 9, Figure 10). The in-situ sampling intervals were placed in the borehole intact parts, in the vicinity of drill core sections sampled for laboratory experiments.

Figure 9 Specially designed borehole packer for long-term collecting of pore water

Figure 10 The in-situ setup for vaccum collecting of the pore water

The chemical composition of groundwater from the Bukov URF and in-situ sampling of the groundwater from the 12th and 24th of the Rožná mine were compared with the experimental results determined from the out-diffusion laboratory experiments. The Piper diagram (Figure 11) clearly shows the comparison of the chemical composition of the pore water, based on lab in-diffusion study and the in-situ experiments. All of the examined pore water samles contain sodium

as the dominant cation. On the contrary the anionic composition differs. The lab pore water samples contain carbonates as the dominant anions, in comparison to pore water samples from in-situ experiments, where carbonates supplement also chlorides and sulphates.

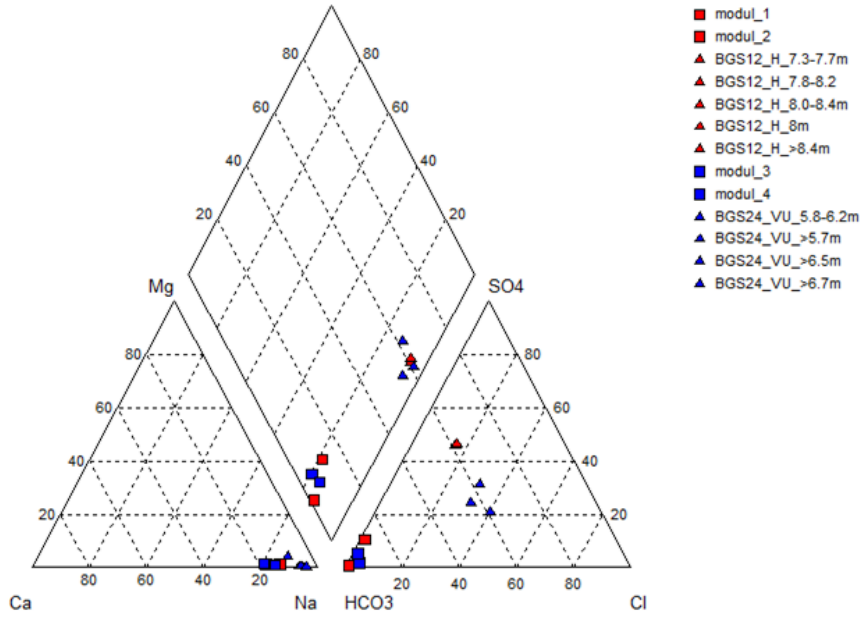

Figure 11 Piper diagram of pore water chemical composition from laboratory experiments (module 1 and 2, 12th level; module 3 and 4, 24th level) and in-situ sampling (BGS12_H, 12th level; BGS24_VU, 24th level; the number at the end stand for the sampling depth)

The software PHREEQC was used for the geochemical modelling representing the three-step equilibrium of groudwater, characteristic for the 12th and 24th level and minerals contained in the representative rock samples (Figure 12).

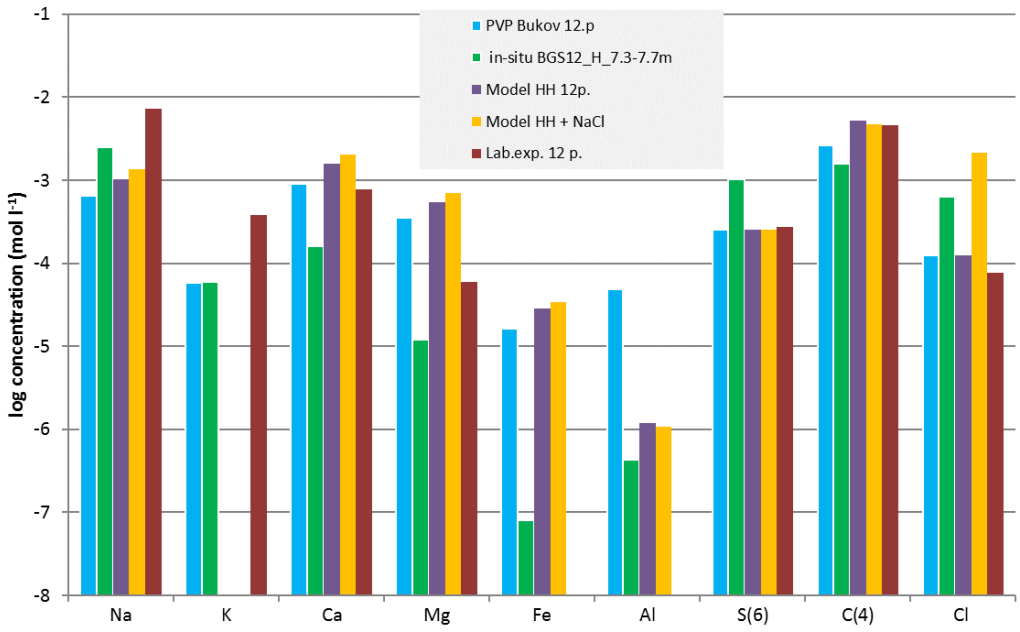

Figure 12 The graf with comparison of out-diffusion experiment with groundwater chemical composition on the 12th level, groundwater chemical composition, sampled in-situ and finally with model representation of water/mineral phases equilibrium (Model HH). Model HH with the additive NaCl steps represents the reaction of equilibrated solution with fluid inclusions/external source of NaCl.

The results can be summarized as follows:

- Evaluation of the chemical composition showed that out-diffusion laboratory experiments did not show consistency with the in-situ sampling, even though they were conducted in the same environment (core vs. well; see results of the analysis in Figure 11).
- Dominant anions in solution, being sampled by the laboratory out-diffusion method, are carbonates. In contrary, chlorides and sulphate suplemment carbonates in in-situ sampled waters. The chloride sources has not yet been clearly clarified. The main sources of chlorides may be biotite/chloritization, saline fossil water or fluid inclusions.
- The chemical composition of the in-situ sampled pore water of the intact rock intervals does not differ dramatically from the groundwater, obtained in opened fractured zones.
- The reliable chemical composition of the pore water from the intact rock intervals should then be derived from the representative number of analyzes (higher number).
- The chemical composition of the pore water samples should be studied with respect to the different types of rock and depth locations. In the case of further studies, we recommend to carry out the sampling more frequently, especially within much longer time period of sampling (e.g. several months – years). Further study of pore water composition would be suitable for determinination of representative geochemical data for safety assessment of DGR.

2.2.3 EDZ characterization

In order to understand the Excavation Damage Zone (EDZ) related to mine works several methods have been used on samples from different mine levels: To study the effect of EDZ on transport characteristics samples from BGS12-H and BGS24-I wells were used and prepared. From the comparison of EDZ samples from 12th and 24th mine levels, it can be concluded that the transport parameters for samples from the 12th and 24th floors are similar. The total porosity in EDZ samples (specifically 0.14 to 0.34 %) is not decisive for the value of the effective diffusion coefficient of tritium $D_{e,HTO}$ (m^2 s^{-1}), but D_e seems to be more influenced by the geometric arrangement and pore shape (geometric factor G). The effect of EDZ is hard to evaluate. EDZ samples have lower diffusion coefficients for both tracers (HTO and $^{36}Cl^-$) than samples from floor horizons and drainage gallery, which is in most cases lower than $D_{e,HTO} < 6 \cdot 10^{-13}$ m^2 s^{-1} and $D_{e,Cl} < 2 \cdot 10^{-13}$ m^2 s^{-1}. The values thus rather reflect the different rock composition and environmental heterogenenity. Small differences between adjacent samples can also be observed depending on the depth (m) of drilled EDZ samples (Figure 13).

Table 2 Comparison of the transport parametres of the EDZ samples and specimen from the floors and drainage gallery

Samples (n) transport parameter	Samples EDZ	Samples – mine level (12–24)	Samples - drainage gallery
ε (%) – median	0,25$_{(16)}$	0,28$_{(18)}$	0,31$_{(4)}$
$D_{e,HTO}$ (m^2 s^{-1}) – median	2,3 · 10^{-13}$_{(16)}$	8,3 · 10^{-13}$_{(18)}$	6,3 · 10^{-13}$_{(4)}$
$D_{e,Cl}$ (m^2 s^{-1}) – median	3,8 · 10^{-14}$_{(8)}$	4,7 · 10^{-13}$_{(8)}$	6,4 · 10^{-13}$_{(2)}$

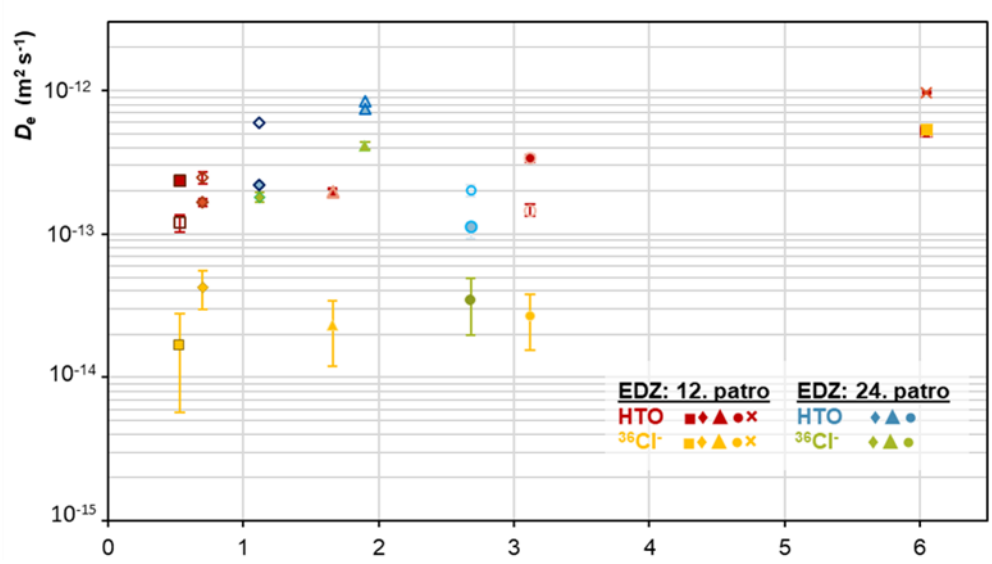

Figure 13 The effective diffusion coefficients (HTO a $^{36}Cl^-$) of the EDZ rock samples in relation to the distance from the top of the borehole

2.3 Influence of the R1 zone and depth on geotechnical parameters

Effect of the R1 zone on physical and mechanical properties (PhMP) and geotechnical properties of intact rocks

Based on the results presented in Chapter 2.3.4 mass properties (i.e. specific gravity and bulk density) of the monitored metamorphic rock clearly reflect their mineralogical composition. Therefore, values of the mass parameters of migmatized biotite gneisses are within the 2680 - 2780 kg.m^{-3} range; of amphibole biotite gneisses around 2800 kg.m^{-3} and in case of garnet amphibolites, they can reach or even exceed 3000 kg.m^{-3}. Accordingly, the obtained values of velocity of ultrasonic waves (UW) and thermal properties correspond to the mineralogical composition of the tested rocks. The UW velocity analyzed on intact rock specimens from the Rožná Mine ranges from about 3.5 to 6.8 km.s^{-1}, thus corresponding to general values of basic rocks and gneisses published, for example, in Milsom (2003). The thermal conductivity coefficient for most of the tested rocks is within the range of approximately 2.5 to 3.3 W.m^{-1}.K^{-1} and is also in conformity with the published data for gneiss rocks (Schön 1983). Except for the biotite quartz to quartzitic gneiss of the large-volume (LV) V-12 sample with λ values around 4.3 to 4.4 Wm^{-1}.K^{-1}, which is clearly related to the dominant quartz content (λ ≅ 7–13 Wm^{-1}.K^{-1}) in this rock.

The total porosity of rocks monitored between the 12th and 24th level of the Rožná Mine, except for the large-volume V-12 sample, is usually below 2% of the rock volume; the open porosity is usually below 0.6% (however, in case of the large-volume V-12 sample up to 1.8 vol%). Values of the effective porosity of most of the tested samples determined by the mercury intrusion porosimetry (MIP) reach approx. 0.1 - 0.5%, exceptionally up to 1%. Water absorption capacity of the studied rocks usually ranges from about 0.05 to 0.25 wt%. Higher density of the rocks is therefore related to lower values of gas permeability and hydraulic conductivity. In terms of laboratory-measured values of the hydraulic conductivity coefficient (in the order of 10^{-11} to 10^{-14} m.s^{-1}), the intact rocks of the Rožná Mine can be characterized as rocks with a very low hydraulic conductivity, for example according to the classification of Singhal and Gupta (2010). Based on the measured values of the gas permeability coefficient, which are in the order of 10^{-17} to 10^{-21} m^2 at a confining pressure of 10 MPa, for example, the studied rocks can be classified as rocks with a very low permeability. However, it should be noted that the permeability characteristics of the rock mass can differ significantly from those of an intact rock sample, depending on the structural fabric of the rock mass (i.e. the frequency of cracks, their filling, crack opening degree, etc.).

The rock abrasiveness of practically all large-volume samples measured by the CERCHAR method reaches an extremely high degree according to the Cerchar abrasivity index (CAI). Paradoxically, the lowest abrasiveness was measured by biotite quartzites to quartzitic gneisses of the large-volume V-12 sample. This was probably caused by the influence of 20 vol% of pyrite (*Mohs hardness*, 6 to 6.5) in the rock.

The compressive strength of the vast majority of the laboratory-tested intact specimens of gneiss rocks from the 12th, 18th, 20th, 22nd and 24th mining level is in the range of approximately 70 to 170 MPa. Rocks of the Rožná Mine can thus be classified as rocks of high to very high strength according to the known classifications of strength (for example, Bieniawski 1989; Hoek and Brown 1997). Average values of the basic *stress-strain parameters*, i.e. modulus of deformation, modulus of elasticity and Poisson ratio, correspond to the measured strength properties and are

similar to values of other crystalline rocks with similar composition and structure. Different values of the modulus of deformation measured at the Institute of Geonics AS CR, v. v. i. and in the laboratories of SG Geotechnika, a.s. can be explained by different methodologies used for the test measurement and evaluation. Average values of the splitting tensile strength are mostly in the 8 to 14 MPa range, occasionally they reach up to 17 MPa.

Based on these results it can be concluded that the measured PhMP values of rocks from the Rožná Mine generally correspond to material properties of crystalline rocks with similar mineralogical composition and genesis (see, for example, Anttila et al. 1999; Kukkonen et al. 2011; Siren et al. 2015, etc.). At the same time, it should be emphasized that a typical feature of rocks in the studied parts of the Rožná Mine is a relatively significant anisotropy of both physical (i.e. velocity of longitudinal ultrasonic waves, thermal conductivity and capacity) as well as of mechanical properties (splitting tensile strength, uniaxial compressive strength). These findings conform with previous findings that were made in other parts of the Rožná Mine, for example within the Bukov URF (underground research facility) construction (Berčáková et al. 2017; Berčáková et al. 2019; Bukovská et al. 2019; Souček et al. 2018; Vavro et al. 2015), and these are generally valid for metamorphites with a markedly developed foliated structure (see, for example, Hakala et al. 2007; Petružálek et al. 2019). It appears that the anisotropy of rock properties increases with an increasing degree of migmatitization of gneiss rocks and increasing size of their grains, i.e. it is directly proportional to the textural anisotropy of the rock.

In addition, the laboratory-determined results presented in Chapter 2.3.4 indicate that the studied PhMP of intact rocks should not depend on the depth of their occurence below the surface or on the distance of the sampling point from the so-called first zone (R1).

The effect of the R1 zone on the rock mass (RM) quality determined by the rock quality designation (RQD) parameter defined on a drill core

Chapter 2.4.1.1 presents the results of the RQD parameter determination on rocks of drill cores from 24 geotechnical boreholes made within the realization of individual geotechnical stations on the 12^{th}, 18^{th}, 20^{th} and 24^{th} levels, as well as on an approximately 130 meters long profile between the GS20/1 and GS20/2 station. Based on the average RQD values determined in the boreholes on the 12^{th}, 18^{th} and 24^{th} level of the R-7S shaft and in relation to the results of previous research activities carried out by the IGN in the Rožná Mine (see, for example, Souček et al. 2018), the average value of the rock mass (RM) of the Rožná Mine ranges from approximately 60 to 65%. With regard to this fact, it can be stated that on the supporting profile on the 20^{th} level of the R-7S shaft, the RM quality was significantly influenced by the presence of the so-called first zone (R1). This can be documented by very low values of the RQD index measured in boreholes drilled at the GS20/1 geotechnical station which is situated in the foot-wall of the R1 structure, very close to the fault plane. Similarly, a significant effect of the first zone on the RM quality expressed by an increase of the RQD index with increasing distance of the analyzed borehole from the described structure was found in four sub-horizontal boreholes drilled for characterization of the excavation damaged zone (EDZ) and situated between the GS20/1 and GS20/2 geotechnical stations. Therefore, the RM quality in the hanging-wall of the R1 structure reaches the RQD values known from other parts of the Rožná Mine first at a horizontal distance of about 40 meters from its roof (Figure 14).

The effect of the first zone R1 on the RM quality is also evident from the number and frequency of fractures analyzed from oriented records of walls of horizontal boreholes on the 20th level. As can be seen in Figure 14, the number of fractures in analyzed length of 15 m in BGS20/1, EDZ20-HB, EDZ20-HC and EDZ20-HD boreholes ranges from 57 to 67, with an average frequency of 3.8 to 4.5 fractures per meter of a borehole; whereas in the BGS20/2-H borehole, the total number of fractures in first 15 meters of the borehole length is significantly lower (i. e. 39) and their average frequency is also lower (i.e. 2.6 m^{-1}). It can therefore be stated that the probable effect of the first zone, as it relates to fracture frequency on borehole walls, extends to a greater distance (about 60 meters towards the R1 hanging-wall) than in the case of the RQD parameter.

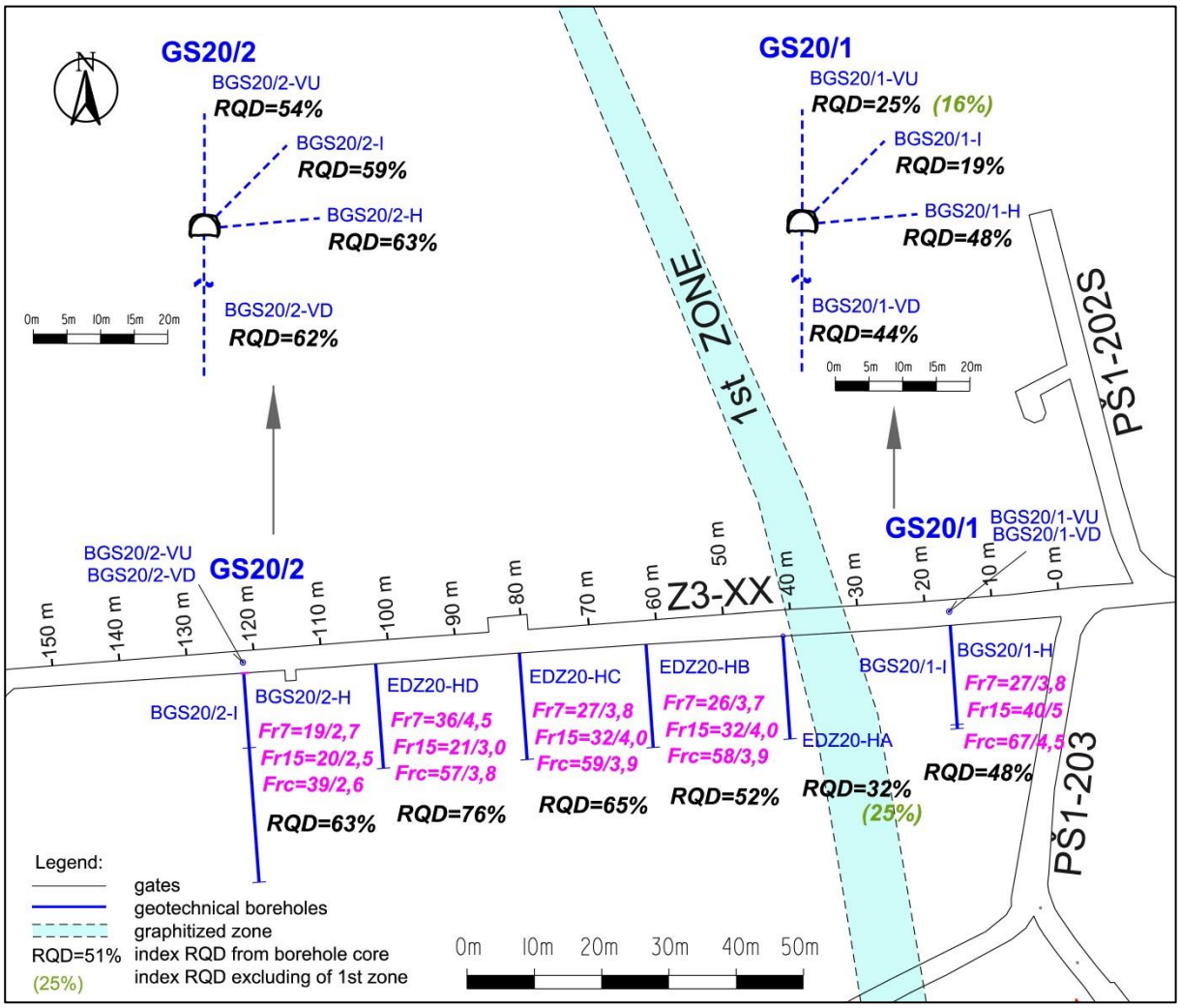

Figure 14 Average values of the RQD parameter of drill core rocks for the entire length of all analyzed geotechnical boreholes on the 20th level and the number and frequency of fractures on the walls of individual boreholes with respect to their position in relation to the so-called first zone (NB: the data concerning the number and frequency of cracks are presented for the distance of 0–7 m from the borehole mouth, distance of 7– 15 m and the entire borehole length of 0–15 m; for example, the record Fr15 = 21/3.0 means that a total of 21 fractures was found at the borehole distance from 7 to 15 m, with an average frequency of 3 fractures per meter)

Effect of the R1 zone on values of the effective porosity determined by the mercury intrusion porosimetry (MIP) method

The results of the pore space characterization of rock samples taken at different distances from the roadway ribside in all 7 sub-horizontal boreholes made for the study of EDZ are presented in detail in Chapter 2.4.7.3.2. Table 3 shows a comparison of values of effective porosity of seven sampling levels determined by means of the MIP method within the pore space characterization. The average effective porosity of the entire borehole is calculated as an arithmetic mean of values measured at individual 1 - 7 sampling levels.

Table 3 Effective porosities determined by means of the MIP method in individual EDZ boreholes

Level / Borehole	1	2	3	4	5	6	7	∅
BGS12-H	0.37	0.28	0.37	0.74	0.45	0.36	0.52	0.44
BGS18-H	0.36	0.40	0.33	0.36	0.49	0.37	0.26	0.37
BGS20/1-H	0.52	0.35	0.44	0.53	0.33	0.80	0.81	0.54
EDZ20-HA	1.67	2.08	2.95	2.56	1.14	2.03	0.79	1.89
EDZ20-HC	1.51	3.38	0.74	0.69	0.57	1.40	0.51	1.26
BGS20/2-H	0.89	0.61	1.23	2.29	0.57	1.63	0.57	1.11
BGS24-H	0.69	0.24	0.50	0.34	0.30	0.32	0.41	0.40

It is apparent from the data in Table 3 that the average values of the effective porosity in horizontal EDZ boreholes on the 12th, 18th and 24th level, as well as in the BGS20/1-H borehole, range from about 0.4 to 0.5%, which corresponds to the results of the porosity determination by MIP made on large-volume samples and in downwards and diagonal boreholes. By contrast, the average porosity in EDZ20-HA, EDZ20-HC and BGS20/2-H boreholes ranges from approx. 1.1 to 1.9%, reaching 3-4 times higher values compared to the values measured in BGS12-H, BGS18-H, BGS20/1-H and BGS24-H boreholes. It can be therefore assumed that the values of effective porosity determined by the MIP method can also be considered as a certain indicator of the first zone effect on the RM properties. However, contrary to the RQD parameter and fracture frequency on borehole walls, an increased porosity occurs even in the BGS20/2-H borehole which is situated in the hanging-wall of the R1 zone, approximately 80 m from its plane.

Effect of the R1 zone on the RQD value determined from a structural-geological mapping made on the opening wall and effect of the R1 zone on the rebound value determined using the Schmidt hammer; the R1 zone effect determinable using a video-inspection of boreholes

Results from in-situ measurements, i.e. from geological mapping on opening walls of sections of interest, including rebound measurements using the Schmidt hammer are described in Chapters 2.4.2.1 and 2.4.2.2. Based on these measurements, profiles of the RQD values, fracture frequency development and rebound values were created which are also presented in the above-mentioned Chapters of the Final Report. The most important profile for mapping was located on the 20th level. The profile was approximately 100 m long and crossed the R1 zone. Measurements and profiles on other levels, which were not directly affected by the R1 zone, were primarily used for reference purposes with value profiles on the 20th level.

The mean value of the RQD parameter based on data from the geological mapping on GS12, GS18 and GS24 ranged in the interval of 74 ± 8%. The RQD on the profile reaches this range of values approx. 17 m behind the R1 zone. Further out from this distance, the RQD parameter reaches the values typical for RM in the area of interest.

Based on the analysis of the development of the fracture frequency value, obtained from data of the structural mapping at GS12, GS18 and GS24, the mean fracture frequency value was set in the range of 8 ± 3. To determine appropriate values of the fracture frequency, we used the value of a higher and softer limit of this interval, i.e. 11, considering RM not affected by the zone. It can be stated that below this limit, RM is approaching the standard conditions of the Rožná Mine, i.e. rock mass, the properties of which are not affected by the first zone. Approximately 26 m away from the R1 zone, the fracture frequency values on the profile on the 20th level reach values below the defined limit of 11. Further, out from this distance, the frequency values are below the above-mentioned limit in more or less 95% of cases.

Based on the analysis of the evolution of rebound values measured by the Schmidt hammer in GS12, GS18 and GS24, we have confirmed that the increased fracture frequency and fracture density at the point of measurement by the Schmidt hammer affect the resulting rebound value. In the areas with a higher fracture frequency, the rebound values ranges from approx. 10 to 30. In sections with a smaller number of fractures, the rebound values range from approx. 30 to 60 - these represent more compact sections of the rock mass. In these geotechnical stations (GS), the values are rather within the second interval; only locally, they reach the values of the first interval. The rebound values measured on the 20th level clearly show that the rebound values in the profile achieve the values of the 30 - 60 interval approximately 16 m behind the R1 zone; only locally, i.e. in short sections, the values are lower. The evolution of the rebound values shows the obvious effect of the first zone (R1) on the rock mass quality even in the direction to the footwall, up to a distance of about 7 m from its base.

In addition, the effect of the R1 zone on the rock mass quality was confirmed by video-inspections of the boreholes. Results of the video-inspection analysis shows that in the EDZ20-HA borehole, which is closest to the R1 zone, the borehole walls were significantly damaged and its circular profile was not preserved (due to overbreaks, irregular shape, etc.) at about 66% of the borehole length. At approximately 26% of the borehole length, the walls were smooth and the circular profile was more or less preserved; however, the walls were damaged by breakup due to fractures, etc. In the EDZ20-HB borehole, which is located 20 m further from the R1 zone than the EDZ20-HA borehole, the circular profile was damaged only at about 2% of the borehole length, about 10%

of the borehole length was damaged by breakup. At about 88% of the borehole length, the walls were smooth and the borehole showed a regular circular profile. The walls of the EDZ20-HC and EDZ20-HD boreholes, located a further 20 and 40 m from the R1 zone, were also smooth and the boreholes had a regular circular profile at about 97% of their length. The geotechnical boreholes on the 20th level in the GS20/2, located approx. 80 m away from the R1 zone, also showed smooth walls with a perfect circular borehole profile at about 95 to 100% of their length. The boreholes in GS20/1, located about 10 m away from the R1 zone in the footwall direction, showed smooth walls with a regular circular borehole profile at approx. 61 to 90% of their length. Borehole walls were damaged by breakup due to fractures at 10 to 16% of the borehole length.

Correlation between depth and geotechnical parameters

The correlation between depth of the samples and their mechanical and physical properties determined by laboratory test was not observed. The higher grain density (density of solids) and bulk density of samples from 24TH floor was caused by its different mineralogical composition. The rock was described as amphibolite. Other tested rocks were classified as migmatitized paragneisses. Higher uniaxial compressive strength and deformation modulus were observed on samples loaded parallel to its foliation in comparison to samples loaded perpendicularly. The results of Brazil tests show that tensile fracture created in the foliation plane has a lower strength than the fracture, which is oriented perpendicularly to the foliation. The laboratory material parameters were not influenced by the presence of fault structure. The heterogeneity of studied migmatitized paragneisses is more considerable than the influence of fault zone.

2.4 Influence of the R1 zone on structural elements and homogeneity of rock environment

Study of rock failure near fault structures (Fault Damage Zone – FDZ), accompanying their origin and development, is one of the key topics of geotechnical and structural geological fields. Over the past few decades, significant progress has been made in identifying different types of FDZ and characterizing the various structures constituting FDZ (Kim et al. 2004; Choi et al. 2016). However, deformation mechanisms and factors affecting the thickness and morphology of FDZ are still not fully understood. Moreover, FDZ and generally fault structures and their origin and development are almost exclusively studied in as homogeneous rocks as possible (e.g. young granites and sediments not affected by older or younger deformations than studied faults) and for purely brittle deformation conditions.

The FDZ can be defined as the area around a fault surface in which rocks are deformed as a result of initiation, propagation and movement on the fault (Segall and Pollard 1980). In general, FDZ can also be described as a zone in which there are a greater number of accompanying fractures than in the surrounding environment outside the impact of the fault zone (Riley et al. 2010; Choi et al. 2016). A great deal of work has emphasized the FDZ's dependence on magnitude by displacement on fractures, its length, kinematics and temperature-pressure conditions (Evans 1990; Knott 1994). These parameters, together with lithology, structure and associated diagenetic processes are the most important for determining FDZ configuration.

While the core length and thickness of the studied tectonic zone are relatively well established (up to 15 km; Kříbek and Hájek 2005), the depth and kinematic conditions in which this zone originated are uncertain. The ore zones of the Rožná Mine were interpreted by Kříbek and Hájek (2005) as left-side transtension structures, but due to poor uncoverability, absence of clear correlation horizons and multiple reactivation, conditions and kinematic framework of tectonic zone formation can be estimated only on the basis of known geological development of wider surroundings. The minimum age of the zone formation was determined as Permian based on fault fill dates (300–290 Ma; Kříbek et al. 2009; Bukovská et al. 2019). This age represents the age of mineralization and alteration in the zone and the actual formation may be considerably older. Ditch structures with normal sense of movement of Permian age (e.g. Boskovice and Blanice trench) have the same directions (NNE – SSW) as the studied first zone, but it is probably a later extensive reactivation of older shear zones of the core scale. The sense of movement of these significant localized deformation zones is considered by most authors as right-sided (e.g. Pitra et al. 1999; Žák et al. 2011). The closest example of such a structure is the nearby Přibyslav Mylonite zone interpreted as a significant right-side transpression structure active at approximately 330 Ma (Verner et al. 2006; Žák et al. 2011). In general, these late Variscan shear zones are considered to be a manifestation of the gravitational collapse of a thickened orogenic root (Schulmann et al. 2014). Given the overall structural framework of the area, orientation, thickness and fill pattern of the studied first zone, it is very likely that this zone represents a primarily analogous smaller scale structure. Based on assumed age and depth, it is certain that this deformation zone was more brittle-ductile than purely brittle (Gueydan et al. 2004). The shear zone itself and its accompanying structures intersect or reactivate older metamorphic structures. Later deformation development was manifested by polycyclic brittle reactivation, mineralization and alteration. These loaded processes caused the current configuration and character of the zone and its surroundings.

Determining the conditions of the formation of the first zone and its character is important not only from the genetic point of view, but is also crucial for determining its resulting impact on the rock massif. The primarily semi-ductile character of the studied fault zone does not allow the determination of FDZ as in the case of the purely brittle fault zones described above. In contrast, ductile to brittle ductile deformation zones in their immediate surroundings manifest themselves with decreasing intensity of related deformation (Ramsay 1967). The character of the deformation around the zone itself depends primarily on temperature conditions and rheological properties (Passchier and Trouw 2005). Various types of accompanying plastic-to-brittle deformation mechanisms, especially in microscale (dynamic recrystallization to microfracturation) may occur in the zone of affection around the brittle-ductile deformation zone (Passchier and Trouw 2005). In general, brittle mechanisms are more pronounced with decreasing temperature, greater intensity and rate of deformation, fluid pressure, etc. The intensity and proportion of different deformation modes will be considerably heterogeneous depending on the location of individual phases, deformation localization and, above all, predisposed structure.

Based on new field observations, results of structural studies and evaluation of the overall tectonic context, we believe that the studied fault zone is a hybrid type. Due to the younger polyphase reactivation and intensive alteration in the core of the zone, its primary structures are completely reworked and its original character cannot be accurately determined. However, it can be assumed that the thickness and morphology of the damage zone will be a combination of the spatially highly variable FDZ for fault zones (Kim et al. 2004; Choi et al. 2016) and the relatively regular region of the accompanying diffusion deformation for purely ductile zones (Montesi 2007).

The influence of the first zone (R1) on the structural record, primarily focused on the brittle rock mass failure, was studied in terms of frequency and orientation of macroscopic fractures. The intensity of rock fractures in the areas of the Rožná mine with respect to the first zone was studied by statistical processing of brittle structures recorded in archive mining maps and also from the obtained structural data. The archival data were processed in several galeries in intersections with the first zone (but often the fourth zone). Changes in orientation of larger brittle structures were also monitored, obtained indirectly from photogrammetric models depending on the distance from the first zone. The performed works thus enable to obtain at least an approximate idea of the character, intensity and extent of the impact of the rock massif by the first zone and accompanying disorders.

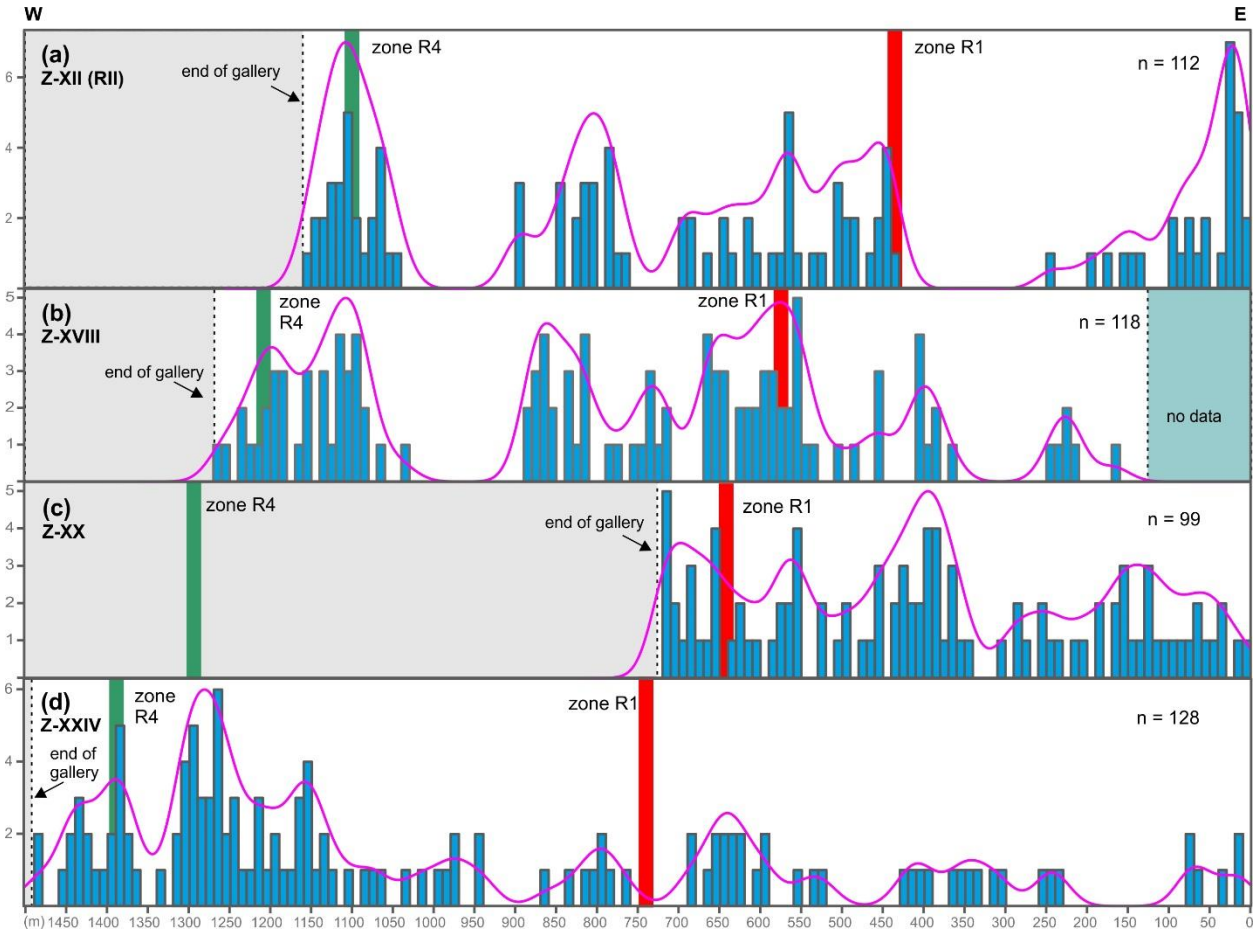

Figure 15 Histograms of frequency and Kernel density distribution of brittle fractures in galleries west of pit R-3. The data were taken over from archival geological maps of scale 1: 200 000. The interval width is 10 m. The localization of the first and fourth zone is taken from the conceptual 3D model

Frequency analysis showed that both failure zones are in most cases manifested by an increased incidence of documented structures. An increased number of failures usually occurs in the range of 40-120 m around the zone itself. However, there is a number of significant frequency maxima in the histograms, that are not near the monitored zones, e.g. in Figure 15. Surprisingly, in some cases the highest failure density is at the site of the failure zone. In addition, in several galleries at the locations of these zones, there was no above-average occurrence of brittle structures or no disturbances were recorded at the locations of the first zone in the map. This may be due to non-systematic documentation, but especially because partial failures within the zones are not documented and are included in the thickness of the zone where the distortions are located, which will then appear as a single disturbance.

The study of spatial changes in the orientation of brittle structures was carried out in three domains throughout the studied part of the mine. Given the limited possibilities of observing the direct relationships of individual structures with the zone itself, determining their genetic relationship with the zone is very problematic. We assume that subparallel failures with the orientation of the first zone occurred in the same stress field and during the same phase of deformation development of the area. Systematic statistical processing of fault orientations depending on the distance from the first zone revealed that in the northern part of the mine with

increasing distance from the zone (into the subsoil) there is a significant increase in structures with a sub-parallel zone. A similar trend can be observed to a lesser extent in the southern part of the mine towards the overburden. This gradient can be interpreted so that in the immediate vicinity of the fault zone, during the fault activity of the first deformation zone, it was largely localized to the zone itself. On the other hand, separate failures occurred at greater distances from the zone at the same time. The occurrence of these failures, which are kinematically consistent with the first zone is not uniform throughout the study area and is rather highly localized, which may also be closely related to different lithologies and their frequent changing, which leads to different mechanical properties of the rock mass. Kinematic structures consistent with the first zone were documented to greater extent only in the 30–120 m subsoil of the first zone and in the central part in the 180–210 m subsoil of the first zone. In the middle part of the mine, the data are available only in a section 120 m from the border of the first zone.

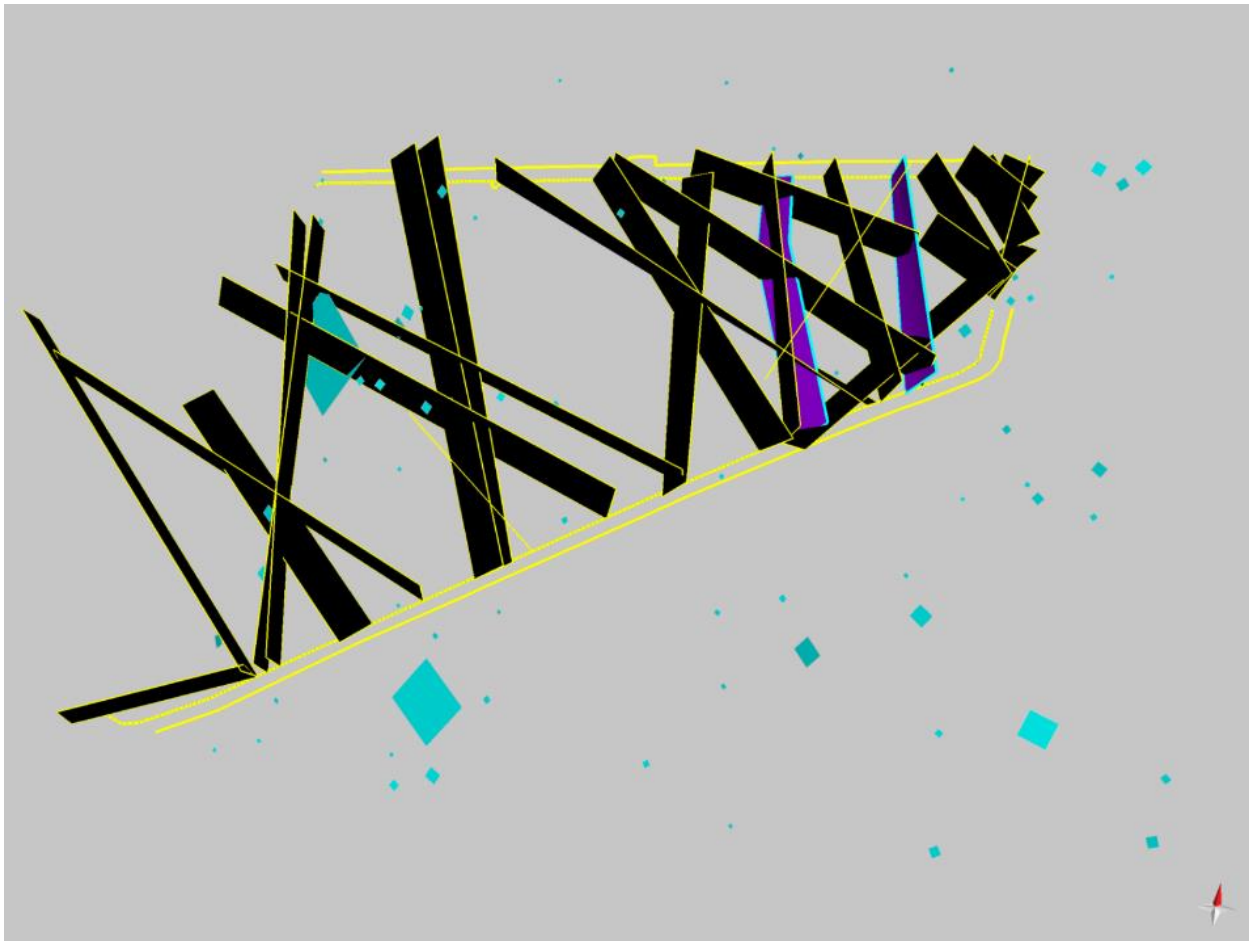

Figure 16 Visualization of the fracture network in a model of the block and of the designed reconstructed structures obtained from the structural documentation of the block (the strike of the galleries delimiting the studied block in yellow; black – fractures documented in-situ, magenta – range of the first zone)

Analysis of the DFN model on the 20th floor in a quasi-homogeneous block based on structural data shows that the least represented are semi-parallel structures with the first zone and N-S striking structures associated with the E-W extension (Figure 16). The modeling results are thus in agreement with other structural observations from the Rožná mine.

The orientation of the other maxima of the more significant brittle structures is kinematically inconsistent with the ~ E – W oriented extension, during which the normal sense zones of the N – S strike occurred. These structures were established at the latest in the Permian (Bukovská et al. 2019; Kříbek et al. 2009). This concept is fully in line with the widely accepted concept of the Upper Palaeozoic development of the Bohemian Massif as well as of Central European Variscides (McCann 2008). With the vertical shortening, it is possible to correlate unevenly developed extensional subvertical fractures of the N – S strike, which are relatively thin, often have a calcite fill and are closed. These fractures usually do not form a morphological edge on the walls and therefore are not significantly included in the data indirectly obtained from photogrammetric models. However, this fracture set does not represent important elements significantly reducing the homogeneity of the rock environment due to its size, character and fill. Other macroscopic structural elements, such as older metamorphic foliations or shear structures belonging genetically to other phases of brittle deformation development, are often open and aquifers. In terms of homogeneity of the environment, apart from the first zone itself, macroscopic structures that are not related to the formation and activity of the zone are more significant.

Processing of archival and new structural data related to the first zone has shown that the spatial distribution of the accompanying structures is very heterogeneous and varies with depth as well as along the strike of the zone. The results of spatial evaluation of failure orientations are in contradiction with the increased occurrence of brittle structures in the location of the zone in archive maps. This discrepancy is partly due to the inhomogeneity of the archive data file, and it can be assumed that the first zone does not actually significantly influence formation of new macroscopic brittle structures out of it´s range. Further, this discrepancy can be explained by a reduction in the strength of the microscopic fractures around the first zone and a more intense failure of this region by younger deformations. The results of geotechnical tests, seismic refractive tomography and HHB characterization showed that the rock environment around the zone (approx. 50–60 m from the zone) shows a significant decrease in strength parameters. This phenomenon is associated with the origin of an interconnected network of intergranular microfractures typical of the immediate vicinity of deformation zones (Choi et al. 2016; Scholz 1968; Vermilye and Scholz 1998). The small number of synkinematical failures near the first zone can also be explained by the dominant localization of the deformation into the mechanically weakened zone. At the same time, the greater impact of the rock mass by the presence of intergranular and intragranular fractures may result in later formation of fractures with kinematic different orientations in such a weakened rock mass. This is also important for the number of fractures that reactivate foliation in the complicated and folded environment of the Rožná Mine. If intergranular microfractures are preferentially occurring along phyllosilicates, where they commonly use basal surfaces (see confocal microscopy in Chapter 0), i.e. areas parallel to foliation, it will very commonly be easier to develop fractures along these foliation surfaces, although they may not be precisely oriented at the given stress field.

In addition to the zone itself, the deformation phase in which the first zone was formed does not substantially manifest itself in the rock environment by the formation of macroscopic brittle failures. Except for in some places, structures that are kinematically consistent with the given

stress regime are not significant. The deformation was realized mainly by formation and movement in relatively localized fault zones. More significant is probably the influence of the first zone in the microscale. The associated formation of a microfracture network and an increase in intragranular and intergranular porosity around the zone will reduce rock strength and facilitate macroscopic failures during subsequent phases of the brittle deformation development of the massif. This is also confirmed by the measurement of porosity, the value of which decreases with distance from the first zone, as shown by GS samples on the 20th floor.

From the point of view of the study of the structural record, the results show an apparent microstructural effect of the fault zone on their surroundings, especially on the predisposition to localization of loaded (i.e. younger) deformations. A more detailed understanding of the mechanism and scope of accompanying mirofracturation and its impact on the weakening of the zone surroundings would require follow-up microstructural research to a much wider extent.

2.5 The R1 zone and its influence to rock massif according to the results of seismic methods

Manifestation of the main fault zone R1 (also called „First Zone“) is very significant in results of geophysical survey of rock massif. Seismic methods were the prevailing part of the geophysical survey, these methods describe the rocks based on the detected velocities of seismic wave propagation. Fault structures are manifested, among other things, by intense fracturing of affected rocks. Consequently, the seismic wave propagation velocity is decreased compared to intact rock environment. The undertaken geophysical survey tries to contribute to the answer to the question of at what distance from the main fault structure is it possible to observe its influence on rock properties represented by seismic velocities.

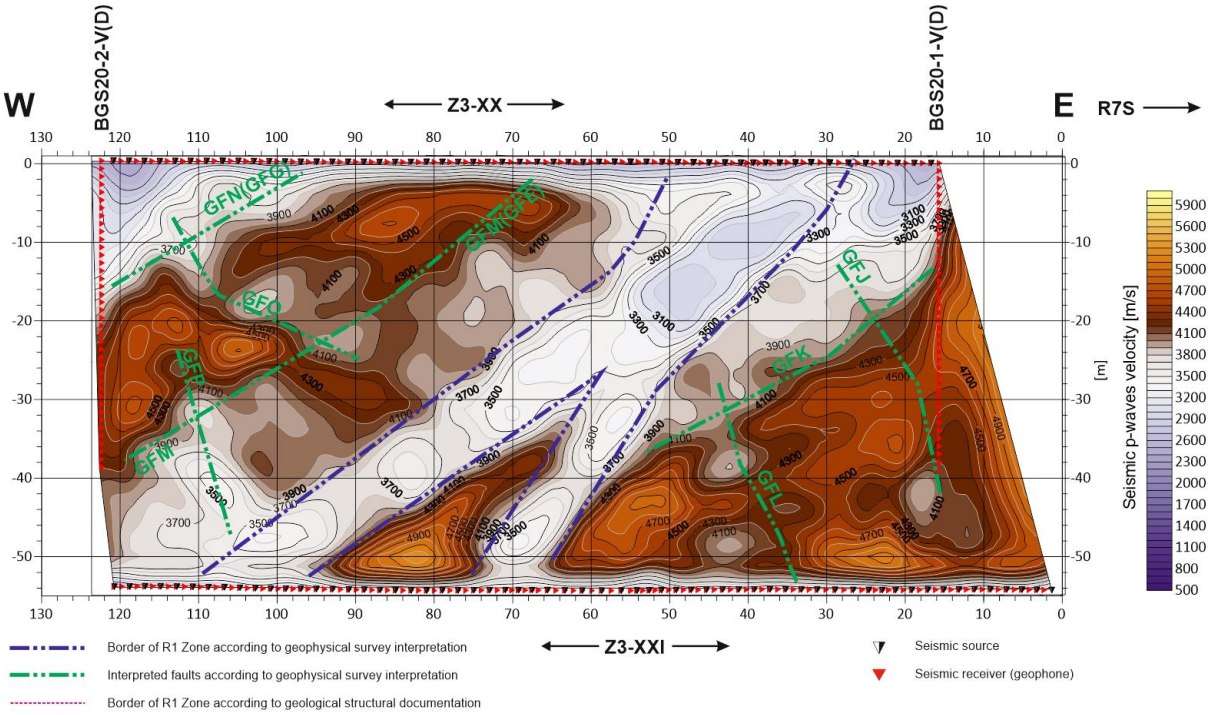

Figure 17 Vertical seismic tomography section obtained between the levels of 20th and 21st floor

Tomographic sections obtained by survey at the level of the 20th floor give an idea of the distribution of seismic velocities around the R1 zone. Figure 17 shows the tomography section, which represents velocity distribution in subvertically oriented block between levels of 20th and 21st floor of the mine. Figure 18 shows the tomographic velocity section oriented in horizontal plane, this section shows the result of the seismic tomography survey of horizontal block at the level of 20th floor. The R1 zone could be defined quite clearly in both sections. The wanted answer is identical with determination of the range of lowered velocities surrounding the R1 zone.

The examined border of the lowered velocities area could be identified in position of structures marked as GFK in the eastern part of the subvertical section in Figure 17. The boundary of the lowered velocities in the western part of the section is identical with the line marked as GFM. In terms of distances, the eastern boundary of the influence of the R1 zone is positioned in the distance of about 15 m from the R1 zone. This distance is observed on the level of 20th floor,

towards the deeper part of the section this distance decreases and the line GFK coincides with the edge of the R1 zone. There is no transition area at the level of the 21st floor, the boundary between the R1 zone and the unaffected rock massif is sharp. The situation is slightly different in the western part of the section, the transition area of lowered velocities located between the R1 zone and GFM line could be observed along the entire R1 fault line. The thickness of this lowered velocities area is about 12–17 m according to the velocity section. A similar thickness of the R1 zone influence was found by RQD observation and joint detection determined by structural geological survey. Rebound (reflexivity) determination measured with Schmidt hammer brought similar conclusions.

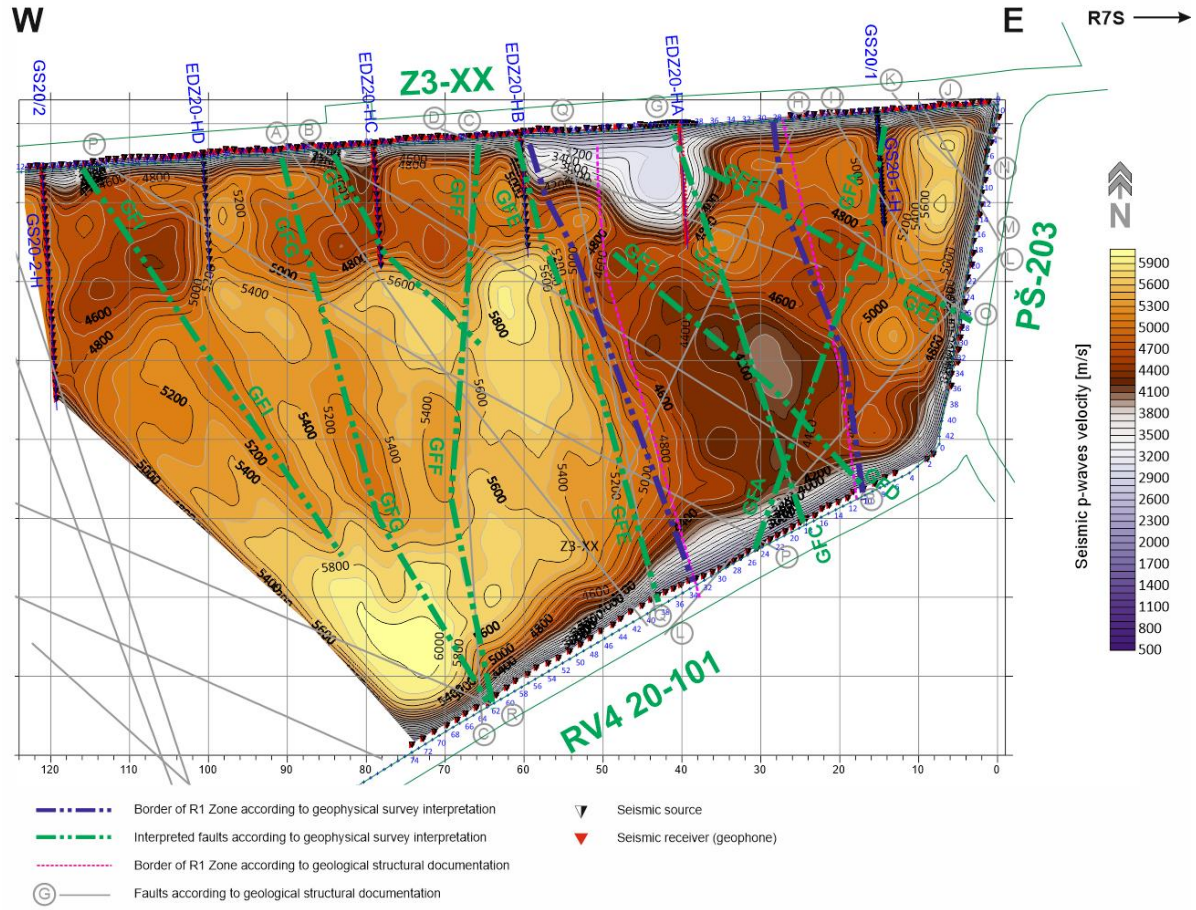

Figure 18 Horizontal seismic tomography section obtained at the level of 20th floor

Determination of low velocity zone and its boundary is not unambiguous in the area east of the R1 zone as well as specifying of the R1 zone influence range according to velocity distribution shown in horizontal tomography section for the level of the 20th floor (Figure 18). The boundary of unaffected rock could be with certainity identified with line connecting points in positions 12 m in gallery Z3-XX – and position 36 m in gallery PŠ-203. The range of R1 zone influence in western part of the section is well determined by line GFE (which is identical with line GFM pictured in vertical tomography section in the Figure 17). The range of influence in the gallery Z3-XX level is about 13 m. This range is lower in the masiff, the farther from the Z3-XX gallery towards the RV4

20-101 gallery, the less the range of influence is. It decreases gradually to the thickness of 5 m and stays on this level in the area close to the RV4 20-101 gallery.

A detailed tomographic velocity section obtained in the surroundings of the EDZ20-HB borehole drilled into the wall of Z3-XX gallery is shown in Figure 19. Significant velocity contrast between the eastern and western part of the section could be seen in the section. Border of R1 zone is interpreted on the stationing 59–60 m according to seismic tomography. Geological border of the R1 zone is determined on the stationing 51 m.

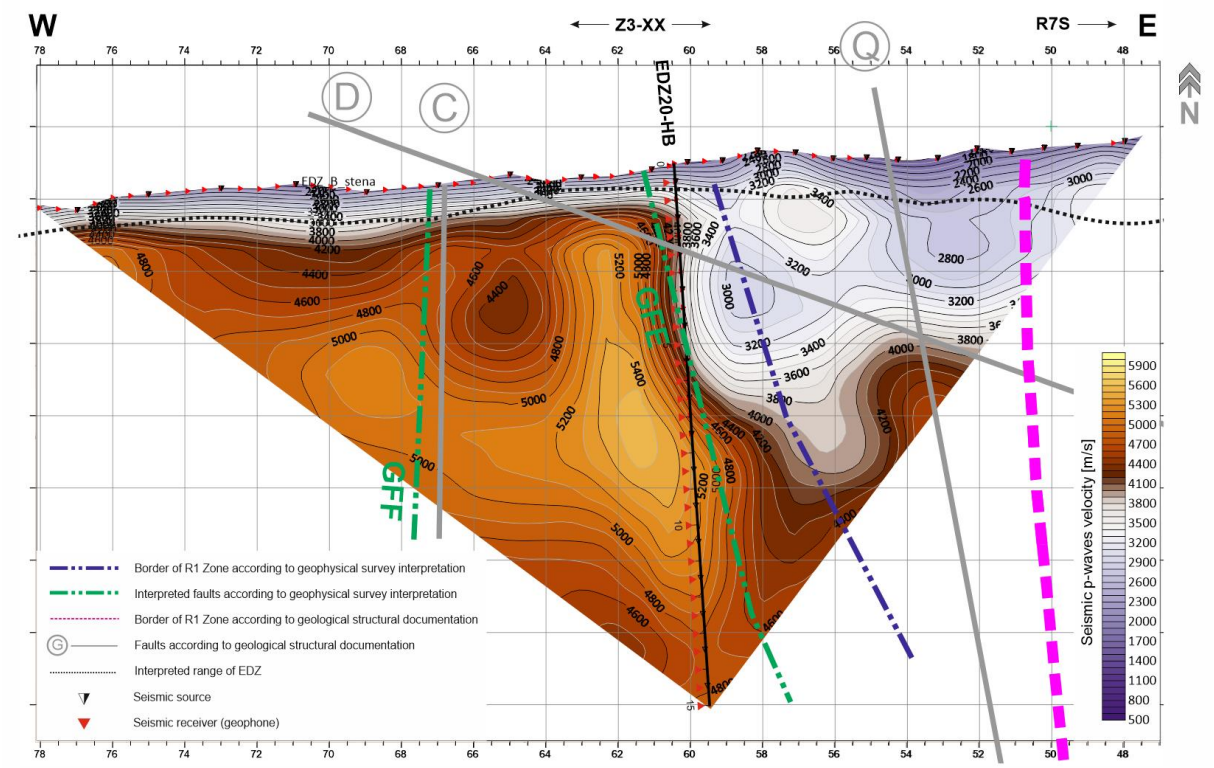

Figure 19 Tomographic section obtained in EDZ20-HB borehole surrounding, seismic tomography between the borehole EDZ20-HB and the wall of Z3-XX gallery

3 Implications

The study coveder broad spectre of methods and topics, which all relate to the deep underground repository siting and safety. As such, following implications for deep repository safety were concluded:

Geotechnical characteristics

Comprehensive assessment of rock properties with all available laboratory methods focused on a deep geological repository for radioactive waste is the main merit of this work. Porosity is the dominant parameter, which influences hydraulic, mechanical and physical rock parameters. Pore space visualization by different methods was studied for example by Autio et al. (1998), Degueldre et al. (1996), Hellmuth et al. (1999) and Menéndez et al. (1999). These methods which differs from the widely used water gravimetry are recommended for further rock porosity study. Confocal microscopy, which was used in this study, is suitable method for pore space geometry changes. The influence of heat on rock' hydraulic parameters is other important topic. Water dynamical viscosity decreases with increasing temperature, moreover rock thermal expansion occurs which is accompanied with microcrack closure and hydraulic conductivity decrease. The structure and mechanical parameters of rock are influenced by raised temperature (for example Chaki et al. 2008; Reuschlé et al. 2006; Takarli et al. 2008). This phenomenon could be evaluated by ultrasonic scanning. We suggest to subject laboratory samples to thermal stress and then to compare the results with unheated samples. This comparison could help to satisy safety of partially filled deep repository during its operation. The assessment of acoustic emission during uniaxial compression is suitable for completion of laboratory study of mechanical parameters (Heap et al. 2009). This method together with microscopy could determine localization and shape of shear planes. The transfer of knowledge from laboratory studies to in situ conditions is crucial. The results of Schild et al. (2001) and Ota et al. (2003) show that the porosity of borehole cores increases up to three times than identical rock in situ due to the load reduce. We suggest injecting the in-situ rock by resin. Subsequent pore space visualization could contribute for example to clarification of radionuclide diffusive transport.

Considering the above mentioned, one could recommended:

- Pore space geometry change observation on a sample series with different damage grade and thus clarification of structural component formation observed at the macroscale
- Assessment of acoustic emission for shear planes localization
- Study of the effect of temperature on rock mechanical and physical parameters using comparison of thermally stressed and unheated samples
- Assessment of acoustic emission for shear planes localization
- In-situ resin impregnation

The following recommendations and issues concerning other possible research activities within the process of preparation and construction of the DGR have arisen from the results obtained during the project solution.

In the area of the laboratory-determined physical and mechanical, and geotechnical rock properties (PhMP):

- A more detailed study of effects of the structural anisotropy on rock properties,

- Effect of loading on rock PhMP changes; for example, the velocity of ultrasonic waves,
- PhMP testing under conditions, which correspond more realistically to the state of the rock mass; for example, the effect of humidity on PhMP values.

Geotechnical works in situ:

- Research into stress conditions of the rock mass (RM) by methods covering a larger area of the rock environment interests, including the time aspect; for example, observation of shape changes of boreholes (ovalization) and excavated mine workings in time, creation and development of breakouts in time, application of a method of the inverse analysis of convergence measurements of deformation of mine workings and boreholes, or RM deformation in the zone in front of the underground openings, etc.
- Verification of the relationship between the RQD parameter measured on a drill core and the RQD parameter measured by the so-called alternative methods (for example, OPTV-OBI, HiRAT-ABI, structural mapping) on other petrographic rock types than gneisses, migmatites or amphibolites.

EDZ:

- EDZ analysis based on permeability of RM in situ, measured at different distances from the excavation wall, taking into account the development of permeability in time.

Effect of important tectonic structures:

- The determined extent of influence of the R1 zone on the rock mass should be investigated on another structure and in different rock environment in terms of the lithology or structural pattern.

Rock transport characteristics

The study of rock transport characteristics were studied by means of extending the set of transport parameters, namely sorption (distribution coefficient Rd) and diffusion parameters (eg. effective diffusion coefficient D_e), which are important for safety assessment of DGR. The study revealed that the rock lithotype plays the most important role for the characteristics, entering the safety assessment. Moreover, the effect of anthropogenic activity (EDZ) is thus diminising. Anionic diffusion was confirmed for metamorphic rocks from the Rožná mine.

The study of parameters was focused mainly on the characterization of the rock itself (rock matrix). For the migration of radionuclides, however, the properties of the fractures, in which the transport predominantly takes place, are important and they are often filled with secondary minerals. Furthermore, based on the characterization of the rock environment (hydrochemistry, determination of solution composition in rock massif) it can be assumed that in-situ conditions for migration (Eh, pH, groundwater and pore water chemistry) will differ, both in relation to rock type and to the depth.

Assuming that the Rožná mine is one of the few available sites where it was possible to obtain samples from depths corresponding to the position of the SNF in the DGR, and for other localities, no samples from the depths more than 100 m are available, there are following potential topics to be considered within the future activities:

- Determination of the transport properties (sorption, diffusion, porosity, CEC, etc.) for rocks from depths corresponding to the depth of the repository (potential sites)
- Determination of the transport properties (sorption, diffusion, porosity, CEC etc.) for fracture fillings (URF Bukov, potential sites) and study of the influence of individual minerals on the retention of the radionuclides. Fracture fillings can play a significant role in the retention of radionuclides and it becomes a too conservative approach without being included in the safety assessment.
- Study of the influence of pore space and the structure of diffusion pores as an important parameter that has a significant effect on the diffusion of radionuclides in the rock (URF Bukov, potential sites)
- Long-term study of the pore water / stagnant water in the rock massif. The available methods for determination of the pore water are unique and very difficult to repeat. Concerning that, prolonged sampling period from the rock massif should be used in stagnant water regions.
- Long-term in-situ study of geochemical conditions in the rock massif (long-term hydrochemical monitoring, pH, Eh, water composition, gases in the massif, etc.)

Description of structural elements

The results of the structural analysis show that within the studied profiles across the first zone, there are areas of increased fracture rates 40-120 m from the core of the zone. In addition, the study of geotechnical parameters and geophysical work indicate an area of approximately 50 m of reduced rock quality from the core of the zone. The results of confocal microscopy indicate the presence of a network of microscopic fractures, but one study sample does not allow determining the possible gradient of the observed microfracturation and its relationship to the study zone. The observed increased incidence of macroscopic failures in the immediate vicinity of the zone may be due to the preferential occurrence of loaded structures in the affected area by varying degrees of microfracturation potentially associated with zone formation. In this case, the zone / zone of influence around the first zone would consist primarily of a microscopic scale fracture system that caused mechanical weakness around the zone utilized by younger loaded deformations. Unfortunately, we are unable to determine with certainty whether the failure observed around the zone has a direct genetic relationship to the formation of the structure itself, its later reactivation accompanied by intensive hydrothermal processes, or a completely different loaded deformation. Subsequent deformations, in the case of suitable orientation of the stress field, dominated by reactivation of the first zone with a lubricated thick secondary fill (clay minerals, graphite). Loaded younger failures could only arise in a relatively narrow range of stress orientations that precluded reactivation of the zone and existing metamorphic structures. The reconstruction of the deformation development of the first zone and its surroundings is significantly complicated by the presence of a complex folded structure of metamorphic fabric representing differently oriented areas of pre-existing mechanical anisotropy (Figure 20).

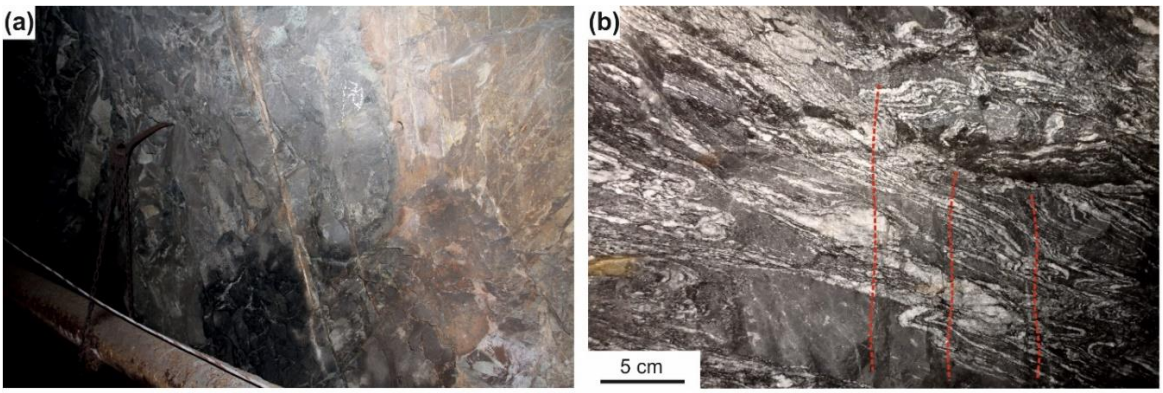

Figure 20 (a) Shear fracture filled with calcite, chlorite and clay (18th floor, R-3); (b) extensional fractures filled by calcite (red)

The study of deformation zones and their manifestations on the surrounding rock massif is currently one of the more complex challenges of structural geology (Carreras et al. 2013; Misra et al. 2015). These metamorphic structures were reactivated during the formation and subsequent polycyclic development of the first zone, causing a significant local disturbance of the stress field and deformation in the rock massif.

The uncertainty of determining the zone of influence around the studied zone is also because of the newly detailed corridors crossing the zone represent only one section (around the pit R-7S). In the case of the more complex FDZ shape typology typical for wedge-shaped FDZ deformation (Segall and Pollard 1980), it is not possible to determine in which part of the fan-shaped FDZ the vertical section of the R-7S is located. In this case, the maximum thickness of the zone of influence around the study zone can be significantly greater. Due to the unresolved characteristics of the studied zone described above and the genetic relationships of the documented structures in its vicinity, it is not possible to determine the exact thickness and shape of the influence zone clearly based on the available data. A more detailed understanding of the origin and development of such a tectonic zone and zone of influence requires further detailed research. In addition, the studied zone represents a very specific structure by its primary nature and secondary mineralization and tectonic development and the acquired knowledge cannot be directly applied to tectonic lines of a different type. On the other hand, it can be assumed that similar reactivated polyphase primary ductile to brittle-ductile deformation zones are relatively common in the Bohemian Massif. Understanding their origin, development and environmental impact is very important for the DGR site selection.

Therefore, the following topics can be recommended for further studies:

- Definition of influence on the environment and deformation manifestation of individual types of failures (brittle vs. brittle ductile and ductile) according to their origin and unification of used terminology according to the nature of structures;
- Study of a sufficiently simple case of rock mass failure by different structures (see previous point) in the most homogeneous environment (e.g. undeformed granites) to define the extent of massive impact by structure, orogin, significance and differentiation of loaded younger deformations. The optimal variant would be a comparison of different types of failures in different rock massifs (e.g. Alpine vs. Variscan) with a different amount of

deformation phases recorded. These data may not be obtained from a greater depth, but current research shows that they can be well used for the depth level of HÚ.
- Clarification of relationships between individual brittle or brittle ductile structures and their spatial extent.

Fracture network modelling and 3D geological structures

Understanding the geometry and properties of fracture networks is an important part for assessing the safety of the planned repository. The fracture network can serve as a preferential path of solutions from the depth of the repository and indicate the geometry of these paths for subsequent hydraulic modelling. In this project, a fracture (DFN) network was created from data obtained through structural documentation, enhanced with key elements for the follow-up DFN modelling (high level of detail, unique structures ID, structure termination). This creates a robust dataset when incorporated into 3D rock wall models (f.e. Figure 21), which describes the structural character of the brittle fracture of the study area. This procedure is applicable in practice to any underground work whose walls are sufficiently exposed. Structural documentation and taking photos for 3D model creation can be done in stages (e.g. during excavation) even under low light conditions. The DFraM program suitably optimized the input of structural data and the simulation of the optimized parameters was almost identical to the data obtained from the structural documentation of corresponding galleries. Based on optimized parameters, 3D DFN models were created in both native * .vtk format and MOVE format, which is used for 3D modelling of geological models. Their results were identical and both variants can be used in the future. A sufficient amount of data (hundreds of measurements) is crucial for the creation of a representative DFN model, which may limit its use in large areas with insufficient data. In the future, it is necessary to solve the use of drilling data, their interconnection of 1D (borehole), 2D (crack traces) and 3D (structure) documentation so that it is possible to capture the fracture network geometry (2D and 3D) as well as provide a sufficiently robust dataset (1D) to help evaluate even less documentable areas, e.g. using drilling works.

Currently, the greatest limit beyond the availability of rock outcrops is the estimation of lengths of individual fractures. Obviously, structures often propagate further into the rock massif, but it is often not possible to determine their actual length.

For further development of knowledge in these topics related to project results, we recommend:

- Using remote sensing methods and detection of morpholineaments, or aquiferous linear zones, to determine the length parameter for DFN models that could be correlated in a well-mapped terrain with rock outcrops by means of directional analysis with measured data from outcrops or quarry walls.
- In the further development of the DFraM program it will be necessary to take into account the spatial variability of the fracture network, e.g. in the form of domains in the vicinity of significant disturbances or in EDZ.

The resulting geological 3D models show in detail the complexity of the lithological structure and the fault network of the northern half of the proposed exploration area of the Kraví hora locality. Utilizing extensive geological data from the complete vertical range of the Rožná deposit, significantly improves the resulting model of this locality and increases its credibility.

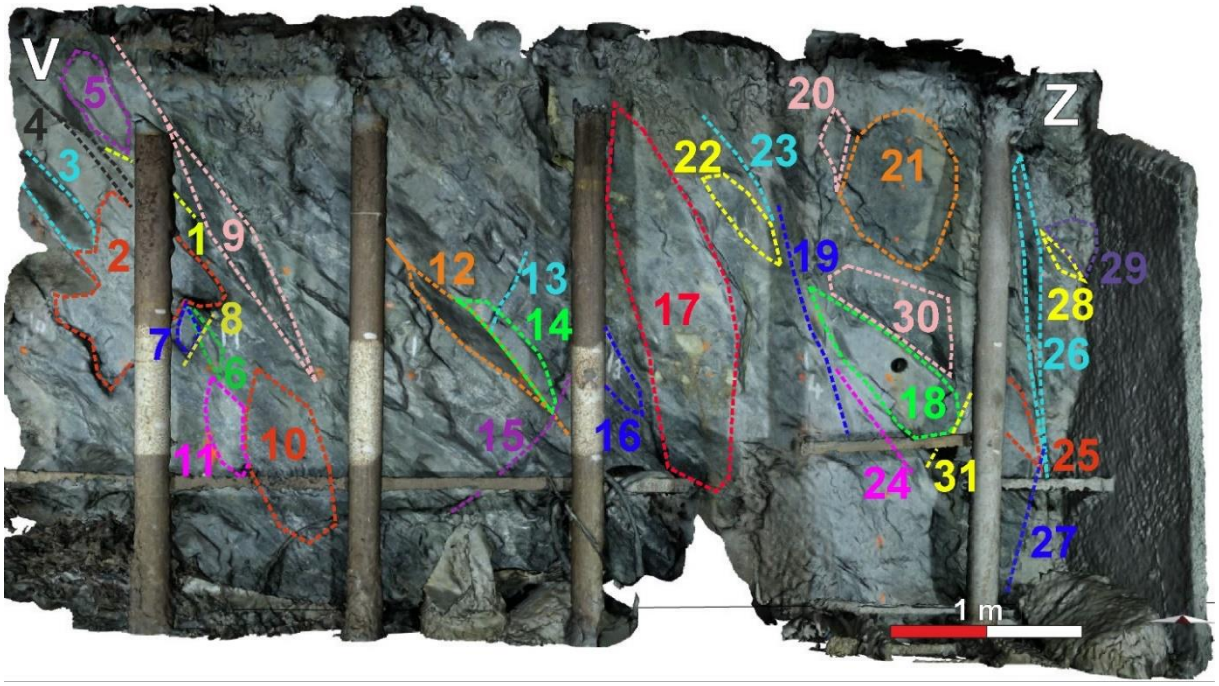

Figure 21 A view of the surroundings of the GS18 geotechnical station with marked significant structural elements – 3D model of rock wall

In terms of recommendations for future projects, structural data (orientation of foliations and fault zones) from deeper parts of the area of interest are of great benefit for model construction:

- In-depth data for the locality under consideration will significantly refine the 3D geological model, and in the future, it will be necessary to obtain it, for example, by a combination of geophysical and drilling exploration.

Geophysical works

The results of the geophysical work show that in-situ surveys (carried out using seismic and other methods) provide insights that are useful to take into account in any further consideration of the long-term behaviour of the rock mass in interaction with the construction and operation of a repository of radioactive waste. Determination of the influence of significant tectonic failure (here zone R1) on the distribution of seismic velocities in its vicinity showed that the minimum distance of the actual between the intended storage facility and significant disturbances in the order of tens of meters is justified and sufficient. Of course, this particular example cannot be considered as a universal rule because of the many specifics of the monitored site, it is necessary to generalize all conclusions carefully.

The issue of EDZ scope and its detection should undoubtedly be an important part of monitoring in the construction of underground structures related to (not only) radioactive waste repositories. Seismic measurements are effective and bring some advantages (speed, almost continuous information, possible determination even without drilling, repeatability – time monitoring). Appropriate extension of knowledge that seismic methods can offer:

• Determining the extent of EDZ using geophysical seismic measurements;

• Detailed monitoring of the correlation between the propagation velocities of longitudinal and transverse waves in the rock environment and comparison of the findings with existing knowledge from other applied methodologies;

• Use of surface wave analysis also deserves attention.

4 Results summary

Within the project, the works included both study of archival data from the Rožná deposit and mine itself, but main part of works focused on in situ works underground at the depth of approx. 550-1200 m. Following works were carried out in laboratories. All these works were aimed to clarify the influence of the tectonic zone (fault structure) on the rock mass and description of rock mass characteristics itself.

The obtained results show the overall state of the rock massif in the area of interest in relation to the significant tectonic structure, but also across the individual depth levels (12 individual floors of the mine). The most important results include the rather complicated relation between the highly metamorphosed, lithologically and structurally diverse rock environment and the fault zone. Mostly the results show questionable relationship in distance from the fault zone and different rock characteristics that can be used in such complicated geological setting in metamorphosed rocks. In the basic concept of a deep geological repository, the quality and condition of a rock massif is one of many basic and significant requirements for its safety. The rock massif represents a significant barrier against the spread of radioactive pollutants. The performed types of in situ work and their results make it possible to evaluate the applicability of individual methods in the field of rock engineering and their predicative ability in the next process of selecting suitable candidate sites for the construction of DGR. The results of the work and the knowledge gained from this project are directly related to the safety of the deep radioactive waste repository.

Petrological and geochemical studies have shown that the studied area is built by a migmatized volcano-sedimentary complex of paragneisses and amphibolites, which were metamorphosed under amphibolite facies. Typical is the large inhomogeneity of the rock type on the scale of cm to m caused on the one hand by the variable representation of the original sedimentary and volcanic component and especially by the different degree of migmatization of gneisses.

The filling of fractures was formed by several generations of veins. The oldest are probably late metamorphic quartz and quartz-feldspar veins with formation temperatures around 350 ° C, a small part of carbonate veins with formation temperatures above 150 ° C represents the ore stage of the Rožná deposit, some show typical post-orogenic signature.

Based on the development of ore bodies and styles of uranium mineralization with depth, the revalidation of the residual deposit potential showed that no significant reserves of uranium mineralization could be expected either on the opened horizons or below the level of the 24th floor.

The study of transport characteristics was focused on diffusion experiments with ^{3}H as a conservative non-absorbing tracer and radionuclides in anionic form (^{125}I and ^{36}Cl, respectively). The highest sorption on rock material was measured in the case of cesium. Radionuclides in anionic form (e.g. Se, U) are mostly not absorbed, except for samples from the 12th floor with higher contents of Fe-minerals. The values of the effective diffusion coefficient thus rather reflect the different rock composition and the variability of the environment.

According to the results of detailed research of physical, mechanical and deformation properties (FMV), it can be stated that the determined values of FMV rocks from the Rožná mine are in general agreement with the parameters of crystalline rocks of similar mineralogical composition and genesis. A characteristic feature of rocks in the evaluated parts of the Rožná mine is often a

relatively significant anisotropy, both physical (e.g. speed of propagation of longitudinal ultrasonic waves, thermal conductivity and capacity) and mechanical properties (transverse tensile strength, compressive strength). The results in the study of the influence of zone R1 on FMV and geotechnical properties of intact rocks show that it is not possible to prove the dependence of studied FMV intact rocks on the depth of their deposition below the Earth's surface or on the distance of the sampling point from the so-called first zone.

The anisotropy of rock properties increases with the increasing degree of migmatization of gneisses and with the increase of their grain size, i.e. it is directly proportional to the degree of textural anisotropy of the rock. At the same time, it should be stated, that from the results of laboratory determinations, the dependence of the studied parameters on the depth of their placement under the Earth's surface or on the distance of the sampling point from the so-called first zone is not evident. The heterogeneity of the properties of the studied rocks is more pronounced than the possible influence of the observed fault zone in the studied area.

The study of the development of the RQD parameter measured on drillcores, obtained from inspection work in wells and on the walls of mine tunnels (video inspection, OPTV probes, HiRAT, structural geological mapping), it can be stated that in general, two to four more pronounced fracture systems were detected in scanned wells at all geotechnical stations (GS). The most pronounced fracture system on all GS is spatially identical to the metamorphic foliation with the general direction of inclination to SW and inclination in the range of approx. 30 ° to 70 °.

From the results in the study of the influence of zone R1 on the quality of rock massif expressed by the RQD parameter determined on the drillcore, it can be stated that the average value of RQD for the rock mass of the Rožná mine is approximately between 60–65 %. The usual RQD values of the rock massif can be foud at horizontal distance 20–40 meters in the hanging wall of the tectonic structure R1. The development of the values of the reflectance also shows the influence of the first zone on the quality of the rock mass in the footwall up to a distance of about 7 m from the first zone. The irregular course of RQD indices in relation to the distance from the face of the excavation confirms that both the determined values of crack frequency and the values of the RQD index reflect the local degree of tectonic impact rather than the area of influence on the rock massif.

From the results in the field of rock massif stress measurements, it can be stated that based on current and previous measurements outside this project, the massif is relatively complicated in terms of demonstrating the shape and size of the stress field. In the field of EDZ evaluation based on the study of the frequency of discontinuities, it is clear that in almost all horizontal wells increased disturbance of rock massif was found in the section to 1 to 4 m from the face of the excavation. Subsequently, the frequency of cracks decreases sharply. Further, in the depth, the rock massif failure is developed completely irregularly.

In the field of EDZ evaluation based on FMV, the only porosity monitored was overall porosity. The determined values of the total porosity reflect the local degree of tectonic impact of the rock mass, especially the location of the boreholes in relation to the first zone (R1), rather than the area of influence of the tectonic zone.

Geophysical survey work was carried out using seismic tomography and geoelectric methods. Selected geophysical parameters of the rock environment (velocity of seismic waves,

electromagnetic properties) were monitored by these methods in exploratory wells and on exposed walls of galleries. The interpretation of geophysical measurements determined the area of influence of the fault zone R1 on the monitored parameters (especially the speed of seismic wave propagation) in its vicinity in the area of the 20th and 21st floors of the mine. The influence of this tectonic structure is obvious and clearly visible in the velocity sections. From the point of view of determining the safe distance for the location of a possible DGR, the speed of seismic wave propagation in the rock is one of the parameters that should be monitored and evaluated. The results of the examination of the rock block on the 20th floor show that the range of the influence of zone R1 in this particular case is in the order of the first tens of meters.

The study of the structural record in the area of the Rožná mine focused on the damage caused by the activity and presence of the first zone within the rock massif, both in the section perpendicular to the zone and along the directional course of the zone roughly north-south, but also with the rock mass depth. The impact of the rock mass is observable on a microscale and is manifested by microfracturing, which clearly mechanically weakens the rocks near the zone, at least to 60 m of the hanging wall. Partial differences directly depend on the specific tectonic structure, its characteristics, manifestation and number of recorded deformation phases and lithological diversity and related variability of the rock mass. The significance of larger tectonic faults/zones should be always determined individually with regard to the above-mentioned parameters, especially in the case of tectonic faults based in a homogeneous rock environment, such as their influence on the rock massif may be very different.

Modeling of disceret fracture networks (DFN) in a quasi-homogeneous rock block on the 20th floor proved the usability of detailed structural recording using 3D photogrammetric models. After optimizing the measured data and calculating the DFN network, its parameters are consistent with structural observations, including the frequencies of structures associated with the first zone. This methodology can therefore be applied in other projects related to the evaluation of the intensity of rock massif fracturing and subsequent hydraulic simulations.

Based on the frequency analysis of fractures on the available sides of mine workings, two quasi-homogeneous rock blocks were defined, which represent a less cracked accessible rock massif. In order to visualize this environment, 3D geological models and geological maps were created for these blocks based on archival data. Furthermore, a 3D geological model was created for the studied area of the Rožná mine and the adjacent sections of Habří and Zlatkov deposits.

For the purpose of deep repository building and ensuring its safety, there should be performed thorough investigation of tectonic zones of the first and second category according to Andersson et al. (2000). Such study should be performed with regard to their extent and manifestation in the rock massif, to determine a sufficient safe and stable distance from the built storage spaces or to use an adequate technical solution. In other kinds of rocks, the extent and impact of the massif can be very different, especially related to the conditions of deformation.

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