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STRUCTURAL ANALYSIS WITHIN THE ROŽNÁ AND OLŠÍ URANIUM DEPOSITS (STRÁŽEK MOLDANUBICUM) FOR THE ESTIMATION OF DEFORMATION AND STRESS CONDITIONS OF UNDERGROUND GAS STORAGE

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ABSTRACT

Uranium deposits, between which gas storage are being designed, the Rožná deposit and Olší deposit, are situated on the east edge of the Strážek Moldanubicum in Bohemian Masiff. Based on structural analysis it was possible to carry out the first rough prediction of potential weak zones in the rock mass. The structural analysis was also one of the supporting materials for determining the geometry and design method for the mine workings for the gas storage and for the advancing exploration of the gas storage region. Until now, the measurement of foliation planes and discontinuity planes in the survey crosscut V1-XXI and in a survey connecting gate GR1-XXI has been carried out. The results of interpretation of the measurement and monitoring of ductile elements (foliations) and joints (ruptures) as well as dislocations interpretation from the mine maps can be summarized and quoted in the contribution.

KEYWORDS: structural analysis, deformation, stress, underground gas storage

1. INTRODUCTION

Underground gas storage is planned in the declining uranium deposit at Rožná. It has been designed by the mining method in the underlying strata of the Rožná deposit in locations not affected by the exploitation of uranium ore where favourable geomechanical conditions for the construction are anticipated (Lazárek and Hájek, 2009; Michálek, 2011). There is a complex of rocks of *Strážek Moldanubicum,* which is primarily composed of fine to medium grained biotic gneiss, migmatized and granitized gneiss. A zone of amphibolites and amphibolitic gneiss is encountered in the upper part of the complex. Within the geological and geo-technical survey of the location of the planned gas storage, structural analysis of the whole complex was also carried out. Based on this analysis it was possible to carry out the first rough prediction of potential weak zones in the rock mass. The structural analysis was also one of the supporting materials for determining the geometry and design method for the mine workings for the gas storage and for the advancing exploration of the gas storage region.

2. SUMMARY OF RECENT KNOWLEDGE OF THE GEOLOGICAL STRUCTURE IN THE ROŽNÁ AND OLŠÍ URANIUM DEPOSITS

Both of the uranium deposits, between which gas tanks are being designed, the *Rožná* deposit and *Olší* deposit, are situated on the east edge of the *Strážek Moldanubicum* near the northeast edge of the core of the Bohemian Massif (see Fig. 1). In the west, the *Strážek Moldanubicum* is demarcated by the *Přibyslav* mylonite zone; in the northeast the *Strážek Moldanubicum* joins the *Nasavrky* Massif, or the southernmost spur of the *Hlinsko* zone and the *Svratka crystalline complex*. The boundary in the southeast is formed by an important fault structure in the northeast direction – *the Bíteš fault*, which separates this boundary from the *Moravicum* in the *Svratka* region. The southwest confinement is formed with the northeast edge of the *Třebíč* syenite massif. According to Urban and Synek (1995), the *Strážek Moldanubicum* was thrust over the *Svratka crystalline complex* and then subsequently the entire complex over the *Moravicum* and *Brunovistulicum*. Tajčmanová et al., (2001), on the basis of structural

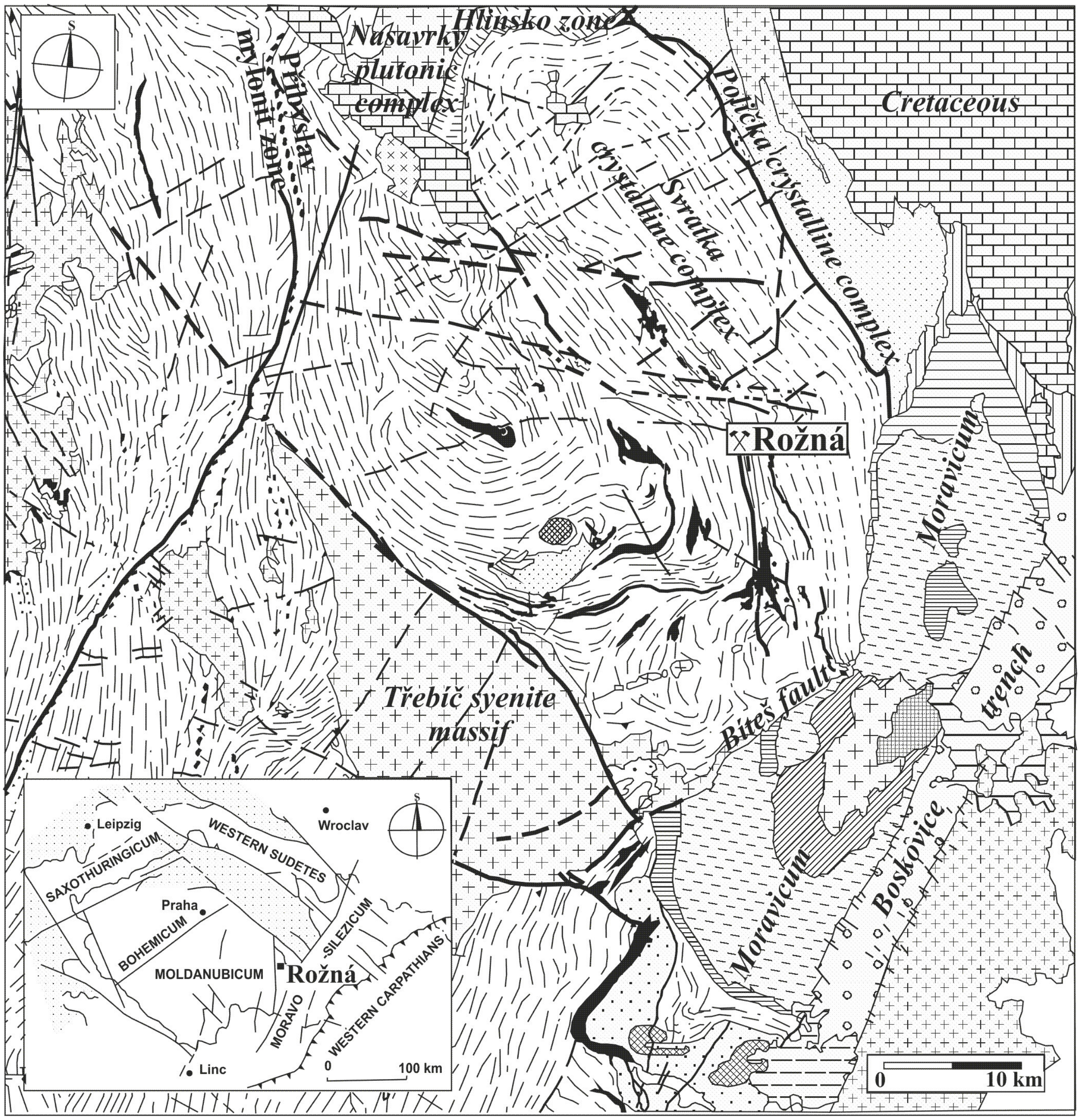

Fig. 1 Schematic map of Strážek Moldanubicum (arranged by Kříbek and Hájek, 2005).

and petrological data, confirms the concept of the overfaulting of the *Strážek Moldanubicum* over the *Svratka crystalline complex* (Hájek et al., 2004, 2005; Verner et al., 2011).

The evolution of the *Rožná* uranium deposit dates back to the period of the Stephanian and Saxonian. This phase of the Varisan orogeny, during which a relatively fast exhumation of the Varisan crust occurred and the basins were formed and filled (the *Blaník, the Boskovice, and the Jihlava furrows*), was preceded by the evolutionary phases of the *Moldanubian* covers, their overfault over the *Moravicum* and by the phases of post-orogeny extension. In the phase of post-orogeny extension, the ductile and later fragile zones expanded; in essence, these zones were the downthrow faults combined with horizontal dislocations. The fault structures, formed in this way and represented by uranium veins (zones), are situated roughly in a north-south direction and are the oldest fault structures in the deposit. In the last evolutionary phase, this region was affected by the post-Varisan, transcurrent tectonics; probably as a reaction to the Alpine orogenesis and the overfault of the West Carpathian over the Bohemian Massif. This was demonstrated by the combined uplift and subsidence and by dextral rotation of individual crust blocks (Kříbek and Hájek, 2005).

The *Strážek Moldanubicum* is formed primarily by cordierite-biotitic gneiss and migmatites, with biotitic and frequently migmatized gneiss and with the intercalated beds of amphibolites, erlan gneiss and magnesian limestone. Less encountered are granulites and granulites gneisses, accompanied by boudins of ultrabasic rocks, serpentinites, pyroxenites and eclogites. Migmatization of gneisses is demonstrated by the evolution of significantly striped rocks formed by melanosome abounding in biotite and leucosome consisting of quartz, plagioclase and, to a lesser degree, of potassium spar. Biotite and garnet occur more rarely in melanosome. A final product of migmatization is the origin of granitic rocks, which form sub-concordant and, more rarely, disconcordant bodies in adjacent gneisses. The thick beds of amphibolites are developed in rock-massif. Amphibolites are often transformed into amphibol-biotic and erlan gneisses. Granulites and granulites gneisses form larger bodies, but they were not found in the area of concern area. The rocks of the *Strážek Moldanubicum* are penetrated with smaller post-metamorphic gabbro bodies; further with melanocratic granites and even syenites (durbachites) abounding in potassium and with two-mica granites. Durbachites of the *Strážek Moldanubicum*, with their modal and chemical composition, are close to rocks of the *Třebíč* Massif.

2.1. FOLD (DUCTILE) TECTONICS

With regard to the global tectonics of the Bohemian Massif, the *Žďár-Strážek* synclinorium, which expands in the direction northwest to southeast (300–320°), is the largest structure. The limbs of the synclinorium have a rather small inclination (35–55°) with the axis bowed northwestward. The synclinorium limbs are complicated by the underfolds. These folds form a general structural scheme of the area of concern (Melichar, 1993, 1995; Melichar and Kotková, 2003).

As regards fold structures, the *Strážek Moldanubicum* is considerably inhomogeneous. It breaks into many zones of elevation and depression, while the central part of the territory is characterized with flat anticlinal and synclinal structures, showing in the general building plan, the sub-horizontal depositing of a metamorphosed group of beds of the *Moldanubicum*. In the peripheral areas, there are typical narrow and compact isoclinal folds of different vergency formed in the locations of highest stress of this *Moldanubicum* block (Zrůstek et al., 1977). The fold planes of these large and extensive folds are oriented in a north-south direction up to a northeast – southwest direction and the vergency in the area of concern is oriented in an easterly direction. The fold axes have the same direction and are parallel with the lineations of mineral expansion. According to Melka et al. (1992), the eastern part of the *Strážek Moldanubicum* was deformed in the lower crust, which led to the formation of isoclinal fold texture.

In the eastern region of the *Strážek Moldanubicum*, it is possible to recognize the three types of structures (Tajčmanová et al., 2001). The older sub-vertical foliation is in a north-south direction and is represented by the extension of quartz grains and quartz-spar aggregates. The lineation falls under a slight inclination in a south and southeast direction. This structure is interpreted as the result of compression under the condition of lower crust. The younger planar system is oriented in a northeast and southwest direction and intersects the older system under an obtuse angle. The youngest planar system is oriented in a northwest and southeast direction with the inclination to the northeast. This youngest structure presents an interim synclinar level in the region of *Bukov* and southward from *Bukov*.

The *Rožná-Olší* ore fields are situated in the eastern periphery of a vast anticlinorium. The core of the ore field is formed with the anticlinal identified as the *Rožná-Rozsochy* anticline (also the Main anticline) with the fold axis in the north-northwest direction. A core of competent rocks is bound to the *Rožná-Rozsochy* anticline. The axis of its fold is overthrown to the east. Therefore, both limbs are inclined to the west at an angle of 45°–70°. The west limb of the anticlinal fold, where the *Rožná* deposit is situated, changes into the *Rozsochy* syncline; the opposite limb changes into the east syncline (*Olší* syncline). The synclinal structures are complicated by faults with the mineralization in the deposits, and these faults, in the majority of cases, are parallel with the principal orientation of rock foliation.

A dominant planar structural element of rock mass of the deposits *Rožná* and *Olší* is the metamorphous foliation, which is defined, on an approximate scale, by interlaminating of individual lithological units with the layers of gneisses, amphibolites, the intercalated beds of erlans, and crystallic limestones with layers abounding in sulphides. In detail, the foliation is defined with the preferentially arranged crystals of phylosilicates, planar aggregates of re-crystallized quartz; in the case of migmatized gneisses, with the interlaminated stripes of mezosomes and leucosome. The metamorphous foliation is transacted locally with the zones of mylonites. Mylonites are formed by the fine grain re-crystallized basic material with the prevailing dark minerals. They contain relict and fragile deformed felspar crystals. The zones of cataclastic rocks of the strike cataclastic zone are oriented in the north-south direction and to the north-north-west and south-south-east; and are occupied with the crushed adjacent rocks with graphite and tectonic breccia. The strike length of the zones is up to 15 km.

2.2. FAULT STRUCTURES

Individual fault systems, according to the geometric relationship to foliation, can be identified as longitudinal, transversal and diagonal. They define the positions of magmatic bodies, hydrothermal alteration

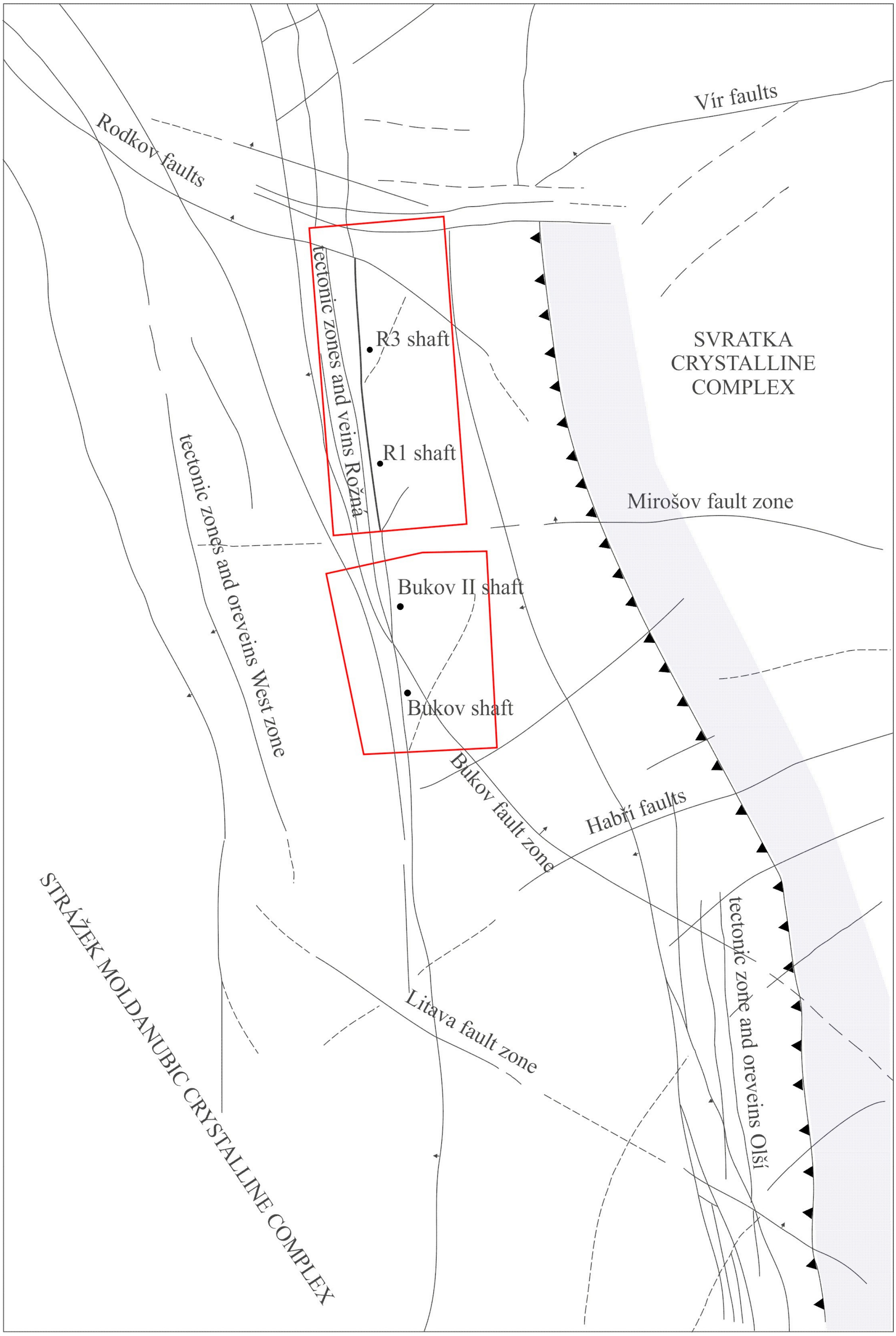

Fig. 2 Schematic map of main fault structures in the area of the easternmost part of *Strážek Moldanubicum.*

of rocks and play a basic role in the spatial distribution of ore accumulations. A schematic map of the main faults and structures in the *Rožná* and *Olší* region is documented in Figure 2.

Longitudinal dislocations are the best developed system in the area within the *Strážek Moldanubicum.* The relatively stable NNW-SSE orientation and a steep western inclination are characteristic there. The main structures of the system do not copy the edge of the *Moldanubicum*, but lead in a western direction from contact with the *Svratka crystalline complex* at the level of the communities of *Habří, Bukov, Dolní Rožínka,* and *Rozsochy.* These structures are also frequently developed in other peripheral parts of the *Strážek Moldanubicum,* where they are usually bound to geomechanically inhomogeneous elements of a variegated group. Longitudinal faults are not often encountered in the central part of the *Moldanubicum*.

The dislocations oriented east/west are defined as transversal dislocations. The *Křídelská* fault, belonging to the most important dislocation, presents a thick fault zone, along which the north block was lifted up and the south block subsided. The *Bobrová* fault also belongs to this system, as well as the faults in the locations of *Pavlovice*, *Rodkov* and others.

The system of diagonal faults oriented in a northwest and northeast direction transects rock bands, geological structures and longitudinal dislocations as well. Their evolution can be discontinuous, often of an *en echelon* type. Their verification is often difficult. The *Světnov* fault and *Kadov* fault are encountered in the northern part. The most important dislocation is the *Vír* fault system, which, with regard to the general evolution, cannot be combined with the more comprehensive dislocation. The *Bíteš* fault and *Vidonín* dislocations also belong to this system.

The most significant tectonic structures are associated with the general geological fold structure and with the character of overthrust of the *Strážek Moldanubicum* over the *Svratka crystalline complex.* These are the overthrust tectonics with a component of horizontal movement. The tectonics are affected also by the presence of ductile zones associated with the fold structure of the edge of the *Strážek Moldanubicum.* These general structures are oriented primarily in a north-south direction with the inclination in the direction of the west and southwest. The faults with the overthrust kinematics fall under steep inclinations in a northeastern direction and almost in an eastern direction. They are, relatively, the oldest systems of fragile deformation. The faults indicate the sinistral rotation. The fault planes fall under variable inclinations in a northwest or southeasterly direction. The sharply superposed planes of the overthrust and slip fault structures fall under the steep to medium angles toward the NNW and NW and carry the striations oriented under medium angles to the NNW. The planes of subordinated fault systems with fault kinematics fall steep to medium steep westward, and almost southwestward. In general, the anisotropy of the area of concern is very fragile.

3. STRUCTURAL ANALYSIS

The structural analysis was carried out with the aim of estimating the effect of geological structure on the stability of mine workings in the locality of concern (Ptáček et al., 2011; Staš et al., 2009). The analysis was focused mainly on the geo-technical aspect, but the general geology, with a focus on the relationships between the structural and general geological properties of rock mass, was estimated as well. At the same time, the wider structural-geological relationships in the area under study were taken into consideration. With regard to the planned localities of underground gas storage, the required measurements and structural analysis were carried out in the northern part of the deposit in the vicinity of shaft R3 and also in the survey crosscut V1-XXI in its central part, at the site of the planned southern gas storage. In both cases, the measurement was carried out in the underlying strata of the *Rožná* deposit at a depth of about 1000 m.

3.1. MEASUREMENTS OF STRUCTURAL ELEMENTS IN THE VICINITY OF SHAFT R3 AND THEIR INTERPRETATION

The compass measurement of foliation planes (ductile elements) and discontinuities (fragile ruptures) was carried out at levels 18 and 20 in the vicinity of shaft R3 and in the survey crosscut V1 at level 21. At level 18 in the vicinity of shaft R3 the measurements were carried out in the crosscuts V-XVIII (stationing at 0-24 m) and in Z-XVIII (stationing at 0-156 m) and at level 20 in the crosscut Z-XX (stationing at 0-33 m in the eastern part and 0-167 m in its western part). In total, 380 m of the crosscut was documented. At level 18, the rock mass is formed by medium to coarse biotic gneiss, which is locally migmatized. In some places, it even transforms into migmatite. A similar rock structure is encountered in the vicinity of shaft R3 at level 20. The rock mass is visually compact. The systems of joints are developed dependent on local stress conditions and open joints were only recorded in two cases.

Tectonic measurements were carried out with a spacing of approx. 5 m, which only changed insignificantly, depending on the occurrence of joint systems in the walls of a roadway. Documentation of the joints was always supplemented by an estimation of the properties, as needed for the determination of geo-technical and geo-mechanical characteristics (the RMR and Q coefficients). In accordance with the methodology of the quantitative description of discontinuities in rock mass (ISRM, 1983), the interval between joints of each system, persistence of joint, roughness of joint plane, joint separation, minerals filling and the amount of the potential inflow intensity of water were monitored.

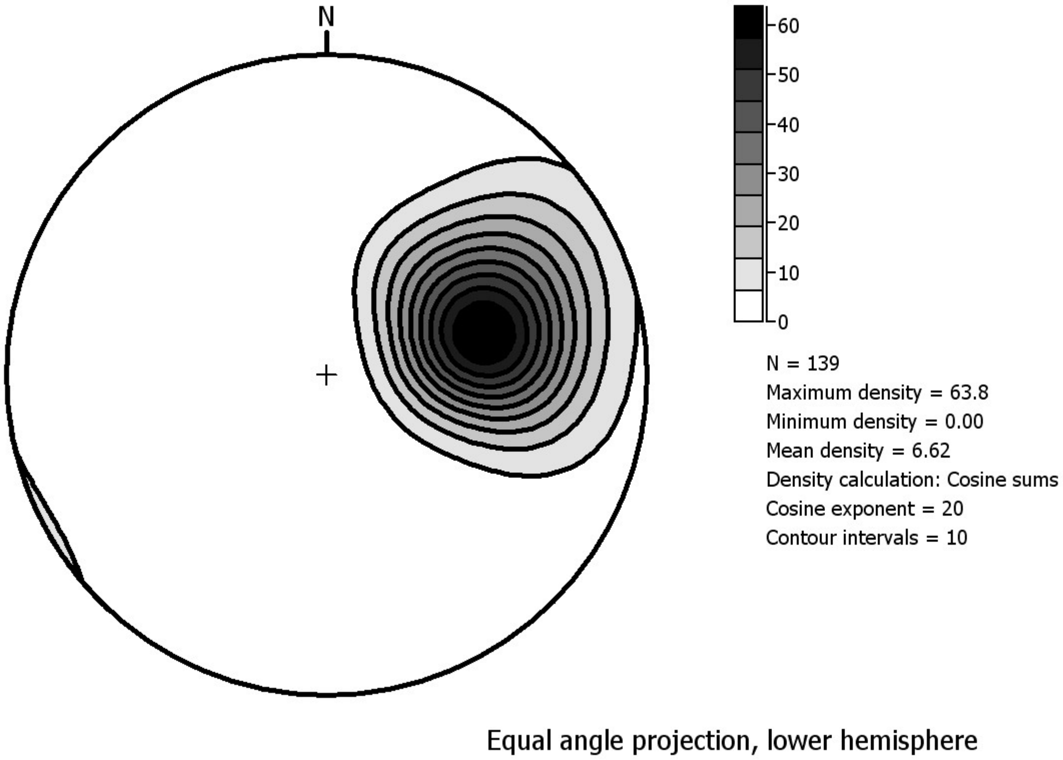

Fig. 3 Cumulative diagram of the metamorphic foliation poles in the region of shaft R3.

The orientation of the joint systems and the foliation were measured with the usual method of using a geological compass. The diagrams of the poles of foliation for the individual levels were prepared separately and the diagrams of the poles of planes for the individual levels were prepared separately as well. The program Stereo 32 was used, which uses the Lambert stereographic azimuth projection on the lower hemisphere. The summarized contour diagram of the foliation in the vicinity of shaft R3 is shown in Figure 3. The diagrams of the measurement of foliation primarily show the regional trend. The maximum concentration of the plane poles at level 18 is 84/30 and at level 20 is 75/42, which represents the foliation planes inclined to the west or in a west-south-west direction. The size of inclination varies from 50º to 60º. Clearly, the summarized contour diagram of the joints shows greater differences between the values measured (see Fig. 4). The diagonal orientation of two principal joint systems is distinct from the individual maximum concentrations in the diagram. This marks the system of subhorizontal joints too. With regard to a subjective view of the importance and the frequency of individual fissure systems, it is not possible to determine the priorities of individual systems. A pole diagram of joints at level 18 shows the paired systems; one with a steep inclination about 80º to the NNW (max. concentration 332/78); the second system, not so apparent, is inclined to the southwest up to a south-south-westerly direction, which, in some places, changes into the direction of foliation. Similar systems are shown in the diagram of joints copying the direction of foliation. Similar systems of the joints were observed at level 20. The above-mentioned system of horizontal joints was observed at the 20 level only.

On the basis of the geo-technical analysis of the samples of drill cores and the samples from the documentation of mine workings in the close vicinity of the boreholes, it can be stated that the foliation planes and the joints are fulfilled predominantly by chlorites, carbonates, quartz and pyrite and mostly by mylonite. They are not persistent in the majority of cases. Thicker fault structures were not recorded either at level 18 or at level 20 in the documented roadways.

3.2. MEASUREMENT OF STRUCTURAL ELEMENTS IN CROSSCUT V1-XXI AND THEIR INTERPRETATION

Until now, the compass measurement of foliation planes and discontinuity planes in the survey crosscut V1-XXI has been carried out at the stationing of 210-495 m and in a survey connecting gate GR1-XXI (stationing 0-30 m). The contour diagrams of the measured values of the foliation (the diagrams row north of the crosscut) and joints (the diagrams row south of the crosscut) are shown in Figure 5. The measured values were statistically processed in the same way as for the area of crosscuts in shaft R3.

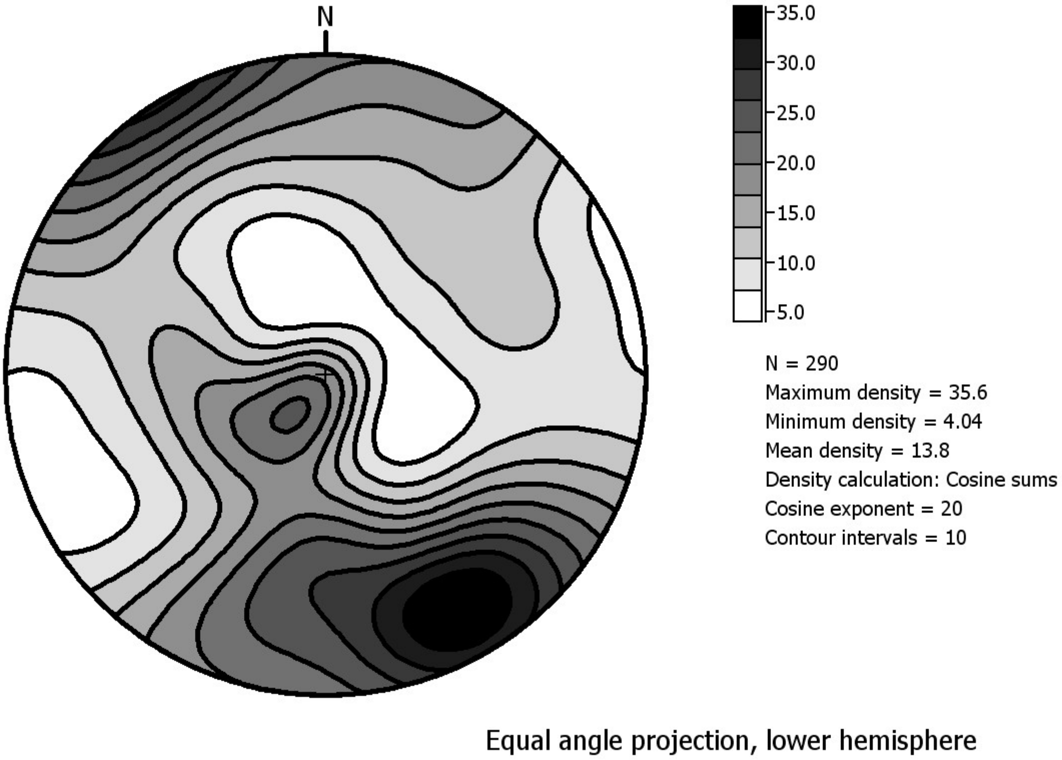

Fig. 4 Cumulative diagram of the joint poles in the region of shaft R3.

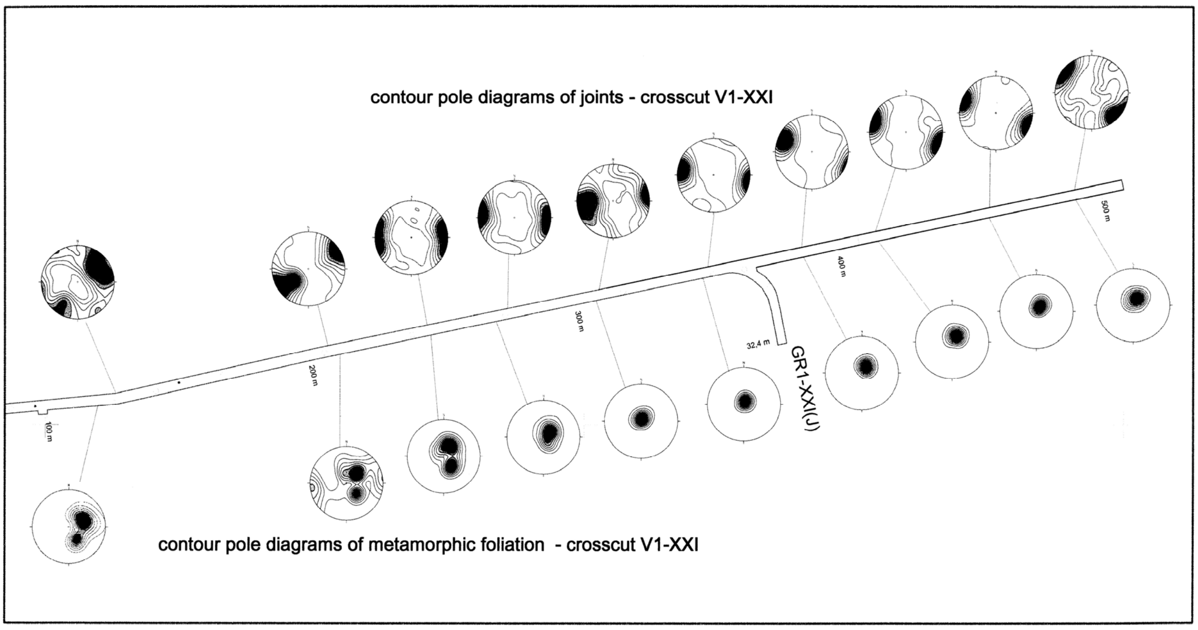

Fig. 5 Map of contour diagrams measured on crosscut V1-XXI (pole diagrams of metamorphic foliation in the row north of the crosscut, pole diagrams of joint systems in the row south of the crosscut).

Fig. 6 Illustration of the deformation intensity in the north side of crosscut V1-XXI in the stationing section 460-510 m.

From the measurements carried out so far, it is apparent that a number of the joint systems which were identified vary from two to three separate systems with one random system. The metamorphous foliation was measured for the purpose of qualifying the effect of its orientation on the roadways' stability. The compass measurements realized within our investigation were supplemented with the measurement carried out previously by the mine geological service in the location of stationing at 150-209 m in the area of the occurrence of amphibolites. All these measurements were statistically processed using the same method and they are documented in Fig. 5. The results of the measurements were used for the definite estimation and the quantification of failure systems to determine the geo-technical coefficients. The quality of the disturbance planes of rock mass was evaluated using the same methodology as for the estimations carried out in shaft R3.

The mapped sections of roadways can be classified in the category of persistent discontinuities mostly up to 1 m (approx. 60 %). For general estimation of the stability of rock mass, the change of inclination of the foliation planes is important. From the spatial documentation of the foliation planes in the contour diagrams (see Fig. 5) it is apparent that the inclination of the foliation planes gradually changes from 40° up to 60° to the west in the western part of the crosscut to almost sub-horizontal planes in the section of stationing at 460-510 m. The change of inclination is accompanied by more extensive fragile deformation. Deformation phenomena cause local slipping of intermediate layers in rocks formed with biotite bands. This slip deformation is also multiplied by a higher degree of migmatization. Increased deformation of mine workings and increased local overbreaks are encountered in this section (see Fig. 6).

3.3. ANALYSIS OF JOINT AND FAULT STRUCTURES FROM GEOLOGICAL MINE DOCUMENTATION

In addition to the measurements realized in the mine, structural data obtained from geological maps and from geological documentation of roadways have been statistically prepared and evaluated. In order to interpret vertically the largest area possible, data from the selected crosscuts in the underlying strata of zone 1 at levels 18, 21 and 24 have been evaluated.

Important joints and faults documented in the geological maps were analyzed. Dislocations reaching the order of several centimeters were taken into consideration. The data for each crosscut were further statistically evaluated and documented in the contoured pole diagrams. The summary diagram of the dislocations on the level 18 is outlined in the contoured diagrams using the same methodology as in the previous measurement in the mine, as shown in Figure 7. The distribution of the dislocations in the mine space differs in different sections of the working field, and both the directions of statistical maximums and the frequencies of the individual paired joint systems change. However, two paired diagonal systems in a southeast – southwest and in a northwest – southeast direction prevail (see Fig. 7).

The persistency of the joints was roughly estimated on the basis of the thickness of a dislocation. In the majority of cases, the joints and tectonic faults are fulfilled with carbonates. Water seepage through the fissures was identified and recorded only sporadically in the crosscut PŠ1-181 in the flawed rock at the stationing of 541 m to 543 m,

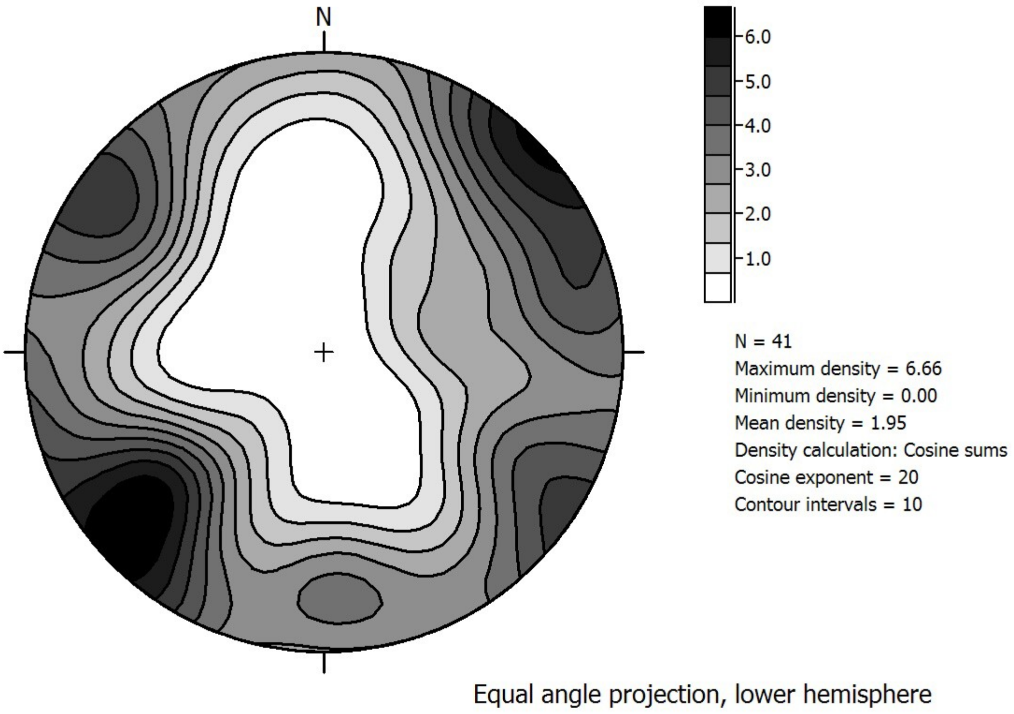

Fig. 7 Cumulative diagram of the joint poles in level 21 underlying zone 1 in the Rožná deposit.

where dripping water was reported and the water from the joints in the crosscut PŠ1-188 (the stationing at 137 m and at 540-543 m). Similar results have been recorded from the analysis of fissures in the crosscuts at level 21 and level 24. Water inflow was not found here at all.

4. SUMMARY AND CONCLUSION

The results of interpretation of the measurement and monitoring of ductile elements (foliations) and joints (ruptures) as well as dislocations interpretation from the mine maps can be summarized as follows (Staš et al., 2009; Ptáček et al., 2011):

- Foliation planes follow the orientation of vein structures roughly in a north-south direction up to a north-north-east and south-south-west direction. In the north part of the region for the planned gas storage *Rožná*, the foliation planes rotate locally in a northeast – southwest direction.
- Two paired systems of joints in diagonal orientation in the direction northwest – southeast and northeast – southwest were recorded as the most frequently encountered systems, and these are most important for the stability of mine workings in the planned location of the gas tanks. The mutual proportions of the frequency of both diagonal systems changes.
- The persistency of diagonal joints is only small. While their thickness reaches the order of 10^{-1} m in the crosscuts, the fissures are not captured in connecting gates, although the distance is only several tens of metres.
- In the majority of cases, the joint and fault zones are fulfilled with carbonates; less often with crushed rock; frequently with mylonite and kaolinite with the presence of chlorite on the contact planes. Water inflow is only sporadic and with a negligible yield. All these joints do not affect negatively the stability of mine workings.
- It is logical that the frequency of fissures will be greatest in the close vicinity of ore zones where the rock mass is most affected tectonically. It is reasonable to expect that the frequency of joints and dislocations in general will reduce eastward in the underlying strata of the ore zone. This is also suggested by the measurements in mine workings oriented in the mine in the direction east-west in the underlying strata of zone 1.
- The orientation of the measured structural elements (Melichar, 1993, 1995, Melichar and Kotková 2003) is in conformity with the axis of fold structure determined by the surface data within the *Svratka crystalline complex* (see Fig. 8). The orientation of the fold structure is parallel with the lineation of the extension identified on the basis of surface data. This primary ductile structure partially pre-determined a rupture plan of rock blocks.

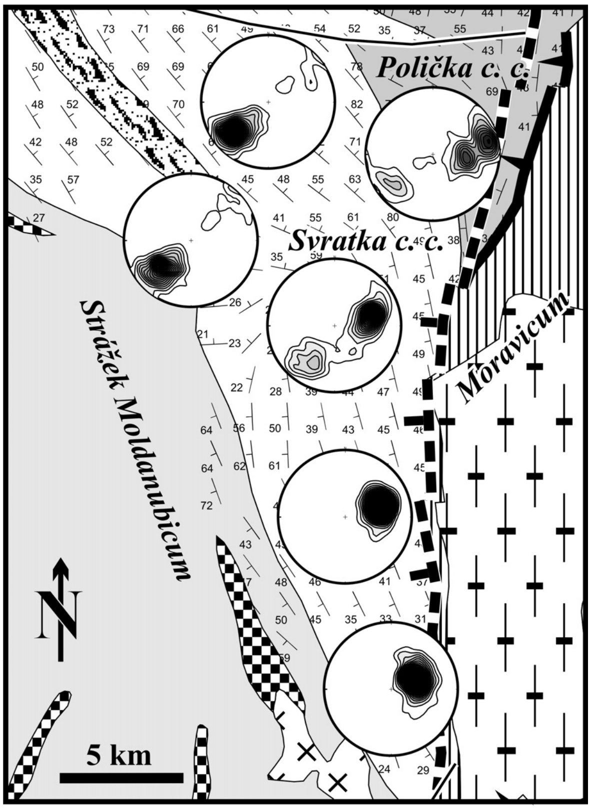

Fig. 8 Map of surface data of metamorphic foliation – contour poles diagram. Foliations in the map were spatially averaged to show the main trend.

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