MORPHOTECTONIC ANALYSIS OF DIGITAL RELIEF MODEL – A SUITABLE MEANS OF SEARCHING FOR ZONES OF ROCK MASS BRITTLE FAILURE

MORFOTEKTONICKÁ ANALÝZA DIGITÁLNÍHO MODELU RELIÉFU – VHODNÝ PROSTŘEDEK PRO VYHLEDÁVÁNÍ ZÓN KŘEHKÉHO PORUŠENÍ HORNINOVÉHO MASIVU

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Abstract

The paper deals with the suitability of using the morphostructural analysis of the digital relief model (DRM) for compiling a geological map fault network focused on brittle failure of the rock mass. Attention is paid to the description of the procedure of interpreting the individual outputs of the morphometric methods selected. An important role in compiling the resulting network of the rock mass brittle fault failure is played by the comparative analysis of the structural-tectonic mapping with the morpholineament network obtained by morphostructural DRM interpretation. Unless the comparative analysis has been completed, the resulting morpholineament network can hardly be considered a fault network of the studied area. Many relief morpholineaments have no geological foundation. Finally, the resulting geological network is compared with the current geological maps and a brief summary is given on the advantages or disadvantages of the morphostructural analysis applied at compiling the fault network of the mass brittle failure. The selected area of interest was the Moravosilesian zone of the Bohemian Massif, which is exceptional for the superposition of three structural levels (Alpine, Variscan and Cadomian).

Abstrakt

Článek pojednává o vhodnosti použití morfostrukturní analýzy digitálního modelu reliéfu (DMR) při sestavování zlomové sítě geologické mapy se zaměřením na křehké porušení horninového masivu. Pozornost je orientována na popis postupu interpretace jednotlivých výstupů zvolených morfometrických metod. Významnou roli při sestavování výsledné sítě křehkého zlomového porušení horninového masivu sehrává srovnávací analýza terénního strukturně tektonického mapování s výslednou sítí morfolineamentů, získaných morfostrukturní interpretací DMR. Bez provedené srovnávací analýzy lze jen velmi těžko považovat výslednou síť morfolineamentů za zlomovou síť zájmové oblasti. Mnohé morfolineamenty reliéfu nemají žádný geologický základ. Závěrem je výsledná zlomová síť porovnána se současnými geologickými mapami a stručně jsou shrnuty výhody či nevýhody morfostrukturní analýzy aplikované při sestavování zlomové sítě křehkého porušení masivu. Vybranou zájmovou oblastí studia byla moravskoslezská zóna Českého masivu, která je výjimečná superpozicí tří strukturních pater (alpínského, variského a kadomského).

Key words: morphostructural analysis, digital relief model.

1 INTRODUCTION

Geological structure plays a crucial role in determining a wide field of relief forms, even in areas where exogenetic factors are regarded as the dominant ones in the landscape (Ahnert 1998; Bloom 1998; Ritter et al. 2002). Morphotectonic analysis of digital relief models (DRM) with many morphometric methods has become a common procedure of compiling geological maps (Weibel, Heller 1991). There is, unfortunately, a divergence in the selection of morphometric analyses, in methodical procedures (Centamore et al. 1996, Hartvich 2004, Jayko 1997, Johansson 1999, Jordan et al. 2003, Kukowski et al. 2001, etc.), and, above all, in the actual interpretation of morpholineaments. The fact is often neglected that the morpholineament interpretation accuracy to some extent depends on the accuracy of the DRM used. This paper tries to propose one of the possible procedures of DRM interpretation with view to brittle tectonics study. The developed methodical procedure of interpreting brittle failure zones of the rock mass from the digital relief model by means of a morphotectonic map set was created within a grant project of the Czech Republic (GAČR 105/05/P545) focused on the study of the fault failure in the Moravosilesian region. To demonstrate the methodology of morpholineament interpretation based on DRM study, a subpart of the Moravosilesian zone was selected in the area where the Bělá fault occurs in the Nízký Jeseník Mts. region.

2 PROBLEM ANALYSIS FROM GEOLOGICAL POINT OF VIEW

The Moravosilesian studied area represents an outstanding example of interrelation of three orogeny cycles within the European geological structure. The oldest structural level represented by Brunovistulian constitutes a common foreland for the Variscan and Alpine structural levels. This Cadomian microcontinent (Grygar, Vavro 1995) played an important role in the formation of the Variscan accretion wedge thrusted to the area approximately from the NW. The Variscan structural level, represented by Rhenohercynian foredeep and Subvariscan sediments together with Brunovistulian, forms a foreland for the Alpine structural level, constituted by Outer Carpathian fore-deep sediments and Outer Carpathians nappes, which were generally thrusted in the area from SE to S.

The structural-tectonic pattern of the Variscan level of the Moravosilesian region is interesting for the lateral course of main fold-thrust structures with view to the general subequatorial trend of the Variscan orogeny. During the Bohemian massif – Brunovistulian collision, the Moravosilesian structural flexure (orocline) of the orogeny zone formed by gradual right-hand rotation of the Rhenohercynian and Subvariscan accretion wedge (Grygar 1992). The dominant deformation system of internal crystalline zones of the Moravosilesian accretion wedge is made of Variscan deformation systems of the D1 and D2 phases (Grygar 1992; Schulman, Gayer 2000). These deformations are characteristic for a very close orientation of virtually all linear systems in the NE to NNE direction with prevailing south-eastern asymmetry. Here the D1 deformation phase corresponds to the generally northward thrust of Variscan synmetamorphic intracrustal nappes during the dextral collision of Variscan internids of the Bohemian massif with the Brunovistulian foreland (Schulman, Gayer 2000). This eartly Variscan collision phase has a distinctive transgressive character. The D2 deformation zone has, approximately from the lateral silesicum elevation zone line, a prevailing south-eastern vergency of nappe thrusts and the corresponding fold system. The course position of structural systems of the regional deformation D2 is influenced by the existence of inherited lateral and oblique Brunovistulian ramps in the south-eastern foreland of the Variscan front thrust wedge. Attention in the target subpart was paid to the study of surface indications of significant failure structures in the Sudetic direction (WNW-ESE to NW-SE), noticeable at the north-eastern edge of the Bohemian massif. Their origin is primarily connected with the D2 and D3 phases, when there were significant dextral strike faults occurring along regional shear zones and partial dislocations in the Sudetic direction. This development was connected with the NW-SE maximum transpression, both of the flyschoid and coal-bearing molasses of the Moravosilesian zone.

The main tectonic failures in the Sudetic direction involve the Bělá fault, which was denoted as a deep fault by many authors (Buday et al. 1995; Kumpera and Blažek 1987; Zeman 1989). The occurrence of neovulcanites and springs rich in CO_2 in places along its course initiate frequent considerations about its deep foundation. Periodic events of earthquake activities (Špaček et al. 2006) reveal its nontectonic activity connected with the post-Variscan development of the area. In the Miocene period, movements of dextral character were rejuvenated on the Sudetic and Elbe system faults. These faults underwent distinctive neoide rejuvenation during the Alpine orogeny development, when the nappes of the Outer Carpathians were thrust to the Bohemian massif foreland from south-east. With view to the Alpine palaeostress fields with prevailing NNW-SSE direction of the maximum compression stress, these faults in the Outer Carpathian nappes foreland acquired a position of radial transtension faults, conjugated with the N-S to NNE-SSW systems of the Outer Carpathian orogeny belt (Grygar, Jelínek 2002). On this assumption, it is possible to determine the present-day geodynamic scenario for the Moravosilesian region and kinematics of movement in the main fault zones (Fig. 1). This palaeostress field was also found in the Devonian-Carbonian formations at the eastern edge of the Variscan accretion wedge (Grygar, Jelínek 2003).

The Bělá fault is a wide zone of brittle deformations of rock mass and cannot be understood as one separate fault passing through the whole Moravosilesian region. The Bělá fault course is described and mapped in detail in the Silesicum area, where it emerges as a south-eastern extension of the border Sudetic fault (see the geological map of the Czech Republic M 1:500 000 – Cháb et al. 2007). In the south-eastern direction, approximately from the south, it restricts the Jeseník metabasite complex, where it subsequently splits into a system of parallel faults extending over neovulcanites to Bruntál. Further continuation of the Bělá fault in the south-eastern direction across the Nízký Jeseník Mts. is drawn very differently by many authors (Fig. 1). Similarly, there are differences in drawing its course under the Carpathian nappes (Buday et al. 1995). Not even the current geological maps on the scale M 1: 50 000 clarified the problem. The Bělá fault brittle failure course is composed of partial faults of diverse directions. In the regional geological map on the scale M 1:500 000 (Cháb et al. 2007), its course is not indicated unambiguously.

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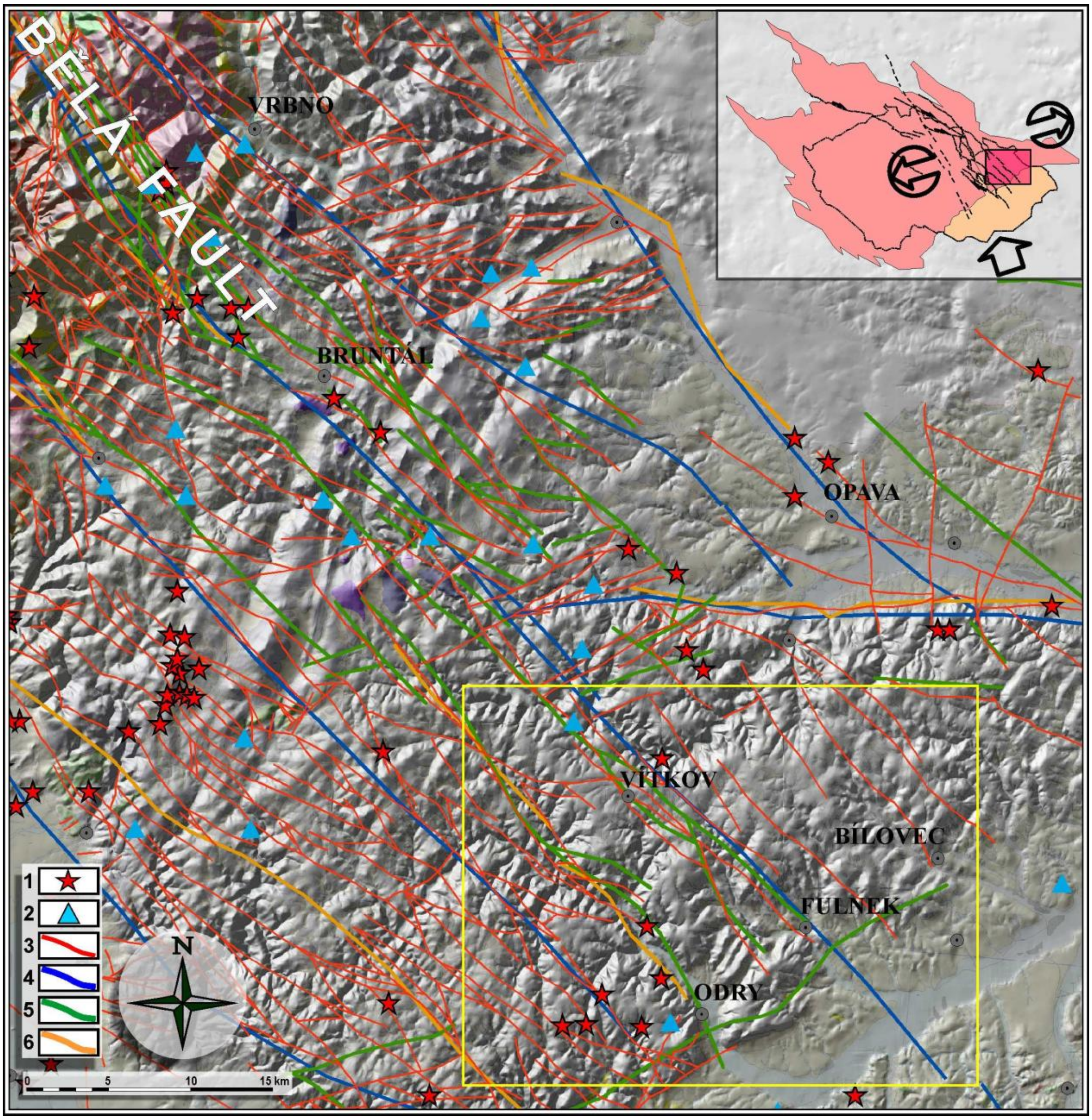

Fig. 1: Digital relief model of wide surroundings of the south-eastern extension of the Bělá fault with attached geological map on a scale M 1:50 000. The yellow rectangle indicates the example area of interest. Legend: 1 – earthquake epicentres registered in 1996 – 2003 (Špaček et al. 2006); 2 – springs containing CO_2 (Špaček et al. 2006); 3 – fault network digitalized from the geological map M 1:50 000; 4 – significant faults interpreted by Buday (Buday et al. 1995); 5 – significant faults digitalized from the geological map M 1:500 000 (Cháb et al. 2007); 6 – significant faults interpreted by Špaček (Špaček et al. 2006).

3 PROBLEM ANALYSIS FROM METHODICAL POINT OF

The solved project tried to ascertain the character and course of significant fault structures in the Sudetic direction in the relief of the Moravosilesian zone of the Bohemian massif on the basis of the created methodical procedure of morphotectonic DRM analysis. The credibility of the created map of the rock mass brittle failure depends on the accuracy of the digital model used and the methodical procedure. The interpretation notices abrupt changes in the relief form and curvature. The more truly the model characterizes the landscape relief, the better these discontinuities will be interpreted. The created model accuracy depends on the selection of a correct model type, density and accuracy of input data and interpolation method. The interpolation methods for model calculation from scattered digitalized points must take the model usage purpose into account. The suitable interpolation method is selected on the basis of data testing in the sample area. In the territory tested, it is necessary to perform a structural analysis, determine directional empiric semivariograms and ascertain the field anisotropy. However, it is often impossible to perform structural analysis of a given value due to insufficient input values. In such cases, it is more reasonable to use an isotropic model than an incorrectly determined

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anisotropic one (Staněk 1999). Practically, however, most interpreters always use the same interpolation method, set in the program used as standard, for all data types, regardless of the structural analysis results. The selection of suitable DRM study methods has a crucial effect on the resulting map of the zones of the rock mass brittle failure. Using an accurate DRM and selecting a suitable method may still not guarantee an optimum result. The interpreter's personal opinion plays an important role here.

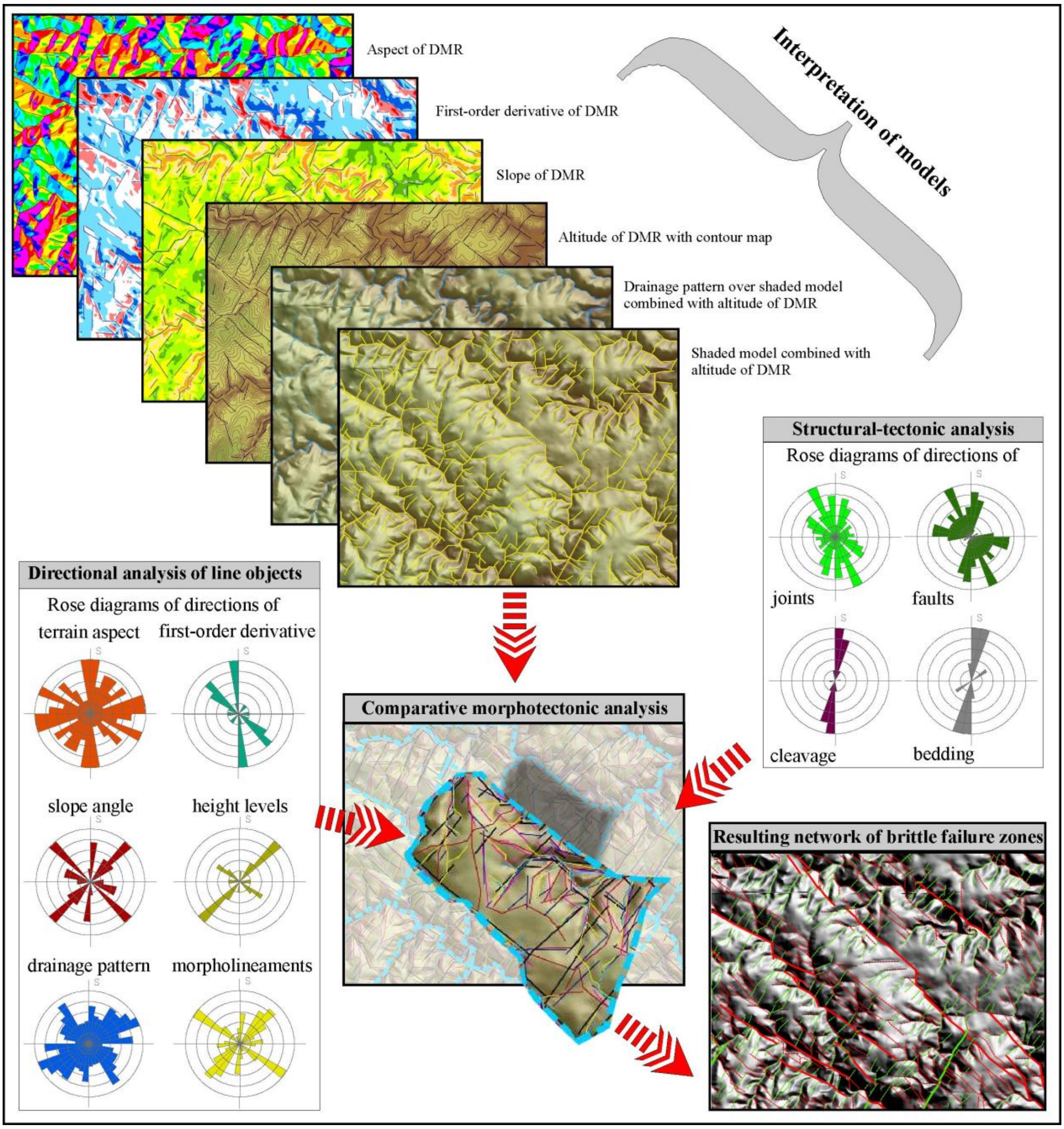

Fig. 2: Scheme showing methodical procedure of interpretation of rock mass brittle failure zones.

4 METHODOLOGY

In terms of its intention, morphotectonic analysis belongs to the structural geomorphology category which tries to solve the relation between morphostructures and surface relief features. The term "morphostructure" denotes the structural-geological base involving both the rock lithology and current influences of old tectonics, attitude conditions, chemical and physical properties of the rocks, jointing, etc. Morphostructures are landforms of tectonic origin, modified with variable intensity by exogenetic processes of a certain type (Bloom 1998; Ritter et al. 2002). They may be formed by recent as well as older tectonic movements. The study focused in this way must notice all landforms, typical geometric characteristics (e.g., straight course of a valley, drainage pattern and valley network oriented identically, with abrupt changes in direction, mountain ridge systems, double ridges, etc.) which are related to their tectonic origin. Enhanced attention was therefore paid to finding regional

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tectonic conditions which help to explain the rather complex tectonic development of the whole area. It is, nevertheless, necessary to perform the analysis carefully. Some structures only appear indirectly in the relief (e.g., in the drainage pattern ground plan) or manifest themselves in the model similarly to tectonic failures, but their genesis may in fact be connected with quite different relief formation processes. Without structural-tectonic mapping, the morpholineaments found cannot therefore be directly denoted as faults.

The morphotectonic DRM analysis focused on rock mass brittle failure is able to disclose, in confrontation with structural-geological findings, complex relations between the ground and geological pattern of the area. Evaluation of the character and rate of impact of brittle tectonics in the current relief of the Moravosilesian region studied necessitated finding the optimum methodical procedure for DRM study. The selection of a particular method was based on the assumption that the method selected had to enable interpretation of landscape elements bearing witness to the rock mass tectonic failure (Burbank, Anderson 2001; Ganas et al. 2005; Ritter et al. 2002; Scheidegger 2004; Wilson, Gallant 2000; etc.). Fault network interpretation by morphostructural analysis is based on visual interpretation of digital models, and on the assumption that the model created resembles the actual relief of the area searched as much as possible. Credibility rate of the resulting network created in this way is directly proportional to the digital model type used, accuracy of its computation, suitability of the selected methods used, methodical procedure and, above all, to the human factor. The human factor causes the final fault network affection by the interpreter's personal opinion. To eliminate errors as much as possible, a methodical procedure has been proposed, based on confrontation of results of selected morphometric methods with the morphostructural DRM analysis, geological maps and structural-tectonic field mapping.

The task was resolved in the ArcGIS 9.0 and Surfer 8 program environments. For complex processing of results and performing all morphotectonic analyses, the ArcGIS program environment was selected, which is a GIS means commonly used. The disadvantage of ArcGIS is a limited choice and setting of interpolation methods of DRM calculation. With regard to this fact, the digital models were compiled and interpolation methods accuracy tested in the Serfer software environment which offers a wide choice of interpolation methods and their settings. Unfortunately, there is currently no software tool for direct transfer of the created grids from Surfer to ArcGIS. Therefore, a grid transfer extension had to be developed so that the user was able to load a grid in ArcGIS directly as another layer and process it further.

The ArcGIS program extensions delivered by the manufacturer do not contain all necessary ground analyses which would solve specific tasks of the structural-tectonic and morphotectonic analysis. The software equipment in common use enables some tasks of morphotectonic analysis to be done, but does not solve the current structural analysis tasks. Those must be implemented by means of other software, totally independently of the results obtained by the DRM study. Therefore, a second extension was created within the methodology, enabling insertion of structural data into the database via the ArcGIS interface. The third module developed does statistical processing and directional analysis of not only the structural data, but also of all layers containing line information obtained from DRM. The graphical output contains rose diagrams (Fig. 2) indicating variable line object orientation of a certain polygon (drainage pattern, contour plan, photolineaments, morpholineaments, etc.) or other structural data (faults, cracks, lineation, bedding, etc.).

5 DIGITAL RELIEF MODEL ACCURACY

Accuracy of digital models depends on the input data accuracy, their density and type of the interpolation algorithm used. DRM of the area studied were created following the data acquired by detailed intelligent digitalization of the contour plan of topographic maps on the scale M 1:25 000 (Jelínek 2004). The accuracy of such a DRM with a grid cell dimension of 50 m was sufficient for studies of regional concernment. The model created allowed to find positions of significant structures on which further survey focused.

Detailed study of brittle tectonics in these partial areas necessitated creation of much more detailed models on large scales. The model elaboration process had to highlight a large number of details emphasising the ground discontinuities searched. Additional data were obtained by intelligent digitalization of topographic maps on the scale M 1: 10 000. The sampling density choice takes depends on the roughness of terrain. Excess points are already eliminated during the actual digitalization of a simple relief. The computer system load and calculation time are thus reduced (Maguire 1991). The digitalization focused on the so-called "very important point"(VIP). These points, indicating relief breaks (ridge, talweg, slope angle changes, tops, depression floors, etc.) are much more important for improving the model than other source points (Weibel, Heller 1991).

The resulting digital model accuracy does not only depend on the data type used, their credibility and density, but also on the interpolation algorithm applied. A digital relief model compilation means finding the most suitable interpolation method which reflects the modelled surface course as truly as possible, while minimizing the data volume. Many DRM interpolation methods are often argued about in literature (Abramowitz, Stegun 1972; Franke 1982; Journel, Huijbregts 1978). There is, however, no universal interpolation algorithm suitable for all DRM applications. The resulting model quality is determined by the spacing and accuracy of original points and suitability of the interpolation function for a certain model. The criteria influencing a particular interpolation method selection are the degree of accuracy and rate of the calculation influence (Yoeli 1977). By means of many other input criteria, the interpolation function may be adjusted to the variable surface characteristic. The most suitable interpolation method was selected by the "boomerang method" (Staněk 1999) and visual comparison of the resulting model with the topographic map. With view to the calculation time, interpolation methods cannot be tested on the whole area model. Therefore, a test area was chosen, including a broken relief which suddenly converts into a simple flat relief. In both ways, the interpolation method of exponential kriging of isotropic data field was selected as the most suitable one. Data field anisotropy cannot be used, because the resulting ground model is distorted in the anisotropic direction (Jelínek 2004).

6 METHODICAL PROCEDURE

The task consisted in finding such relief elements which are indicative of tectonic origin of its genesis. Qualitatively, the interpretation result can be influenced by choosing suitable methods and their combination. Methods viewing the problematic from different angles were selected. Conclusions with higher degree of credibility are drawn by mutual comparison of results of the analyses used. Following the study of professional literature dealing with morphostructural analysis (Burbank, Anderson 2001; Formento-Trigilio 2002; Ganas et al. 2005; Johansson 1999; Jordan et al. 2003; Kukowski 2001; Pánek 2004; Scheidegger 2001 etc.), own experiences from previous projects (Grygar, Jelínek 2002; Jelínek, Grygar 2002; Jelínek 2004) and character of the available data, the following methods have been selected:

1. **set of morphometric methods;**
   - interpretation of altitude model with contour map;
   - interpretation of slopes;
   - interpretation of aspect;
   - interpretation of the first-order directional derivative;
   - interpretation of shaded relief;
2. **set of directional analyses of line objects;**
   - morpholineaments found by interpretation of the altitude;
   - morpholineaments found by interpretation of the slope;
   - morpholineaments found by interpretation of the aspect;
   - morpholineaments found by interpretation of the first-order directional derivative of DRM;
   - morpholineaments found by interpretation of the shaded DRM;
   - directional analyses of the drainage pattern;
3. **structural-tectonic analysis;**
4. **comparative morphotectonic analysis.**

The proposed DRM interpretation procedure involves work in steps which must not be omitted or interchanged in sequence. Breach of this procedure may influence the interpreter's opinion and reduction of credibility of the brittle failure zones interpreted. Time plays an important role in interpretation of digital relief models as well. If the interpreter is stressed for time, the result will probably be more affected by human factor errors. It is much more suitable to do the interpretation in several time-independent versions. Even an experienced interpreter is not able to create entirely the same morpholineament network by DRM interpretation every time. These inaccuracies result from details unnoticed by the interpreter at an earlier or later model interpretation. Therefore, it is preferable to perform the interpretation several times, with as long a time offset as possible. The results are compared with each other and consistent lines are chosen. Credibility of lines occurring in one of the interpretation versions only must be evaluated additionally. Still, the interpreter's personal opinion cannot be eliminated completely.

The interpretation of the rock mass brittle failure was done in four phases (Fig. 2). In the first phase, networks of line objects (morpholineaments) were created by the individual methods of morphometric DRM analysis. Owing to the fact that every method displays different relief parameters, there is no absolute compliance of these networks. The morpholinement directions conform in many places, but their positions do not correspond. An exact location of the lines interpreted is not decisive in this phase of work. The morpholineaments cannot be directly regarded as faults and their location is only informative. The suitability of usage of individual methods in different relief types is also different. In level relief, for example, the height level model with indicated contour plan proved excellently.

In the second work phase the resulting morpholineament networks were compared with each other. The results acquired had to be evaluated statistically to determine dominant morpholineament directions. Directional analysis of line objects was used and done in partial areas. Testing was done separately for partial areas selected with respect to the morphology, lithology and geological pattern of partial areas. The obtained rose diagrams of morpholineament directions interpreted by individual methods were compared with each other for the partial areas and subsequently confronted with the results of the analysis of drainage pattern directions.

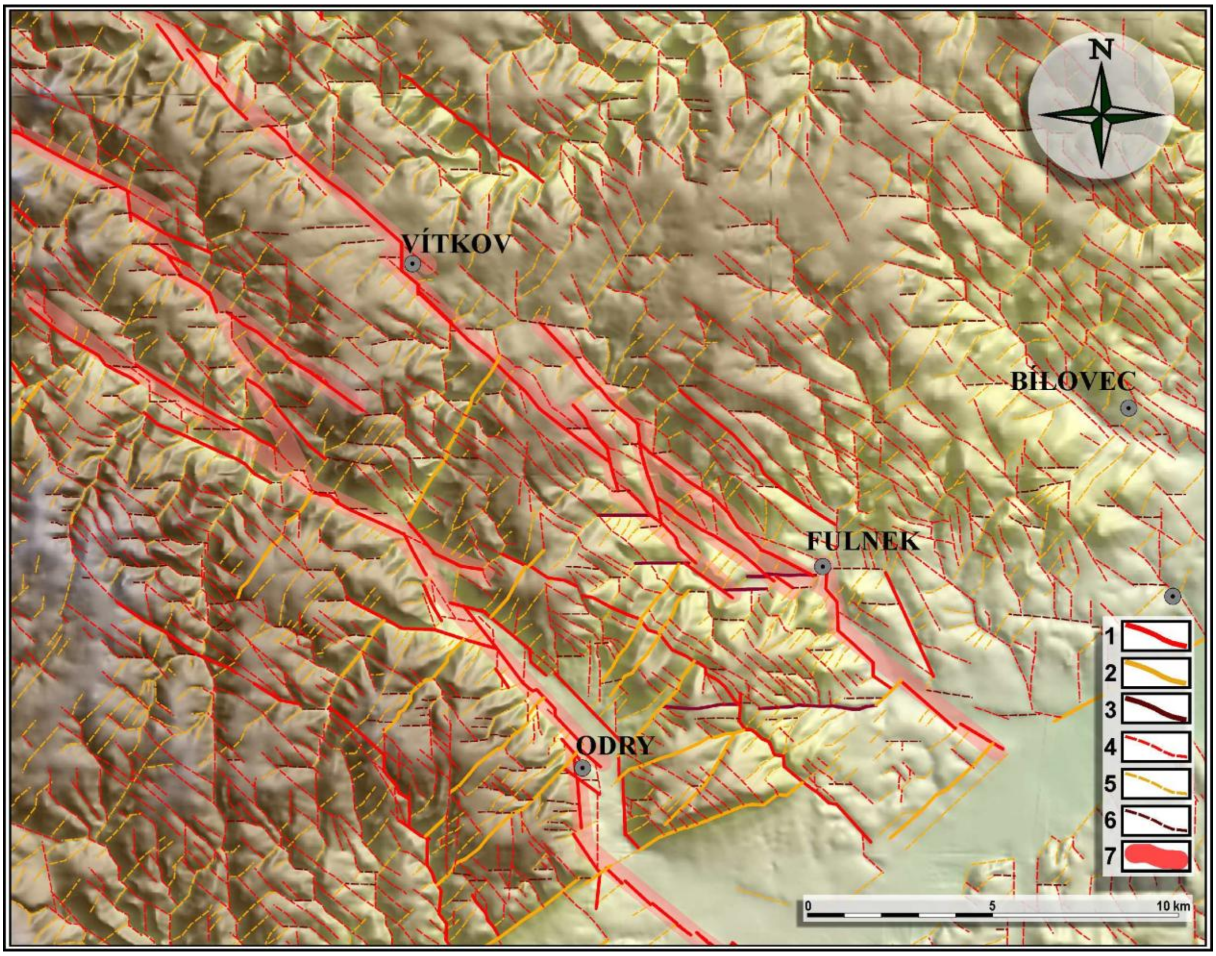

Fig. 3: DRM with rock mass brittle failure zones interpreted by morphotectonic analysis. Legend: 1 – distinct zones in Sudetic direction; 2 – distinct zones corresponding to fold thrusts and cleavage; 3 – distinct zones in the W-E direction; 4 – supposed zones in Sudetic direction; 5 – supposed zones corresponding to fold thrusts and cleavage; 6 – supposed zones in the W-E direction; 7 – significant zones of failure belt in the Bělá fault.

The information obtained from the drainage pattern directional analysis and morpholineaments interpreted were compared with the structural-tectonic analysis results. For the partial areas, it was necessary to find out whether the morpholineament interpreted from DRM may occur in the landscape relief and whether it is conditional on endogenetic or exogenetic processes. During the morphotectonic analysis, the interpreter must often decide whether an interpreted lineament of a certain direction exists in the given place at all or it is a combination of many small lineaments in two different directions. The structural-tectonic analysis results help with this decision. Crack and fault systems, level surfaces or foliations, eventually cleavage or fold b-axes, are evaluated separately for the individual partial areas. It is important to find out whether the morpholineament found in a certain area is of structural origin and, if so, of which one.

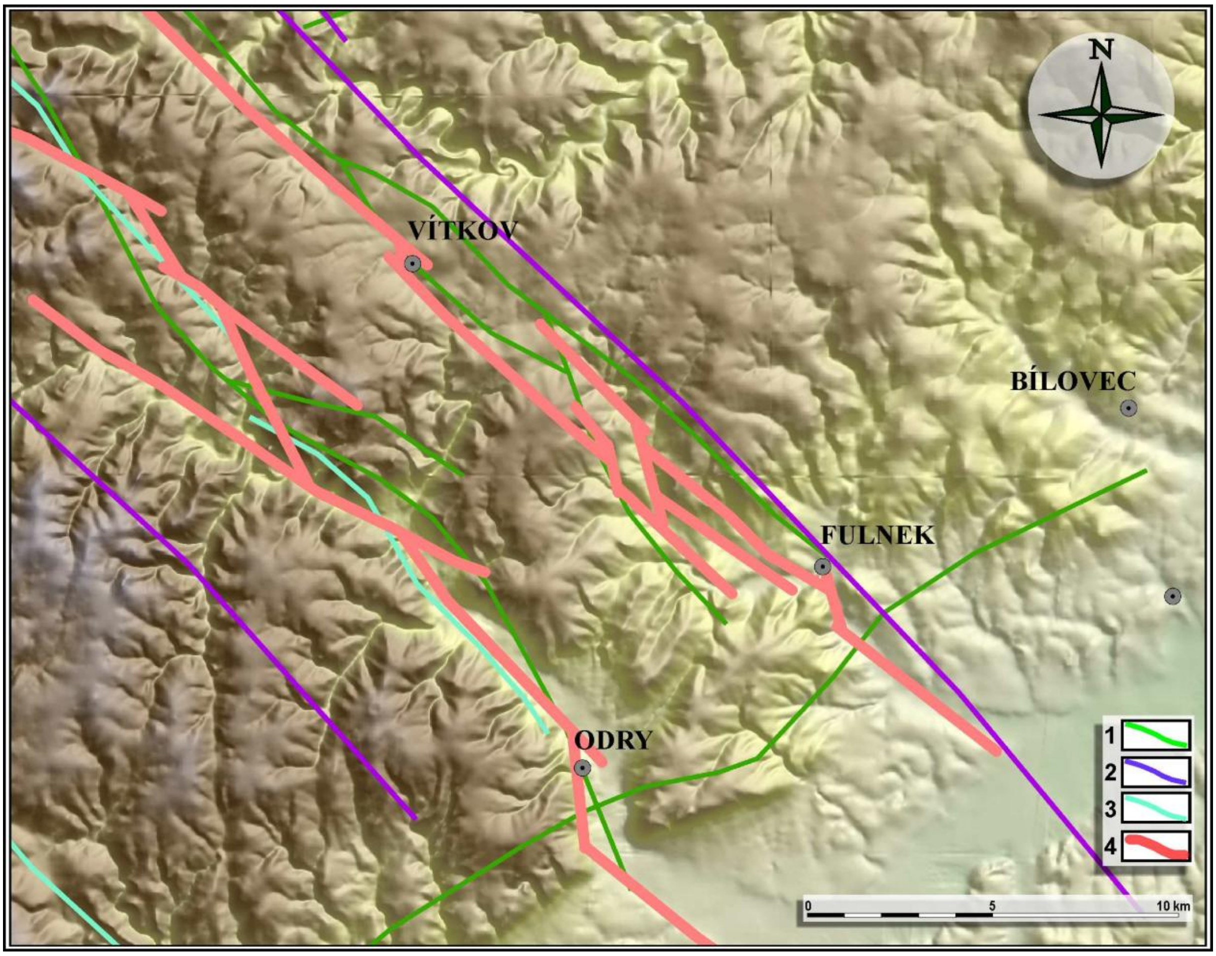

Fig. 4: DRM with various interpretations of the Bělá fault course. Legend: 1- main faults digitalized from the geological map M 1:500 000 (Cháb et al. 2007); 2 – main faults interpreted by Buday (Buday et al. 1995); 3 – main faults interpreted by Špaček (Špaček et al. 2006); 4 – significant zones of the failure belt of the Bělá fault interpreted by morphotectonic analysis.

This items of information are then taken into account in the forth and final work phase, the actual comparative morphotectonic DRM interpretation. Morpholineaments interpreted by one of the analyses only had to be verified additionally to increase their credibility. Positions of the individual brittle failure zones were modified by morphostructural analysis by means of spatial display methods. There are differences in location of morpholineaments between the methods used. In the aspect map, the line is placed to the point where the slope angle changes (in the talweg); in DRM it is located at the slope base. The found morpholineaments obtained by morphotectonic DRM analysis may not be zones of mass brittle failure. A morpholineament occurrence may be conditioned by selective rock erosion, boundary between two lithological units, gravitational deformation and course of the ridge or fold b-axis, etc. In this final phase, an important role is played by knowledge of tectonic development of the area, fault network character and spatial course of main fault zones. After all this information has been considered, morpholineaments are reclassified into zones of mass brittle failure. Morpholineaments the occurrence of which was not proved by the structural analysis are excluded from the resulting morpholineament network. Brittle failure zones are further divided according to the regional structure of the area and credibility of their existence.

7 RESULTING NETWOTK OF ZONES OF ROCK MASS BRITTLE FAILURE

The created network of rock mass brittle failure zones in the target example area covers two significant systems. The most significant system runs in the NW-SE direction and corresponds to the joints and faults in the Sudetic direction (Fig. 3). The important zones observed in this system are complex faults without a straight course and level fault surface. They are often composed of more faults of similar direction and angle. These distinct tectonic zones are not continuous. They consist of a system of parallel, echelon or pinnate faults sporadically interconnected by transform zones of NNW-SSE direction. In such cases, it is very difficult to determine the dominant fault. The second significant fault system runs in the NE-SW direction. These failure

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zones correspond to the bedding, cleavage and fold thrusts of unproductive Carboniferous. The continuity of these zones is not as distinctive as that of the Sudetic direction. This finding proves the fact that the original fold-thrust structure of the Moravosilesian region was subsequently distorted by much younger faults in the Sudetic direction. In the south-eastern part of the studied area, these zones merge into the ENE-WSW direction, which complies with the Odra faults course. The systems described distort the least distinctive system in the E-W direction, which is noticeable in the south-eastern part of the studied area in particular. The south-western part of the studied area with zones occurring in the N-S direction is very interesting. Here the system may be related to the fold axes displacement in the NNE-SSW direction. Valleys are based here on the combination of the NNE-SSW cleavage directions with joint zones in the WNW-ESE direction.

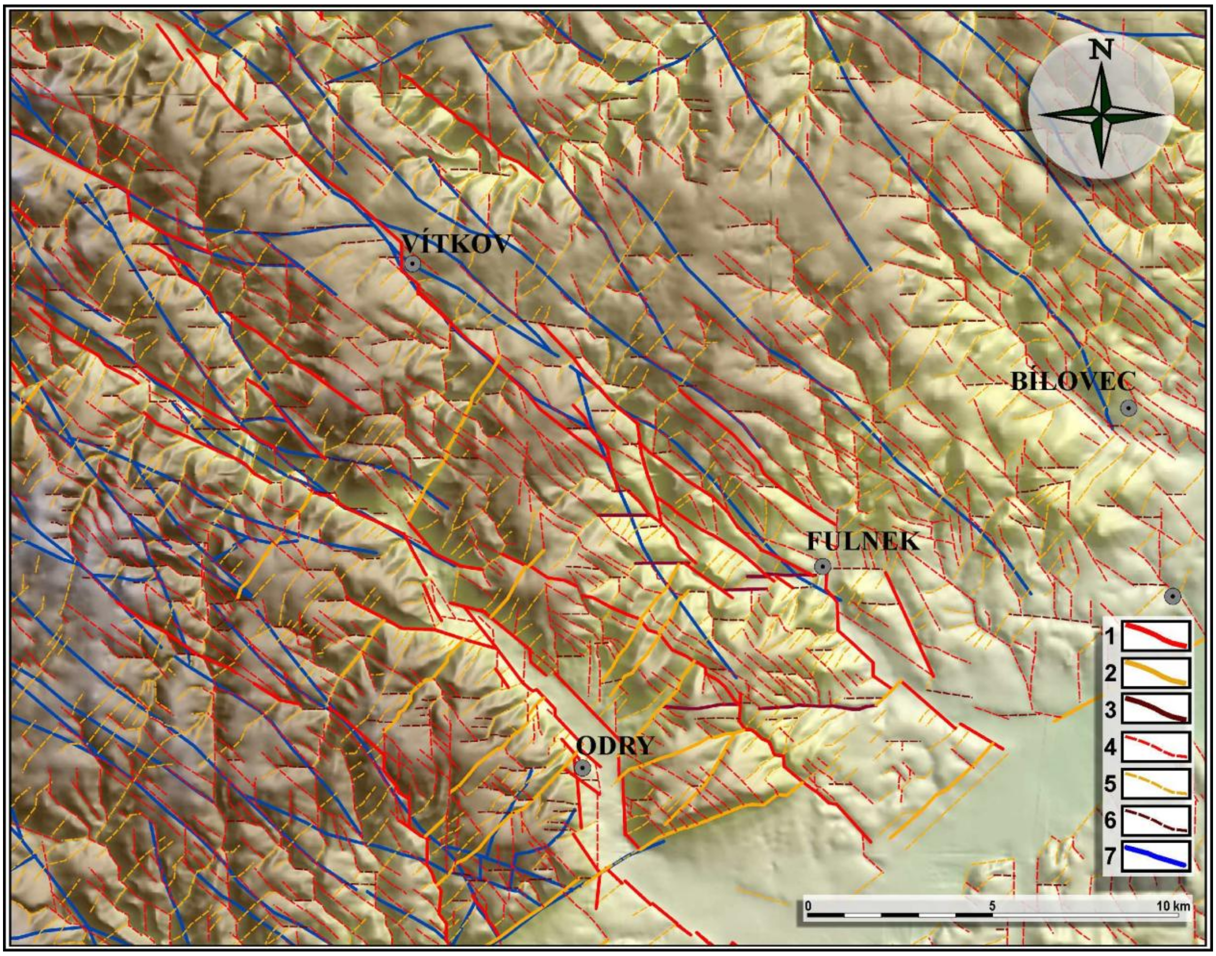

Fig. 5: DRM with rock mass brittle failure zones interpreted by morphotectonic analysis and faults of geological map on the scale M 1:50 000. Legend: 1 – distinct zones in Sudetic direction; 2 – distinct zones corresponding to fold thrusts and cleavage; 3 – distinct zones in the W-E direction; 4 – supposed zones in Sudetic direction; 5 – supposed zones corresponding to fold thrusts and cleavage; 6 – supposed zones in the W-E direction; 7 – faults of the geological map on the scale M 1:50 000.

The created network of brittle failure zones shows two variants of the Bělá fault south-eastern continuation. The first variant is relatively straight, but in the Oderské Vrchy Mts. region it starts to split into a system of pinnate zones interconnected by transform zones (Fig. 3). The second variant emerges as a wide zone of pinnate faults interconnected by transform zones from the beginning already. Comparing both the variants with the Bělá fault interpretations mentioned in literature (e.g., Buday et al. 1995; Špaček et al. 2006; geological map of the Czech Republic M 1:500 000 – Cháb et al. 2007), we cannot decide simply which of them is correct (Fig. 4). Anyway, none of the variants can be drawn as a single fault zone in the NW-SE direction. Comparing the zones interpreted with the fault network of the geological map M 1:50 000, we can find them consistent in general outlines (Fig. 5). The Sudetic direction faults, distorting the Variscan level here, have the WNW-ESE to NW-SE direction, and are interconnected by transform faults in the NNW-SSE direction. No distinct fault is found here passing through the whole area of interest in the direction of the Bělá fault drawn in literature. Therefore, it is more suitable to denote the area between the two variants found as a zone of south-eastern continuation of the Bělá fault.

Streams formed valleys which are mostly based on two-system combinations. The Sudetic direction is the most significant one. Nevertheless, it is very interesting that the valleys are primarily based on the N-S and WNW-ESE direction combinations in the south-eastern part of the studied area, whereas the NW-SE and NE-SW directions prevail in the north-eastern area. The dividing area is the Bělá fault zone. The Sudetic direction failure zones have the WNW-ESE direction to south-west of this zone, while the course is NW-SE to north-east.

The course character of the Bělá fault corresponds to the stress field described by Grygar and Jelínek (2002). In the Outer Carpathian nappes foreland, the Bělá fault get during the Alpine orogenesis to the position of transtension fault conjugated with N-S to NNE-SSW systems of the Outer Carpathian belt. Based on this assumption, movement kinematics was determined in the main fault zones (Fig. 1). A dextral movement component corresponds to the Bělá fault. Then the Sudetic direction faults of the Bělá fault zone correspond to Riedl fractures in the deformation ellipsoid.

The resulting network of brittle failure zones was confronted with the geological map on the scale M 1:50 000 (Fig. 5); in general outlines, it complies with the faults mapped. The map indicates the Sudetic fault system, mostly in the NW-SE direction, which sporadically merges into the WNW-ESE or NNW-SSE directions. The fault network does not reflect the overall character of brittle failure with echelon faults in the Sudetic direction interconnected by transform zones (Fig. 5). Sporadically, the course of the brittle failure zone interpreted fully corresponds with the fault course. However, we cannot find a fault indicated in its whole course. Field mapping revealed faults which were not visualized by any of the morphometric methods. This primarily applies to the areas of peneplenized relief of the Nízký Jeseník Mts. The morphotectonic analysis revealed a number of distinctive zones not displayed in the map. This may be due to different drawing details on different scales. This fact may also be the cause of the relatively straight course of faults drawn in geological maps, irrespective of the ground curvature. It is necessary to realize that the fault line is an intersection curve of the ground and the fault surface distorted in various ways. Unfortunately, the geological maps evaluated are to large extent affected by inaccuracies caused by the scale detail or influenced by the interpreting geologist's personal opinion. The fault network drawn in geological maps is not determining and cannot fully be used to verify the correctness of the failure zone network created.

8 CONCLUSIONS

The methodical procedure created, focused on finding brittle tectonics by means of DRM interpretation by morphotectonic analysis, is an additional technique suitable for creating geological maps. Its results may be employed both in the preliminary phases of exploration and in the final phase when the geological map is finalized. Within the preliminary exploration, tectonic failure systems can be found out based on the DRM interpretation. At the same time, suitable places are determined to verify the existence of interpreted faults and, above all, character of intersection of different system faults. The author of the geological map has enough information in the final phase of its drawing, from DRM study on small scales and the palaeostress analysis, to determination significant faults. DRM helps to determine precise location and course of the fault intersection curves with the relief. Observing the methodical procedure may eliminate inaccuracies in drawing the faults. The scientist may use the morphostructural DRM analysis results to draw faults under cover deposits. The methodical procedure was employed in the course of solving the grant project GA ČR 105/06/1264 "Digital model of South Moravia lignite coalfield – base of representative modern complex evaluation of coal deposit for future exploitation".

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RESUMÉ

Vyvinutý metodický postup interpretace zón křehkého porušení horninového masivu morfotektonickou analýzou DMR byl zaměřen na studium zlomového porušení moravskoslezské oblasti. Centrem pozornosti bylo zjištění charakteru a míry projevů variské tektoniky v reliéfu odkryté části variského strukturního patra moravskoslezské oblasti. Pro demonstraci metodiky byla vybrána dílčí část moravskoslezské zóny, v prostoru výskytu bělského zlomu v oblasti Nízkého Jeseníku. Průběh bělského zlomu je podrobně popsán a zmapován v oblasti silezika, kde vystupuje jako jihovýchodní pokračování okrajového sudetského zlomu (viz geologická mapa ČR M 1:500 000 – Cháb et al. 2007). Jihovýchodní pokračování bělského zlomu přes Nízký Jeseník mnozí autoři vykreslují značně odlišně (obr. 1). Stejně tak se liší při vykreslování jeho průběhu pod příkrovy Karpat (Buday et al. 1995). Jasno do problému nepřinesly ani aktuální geologické mapy měřítka M 1 : 50 000. Průběh křehké zóny bělského zlomu je složen z dílčích zlomů odlišného směru. Dokonce ani v nové regionálně geologické mapě měřítka M 1:500 000 (Cháb et al. 2007) není jednoznačně vykreslen jeho průběh.

Morfotektonická analýza DMR je schopna odhalit v konfrontaci se strukturně geologickými poznatky složité vazby mezi terénem a geologickou stavbou oblasti. Posouzení charakteru a míry projevů křehké tektoniky v současném reliéfu si vyžádalo nalezení nejoptimálnějšího metodického postupu studia DMR. Interpretace křehkého porušení horninového masivu probíhala čtyřfázově (obr. 2). V první fázi byly vytvořeny sítě liniových objektů (morfolineamentů) jednotlivými metodami morfometrické analýzy DMR (sklonitosti terénu, výškových hladin, orientace ke světovým stranám, stínového modelu, první derivace DMR). Vzhledem k faktu, že každá z metod zobrazuje jiné parametry reliéfu, neexistuje absolutní shoda těchto sítí. Rozdílná je také vhodnost použití jednotlivých metod v různých typech reliéfu. V druhé fázi prací byly vzájemně posouzeny výsledné sítě morfolineamentů. Pro určení dominantních směrů morfolineamentů bylo nutné získané výsledky statisticky posoudit. Použita byla směrová analýza liniových objektů provedená v dílčích oblastech. Testování probíhalo zvlášť pro dílčí oblasti, které byly voleny s ohledem na morfologii reliéfu, litologii hornin a geologickou stavbu dílčích oblastí. Získané růžicové diagramy morfolineamentů interpretovaných jednotlivými metodami byly pro dílčí oblasti navzájem porovnávány a následně konfrontovány s výsledky analýzy směrů říční sítě. Získané informace byly porovnány s výsledky strukturně tektonické analýzy. Úkolem bylo zjistit pro dílčí oblasti, zda je výskyt interpretovaného morfolineamentu z DMR v reliéfu krajiny možný a zda je podmíněn endogenními nebo exogenními procesy. Při morfotektonické analýze se interpretátor musí často rozhodovat, zda interpretovaný lineament určitého směru vůbec v daném místě existuje, nebo se jedná o kombinaci mnoha drobných lineamentů dvou různých směrů. Výsledky strukturně tektonické analýzy pomáhají při tomto rozhodování. Zvlášť pro jednotlivé dílčí oblasti se vyhodnocují puklinové a zlomové systémy, vrstevní plochy či foliace, případně kliváž nebo b-osy vrás.

K těmto informacím je pak přihlíženo při konečné čtvrté fázi prací, vlastní srovnávací morfotektonické interpretaci DMR. Morfolineamenty interpretované pouze některou z analýz bylo nezbytné pro zvýšení jejich věrohodnosti dodatečně ověřit. S využitím prostorových zobrazovacích metod byly morfostrukturní analýzou

upraveny pozice jednotlivých zón křehkého porušení. V této konečné fázi prací hraje významnou roli znalost tektonického vývoje oblasti, charakteru zlomové sítě a prostorového průběhu hlavních zlomových zón. Po uvážení všech těchto informací se přistoupí k reklasifikaci morfolineamentů na zóny křehkého porušení masivu. Z výsledné sítě morfolineamentů se vyloučí ty morfolineamenty, jejichž výskyt nebyl strukturní analýzou potvrzen. Zóny křehkého porušení se dále roztřídí v závislosti na regionální stavbě oblasti a věrohodnosti jejich existence.

Vytvořená síť zón křehkého porušení příkladové oblasti zobrazuje dvě varianty jihovýchodního pokračování bělského zlomu. První varianta je zpočátku relativně přímá, ale v oblasti oderských vrchů se začíná rozpadat na systém speřených zón propojených transformními zónami (obr. 3). Druhá varianta už od počátku vystupuje jako široká zóna speřených zlomů propojených transformními zónami. Pokud porovnáme obě varianty s interpretacemi bělského zlomu uváděnými v literatuře (např. Buday et al. 1995; Špaček et al. 2006; geologická mapa ČR M 1:500 000 – Cháb et al. 2007) nemůžeme jednoduše rozhodnout, která z variant je správná (obr. 4). V každém případě žádnou z variant nelze vykreslit jako jednu zlomovou zónu směru SZ-JV. Porovnáme-li interpretované zóny se sítí zlomů geologické mapy M 1:50 000 zjistíme (obr. 5), že v generelních rysech se shodují. Zlomy sudetského směru porušující zde variské patro mají směr ZSZ-VJV až SZ-JV a jsou propojeny transformními zlomy směru SSZ-JJV. Nenachází se zde žádný výrazný zlom procházející přes celou zájmovou oblast ve směru vykreslovaného bělského zlomu v literatuře. Proto považuji za vhodnější označit oblast mezi zjištěnými dvěma variantami za pásmo jihovýchodního pokračování bělského zlomu. Charakter průběhu pásma bělského zlomu odpovídá napěťovému poli, které popsal Grygar s Jelínkem (2002). Bělský zlom se dostal v předpolí vněkarpatských příkrovů při alpinské orogenezi do pozice radiálního transtenzního zlomu, konjugovaného se S-J až SSV-JJZ systémy vněkarpatského orogenního oblouku. Na základě tohoto předpokladu byla stanovena kinematika pohybu na hlavních zlomových zónách (obr. 1). Bělskému zlomu odpovídá dextrální pohybová komponenta. V deformačním elipsoidu potom dílčí zlomy sudetského směru bělského zlomového pásma odpovídají Rendlovým střihům.

Metodický postup, zaměřený na zjišťování křehké tektoniky prostřednictvím interpretace DMR morfotektonickou analýzou, je vhodnou doplňkovou technikou pro vytváření geologických map. Její výsledky se mohou uplatnit jak v předběžných fázích průzkumu oblasti, tak i v závěrečné fázi, kdy se vytváří konečná podoba geologické mapy. V předběžném průzkumu lze na základě interpretace DMR zjistit základní systémy tektonických poruch. Zároveň se určí vhodná místa, ve kterých se ověří existence interpretovaných zlomů a především charakter křížení zlomů různých systémů. V závěrečné etapě skreslování geologické mapy má její autor dostatek informací, ze studia DMR malých měřítek a paleonapěťové analýzy, pro určení řídicích zlomů. Dodržením metodického postupu se zamezí nepřesnostem při vykreslování zlomů. Výsledky morfostrukturní analýzy DMR může řešitel využít při vykreslení zlomů pod pokryvnými útvary.