

# USING GEOMORPHOLOGICAL AND GEOPHYSICAL SURVEY TO RESEARCH RELATIONS BETWEEN LANDFORMS AND JOINT TECTONICS IN THE BROUMOVSKÁ VRCHOVINA (CZECH REPUBLIC)

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## ABSTRACT

We analyze relationships between fault and joint tectonics and landforms in the south-western part of the Broumovská vrchovina (Bohemian Massif), where the surface topography is strongly influenced by the tectonics and lithology of the Upper Cretaceous and Permo-Carboniferous sedimentary series. We examine joint orientation using field measurements and 3D seismic tomography. The orientation of linear topographic features (morpholineaments) shows a clear dependency on two perpendicular joint systems, which exhibit either a NE-SW or a NW-SE orientation. Morpholineaments oriented in a NW-SE direction are more apparent in the surface topography and their frequency is higher. This can be attributed to the mechanical properties of NW-SE striking joints, which tend to be more open and penetrate to greater depths, making them more favourable for erosion processes.

**Key words:** Broumovská vrchovina, morpholineaments, 3D seismic tomography, joint tectonics.

## 1. Introduction

The evolution of landforms in Upper Cretaceous and Permo-Carboniferous sedimentary basins of the Bohemian Massif has been strongly influenced by the presence of Saxonian tectonic joints. The distribution and spatial orientation of subvertical joints in the rock massif is frequently viewed as a crucial factor influencing the morphology of macro-, mezo- and microforms in the relief. In addition, such joints can also be an important factor influencing slope deformations.

This paper presents an analysis of relations between landforms and joint and fault tectonics in Permo-Carboniferous and Upper-Cretaceous sediments in the south-western part of the Broumovská vrchovina (North-East Bohemia), an area with typical and well developed structural landforms. Similar research was realized in the watershed of Jihlava River by Balatka et al. (1999 and 2000). The orientation of tectonic joints in the Broumovská vrchovina was studied using field measurements on rock outcrops as well as shallow seismic prospection to detect the mechanical properties of joints in deeper parts of the rock massif. The analysis of landforms was carried out in Arc GIS, based on a 1 : 10,000 digital elevation model.

## 2. Geological and geomorphological settings

The studied area (Fig. 1) is situated in the south-western part of the Intra-Sudetic Basin. The present extent of the basin is marked by the presence of Carboniferous and Permian sediments north-east of the

Hronov-Poříčí fault zone (HPFZ), on the territory of NE Bohemia and adjacent areas of Poland. The Intra-Sudetic Basin was formed during the early Variscan tectogenesis and has been continuously filled with terrestrial and, to a certain extent, also with marine sediments and volcanics, from the Lower Carboniferous to the Upper Triassic. Local sedimentation was interrupted by post-Triassic tectonic movements that resulted in the denudation of the youngest sedimentary series. The period of denudation was terminated by an Upper Cretaceous (Cenomanian) sea transgression.

The present-day brachysynklinal structure of the basin with its NW-SE oriented axis originated during the post-Cretaceous Saxonian tectogenesis. In its early stages, the surface of flat lying Cretaceous deposits was warped by transversal anticlines and synclines and was, in later stages, also disrupted by transversal and longitudinal faults (Tásler et al. 1979).

The entire studied area is characterized by increased seismic activity, in comparison with the rest of the Bohemian Massif. According to the seismic zoning of Kárník et al. (1984), the entire Broumovská vrchovina is part of the Náchod-Kłodzko seismic region. The strongest seismic events in this zone are related to the HPFZ, while some weaker seismicity has also been observed along faults in the eastern part of the Krkonoše Mountains and Kłodzko graben in Poland. One of the strongest earthquakes ever observed in Bohemia was recorded on January 1, 1901 along the HPFZ (Schenk et al. 1989). Its macroseismic effects reached an intensity of 7° MSK-64.

In terms of geomorphological regionalization (Demek ed. 1987; Sládek 1977), the study area lies

within four lower-order geomorphological units: Polická vrchovina, Jestřebí hory, Rtyňská brázda and Hronovská kotlina.

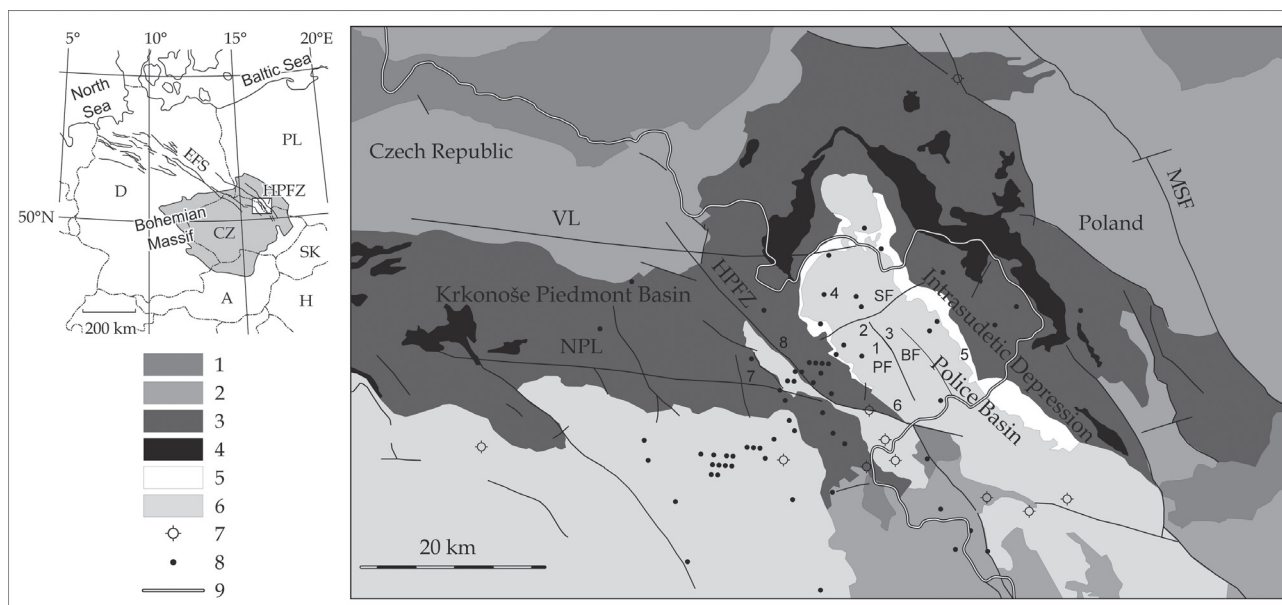
Polická vrchovina corresponds to the axial part of the Intra-Sudetic basin composed of Upper Cretaceous sediments up to 500 m thick. Sandstones, siltstones and marlstones from the Cenomanian to Upper Turonian ages dominate the lithology of surface sedimentary series. The age of the youngest Upper Cretaceous sediments remained unknown for a long time. Eventually, Vejlupek (1984) confirmed their Coniacian age, on the basis of paleontological studies. This concerns the thick bedded sandstones, located in the Adršpach-Teplice basin, and the mesas of Ostaš, Hejda, Hejšovina and Bor, that were preserved as denudation remnants along the axis of the Intra-Sudetic basin. Tásler and Kotlár (1987) attribute these sandstones, with an incomplete thickness of 130 m, to the Březno series.

Polická vrchovina is divided by the transversal Skály fault (oriented WSW-ESE) into two parts with different tectonic properties. The northern, relatively uplifted part is characterized by transversal faults, primarily with a SW-NE or WSW-ESE strike, while the southern part typically exhibits NW-SE oriented faults. Besides the Skály fault, other principal tectonic dislocations include the Police fault (striking NW-SE) responsible for the subsidence of the Hejda and eastern reaches of the Ostaš mesa by approximately 60 meters (Vejlupek 1986) and the Bělý fault (striking NNW-SSE), along which the eastern block of the Police basin subsided approximately 60 meters (Demek, Kopecký 1994).

Landforms and geomorphological processes in Polická vrchovina are strongly influenced by the structure and lithology of Upper Cretaceous sedimentary series. The main geomorphological features were most likely already present in the Pliocene. The selective denudation of brachysynclinally layered sedimentary series with different lithology gave birth to two parallel cuesta belts along the margins of Polická vrchovina and structural plains in its central part. The gradual uplift of the Intra-Sudetic basin, by approximately 100 m compared to the northern part of the Bohemian Cretaceous Basin, resulted in a Pleistocene rejuvenation of erosion processes and a series of present-day river networks, belonging to the catchments of the Metuje and Úpa Rivers (Tásler et al. 1979).

The Jestřebí hory (mountains) are situated parallel to the HPFZ in a relatively uplifted block. The subsided block – the Hronov-Poříčí graben – includes the remaining two geomorphological units – Rtyňská brázda (Fig. 2) and Hronovská kotlina. The relief is developed in Permo-Carboniferous (sandstones, conglomerates, siltstones, claystones and arcoses) and Upper Cretaceous sediments (sandstones, siltstones, marlstones). Upper Cretaceous sediments were only preserved in the subsided block, while the Permo-Carboniferous is exposed within the Jestřebí hory, where the Cretaceous was completely denudated.

The ridge of the Jestřebí hory (Fig. 2) reaches its highest altitudes in its NW part (Žaltman 739 m, Kolčarka 691 m), which corresponds with the maximum thickness of resistant arcoses and conglomerates of the Jívka



**Fig. 1** Geology and tectonics of the study area (based on Biely et al. 1968; Jetel and Rybářová 1979; Schenk et al. 1989; Schreck et al. 2002; Cymerman 2004). 1 – plutonic rocks (granites, granodiorites), 2 – metamorphites (gneisses, schists, granulites, migmatites), 3 – Permian and Carboniferous sediments, 4 – Permian volcanics, 5 – Triassic sediments, 6 – Cretaceous sediments, 7 – CO<sub>2</sub>-rich mineral springs, 8 – epicentres of seismic events recorded from 1985 to 2005, 9 – state boundary. HPFZ – Hronov-Poříčí Fault Zone, MSF – Marginal Sudetic Fault, EFS – Elbe Fault System, VL – Vrchlabí Lineament, NPL – Nová Paka Lineament, PF – Police Fault, BF – Bělý Fault, SF – Skály Fault. Localities of the joint measurements: 1 – Ostaš, 2 – Hejda, 3 – Kočičí skály, 4 – Teplické skály, 5 – Broumovské stěny, 6 – Metuje and Ledhujka valley SW of Police nad Metují, 7 – Úpa valley NW of Úpice, 8 – Jestřebí hory.

series (Upper Carboniferous – Stephanian). In this area, the ridge exhibits the characteristics of a cuesta. The denudational SW facing slope under the steep cuesta scarp is developed in less resistant aleurolites of the Svatoňovice series (Upper Carboniferous – Westphalian, Stephanian). The structural backslope of the cuesta, facing to the NE is inclined more or less to conform (10–20° to the NE) to the dip of arcoses and conglomerates of the Jívka series (25–30° to the NE). The ridge-crest runs parallel to the HPFZ and is not dissected by the backward erosion of streams flowing in the lower parts of both marginal slopes of the Jestřebí hory. Further to SE the Jestřebí hory range exhibits lower altitudes (Maternice 546 m). Compared to the Žaltman area, the ridge crest is more frequently dissected by backward erosion. The lithology of sedimentary series is characterized by the predominance of aleurolites over arcoses and conglomerates, which results in a prevalence of smooth landforms.

Rtyňská brázda and Hronovská kotlina are tectonic depressions situated along the foot of the Jestřebí hory, on the territory of the Hronov-Poříčí graben. They are characterized by smooth reliefs formed in Upper Cretaceous deposits and by the occurrence of flat floored and shallow fluvial valleys. Both depressions are bounded by relatively uplifted fault scarps. Morphologically the most apparent is the NE boundary, the marginal fault scarp of the Jestřebí hory.

### 3. Methods

#### 3.1 Joint measurements

Within the studied area, joint measurements were carried out in different sedimentary formations in following localities (Fig. 1):

- Thick bedded sandstones from the Březno series (Upper Cretaceous – Coniacian). Measurements were carried out in the following localities: Ostaš, Hejda, Kočičí skály and Teplické skály.
- Thick bedded sandstones from the Jizera series (Middle–Upper Turonian). Measurements were carried out in the middle part of Broumovské stěny, east of the municipality of Slavný.
- Spongilites from the Jizera series. Measurements were carried out on outcrops in the Metuje and Ledhujka valleys SW of Police nad Metují.
- Permo-Carboniferous sediments. Measurements were carried out in sandstones from the Trutnov series on outcrops in the Úpa river valley, NW of Úpice and on outcrops of Žaltman arcoses (Jívka strata) in the NW part of Jestřebí hory.

Most of the measurements (1,113 in total) were carried out in the thick bedded sandstones of the Březno and Jizera series, thanks to a large number of outcrops in the rock cities. There were considerably less measurements carried out in the spongilites of the Jizera series



**Fig. 2** The flat relief of Rtyňská brázda furrow near Batňovice. The uplifted block of Jestřebí hory is located in the background

(180 in total) and in the Permo-Carboniferous sediments (153 in total), where the presence of surface outcrops is significantly limited. The measurements in different localities are shown in Fig 3.

For comparison the orientation of tectonic joints and faults (Fig. 4), the orientation of faults was measured in 1 : 25,000 and 1 : 50,000 geological maps. Altogether, 88 km of tectonic faults were subject to analysis in Permo-Carboniferous sediments and 64 km in Upper-Cretaceous sediments.

### 3.2 Analysis of morpholineaments

In order to assess manifestations of fault and joint tectonics in landforms' morphology, we used a spatial analysis of morpholineaments method (Badura et al. 2003; Štěpančíková et al. 2008). Morpholineaments are defined as linear elements of relief, e.g. mountain fronts, ridge-crests, river networks, linearly distributed groundwater springs, etc. Within the studied area, we treated separately morpholineaments in the Upper Cretaceous sediments of the Polická vrchovina and Permo-Carboniferous sediments of the Jestřebí hory. The reason for this separate treatment was the detection of possible differences in the manifestations of fault and joint tectonics, in areas differing in basement lithology. In addition to that, we distinguished between morpholineaments delineated along the drainage network and morpholineaments delineated as straight-line ridge-crests, cuesta scarps or foothills of structural scarps or fault scarps. For the purpose of simplification, these two groups of morpholineaments will be referred to hereafter in the text as valley-type and topographic lineaments, respectively.

All morpholineaments were delineated based on digital topographic maps of 1 : 10,000 scale and processed in Arc GIS. The valley-type morpholineaments were obtained by converting the drainage network into polylines, composed of a varying number of segments with various lengths and azimuths. The topographic lineaments were delineated in a more subjective way, compared to all the other straight-line elements of the relief. In the subsequent spatial analysis, only morpholineaments longer than 200 m were taken into account. These were compared with the orientation of tectonic faults and joints within the studied area. Altogether, we analyzed 77 km of valley-type and 28 km of topographic morpholineaments in Permo-Carboniferous sediments and 181 km of valley-type and 78 km of topographic morpholineaments in Upper Cretaceous sediments. All the morpholineaments, including those shorter than 200 m, are shown in Fig. 5. The orientation of morpholineaments is shown in Fig. 6 and VII.

### 3.3 3-D seismic tomography

The detection of fractures and the designation of their direction, density, depth of penetration and

“intensity of fracturing” are issues often examined by near-surface geophysics. Many geophysical methods have been successfully applied to resolve these issues, often utilising azimuthal change in certain physical parameters. For example, a common technique in shallow seismic refraction is measurement along the profiles in different orientations. Changes in the velocities of seismic waves along individual profiles make it possible to estimate profiles which are parallel (faster) or perpendicular (slower) to the strike of a fracture system (e.g. Příklad et al. 2004). In our study, we use a solution based on 3D seismic tomography (e.g. Valenta and Dohnal 2007).

Fractures form in-homogeneities in the rock massif, which might be further accentuated by increased intensities of weathering in the near-surface zone. The weathering process essentially decreases the velocities of seismic waves in the rock. If fractures form entire fracture systems and are oriented in a certain direction (as in the case of fractures controlled by tectonic stress) then they are responsible for anisotropy of seismic waves. It should be emphasised that the wavelength of seismic waves as well as the geophone step are much larger than the size of the fractures and, consequently, the individual fractures cannot be determined.

In the event that fractures are localised in certain predetermined zones (e.g. zones with different mineralogical composition, structure, different parts of folds, etc.) and these zones are sufficiently large (compared to the size of the mesh of seismic inversion method applied), then they can be detected directly using seismic methods. Mechanical disintegration followed by an increased intensity of weathering results in a decrease in the velocities of seismic waves and the zones would appear as elongated low velocity zones. In contrast, if the zones are too small (again, compared to the size of the mesh of the seismic inversion) to be resolved directly, we end up with low and high velocity zones but, due to low resolution, these resolved zones might not necessarily be identical to the actual zones.

The testing locality was situated on a slightly inclined structural plain, at the foothill of the Ostaš mesa in the central part of the Polická vrchovina. The underlying rock is formed of sub-horizontally layered spongilites and fine-grained sandstones of the Jizera series. The strata dip is up to 10°. Seismic receivers were distributed along two concentric circles with the diameters of 30 and 60 metres. A sledgehammer was used as a source of seismic energy. To record seismic waves three-component BR3 seismographs were used (Brož 2000); however, in this case, only the P-waves were processed. The sites of the “shots” were identical with the locations of geophones and additional “shots” were deployed outside of the outer circle and inside the inner circle. A total of 13 seismographs and 21 shots were deployed. This configuration made it possible to reach an effective survey depth of 15 metres (Valenta 2007). Data were processed by the first arrival

picking. The maximum error of reciprocal travel times was less than 5%. Picks were processed by FAST, a travel time tomography package by Colin Zelt (Zelt and Barton 1998). This program uses finite difference calculations for travel time and time field computations. Ray tracing is performed “backwards”, perpendicular to the isochrons of the time field. The program uses smoothness and flatness constraints, thus seeking the smoothest and flattest model.

## 4. Results and Discussion

### 4.1 Analysis of joint measurements

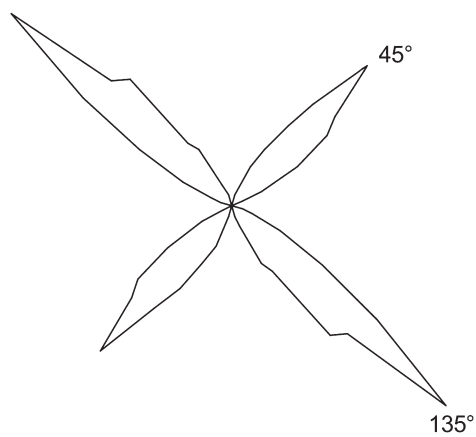
The results of joint measurements are shown in Fig. 3. They can be summarized in the following points:

- Joint tectonics in the area of Broumovská vrchovina (i.e. East of HPFZ) exhibit two dominant directions – approximately NE-SW and NW-SE. More precisely, the following directions were identified: 40–50° and 130–140° in thick bedded sandstones (Localities 1–5), 40–60° and 120–140° in spongilites of the Jizera series (Locality 6) and 30° and 125° in the Žaltman arkoses (Locality 8). These primary directions are always slightly shifted to the North (i.e. counter clockwise) with respect for the orientation of the main tectonic faults (cf. Fig. 4A) manifesting a prevailing strike of 50–80° and 130–170° in the Upper Cretaceous formations of Polická vrchovina and 60–80° and 140° in the Permo-Carboniferous sediments of Jestřebí hory.
- Joint orientation in sandstones from the Trutnov series in the Úpa valley (West of HPFZ) exhibits substantially different prevailing directions: 80–90° (N-E) and 170° (E-W). The reason for the different orientation of tectonic joints in areas E and W of HPFZ can be seen in the differing orientation of stress fields along both sides of HPFZ at the time when the joints originated.
- The joint measurements exhibit considerably higher variation in sediments different from the Upper Cretaceous thick bedded sandstones. Several different directions can be observed both in arcoses of the Jívka strata and, particularly, in spongilites of the Jizera series, where N-S is the most pronounced direction.
- Different localities selected for joint measurements in the thick bedded sandstones of Polická vrchovina were selected so that they were situated in different tectonic blocks (Fig. 1), i.e. Teplické skály N of the Skály fault, Ostaš S of the Skály fault and W of the Police fault, Hejda and Kočičí skály S of the Skály fault and between the Police and Bělý fault and Broumovské stěny S of the Skály fault and E of the Bělý fault. Between particular localities no significant differences in joint orientation were observed, which suggests uniform orientation of stress fields throughout the entire basin at the time of the joints' origin.

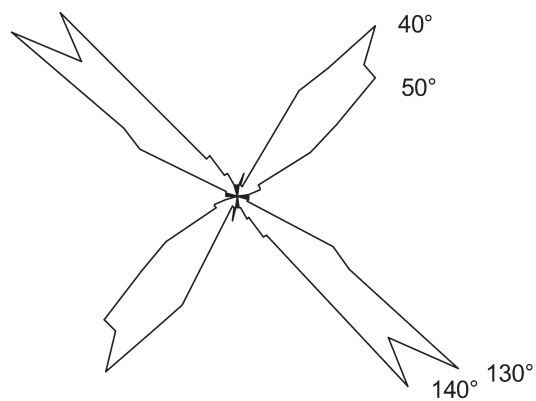
### 4.2 Analysis of morpholineaments

Summarizing the results of spatial analysis of morpholineaments, we came to the following observations:

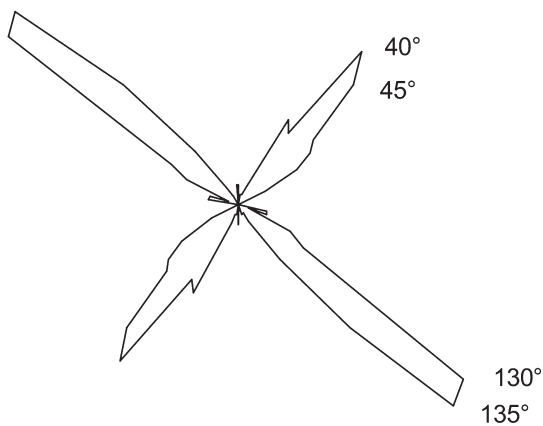
- In all cases we can clearly observe more or less pronounced directivity of morpholineaments, typical with one or two maxima of concentration in the NE-SW or NW-SE quadrant, respectively.
- The orientation of valley-type morpholineaments in the Upper-Cretaceous sediments in Polická vrchovina has maxima between 40 and 70° in the NE quadrant and 140 and 160° in the SE quadrant (Fig. 6A and B). Upon removing the Metuje river valley measurements, where we can expect a lower degree of dependency on joint tectonics, we observe the same orientation of maxima for the entire remaining set of morpholineaments; however, these maxima are much more dominant due to the lower variability of observations (Fig. 6B). In both cases (i.e. with and without the Metuje valley), there are two obvious maxima in both quadrants, where the first one (40 and 140°) corresponds to the orientation of joints and the second one (140 and 160°) corresponds to the orientation of faults.
- The orientation of topographic morpholineaments in Polická vrchovina (Fig. 6C) reaches its maximum frequency at 140 and 160°. The maxima in the NE quadrant (40 and 60–80°) are somewhat suppressed by the presence of long straight line fault scarps along the Police and Bělý faults and cuestas striking NW-SE. Similar to the valley morpholineaments, two maxima in the SE quadrant are observed, which correspond to the orientation of tectonic joints and faults.
- The orientation of the valley-type morpholineaments in the Permo-Carboniferous sediments of Jestřebí hory (Fig. VIIA) has maxima at 70, 130 and 150°. The two maxima that are related to the different orientation of joints (150°) and faults (130°) can be identified in the SW quadrant only.
- The topographic morpholineaments in the Permo-Carboniferous sediments (Fig. VIIB) have only one distinct maximum, at 140°. The second maximum in the NE quadrant is again suppressed by the presence of the NW-SE direction, along which the whole ridge of Jestřebí hory is oriented.
- Generally the valley-type morpholineaments exhibit considerably higher variability of directions. This is especially apparent when the Metuje river valley (Fig. 6) is included. The reason is clearly the higher intensity of erosion developments in the river valleys, as compared to the straight fault scarps which are not affected by river erosion and which represent the majority of the topographic morpholineaments.
- Both in the Upper Cretaceous sediments of the Polická vrchovina and the Permo-Carboniferous sediments of the Jestřebí hory we observe that both types of



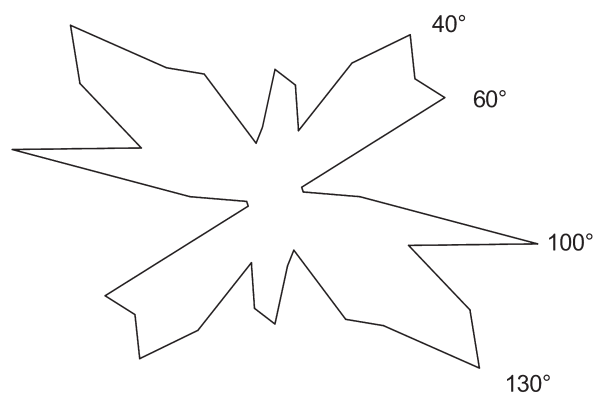
**Locality 1, 2 and 3**



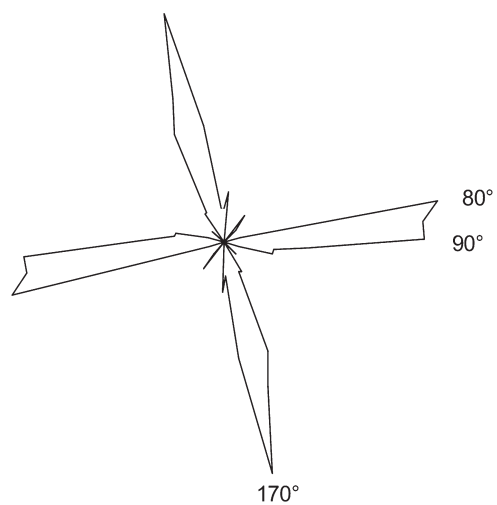
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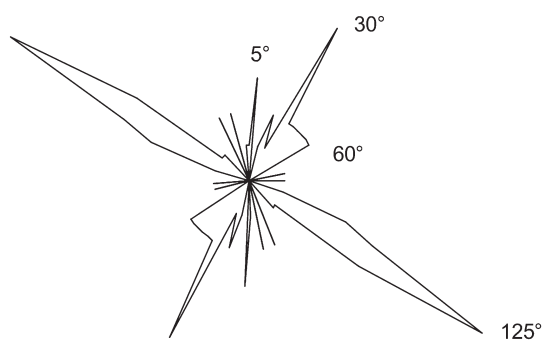
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**Locality 6**

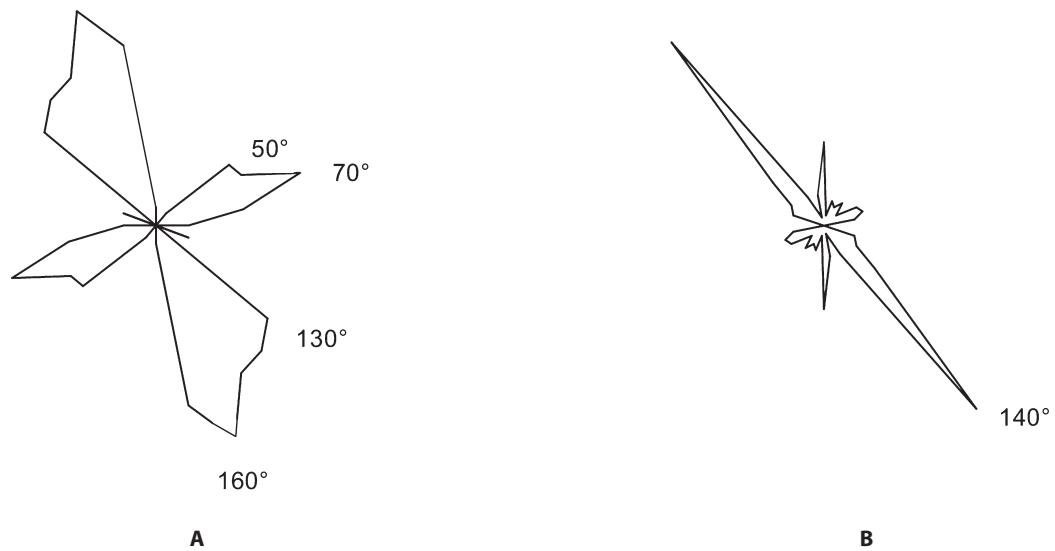


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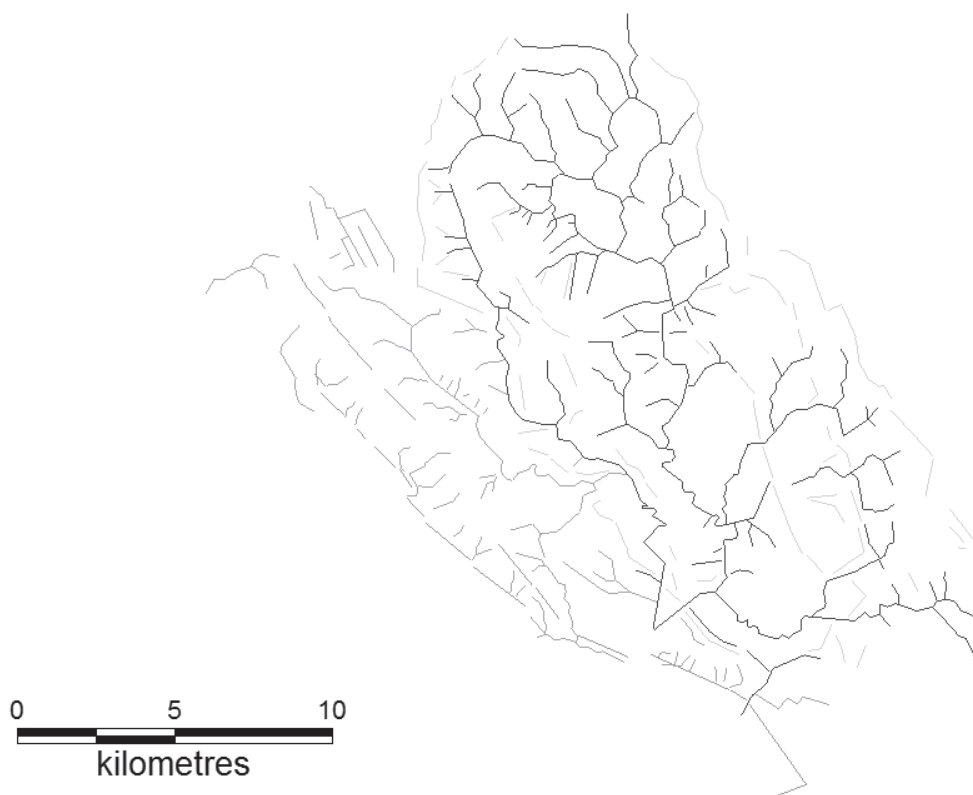
**Fig. 3** Joint measurements in different sedimentary series. Number of measurements made: localities 1, 2 and 3 – 713, locality 4 – 200, locality 5 – 200, locality 6 – 180, locality 7 – 100, locality 8 – 53



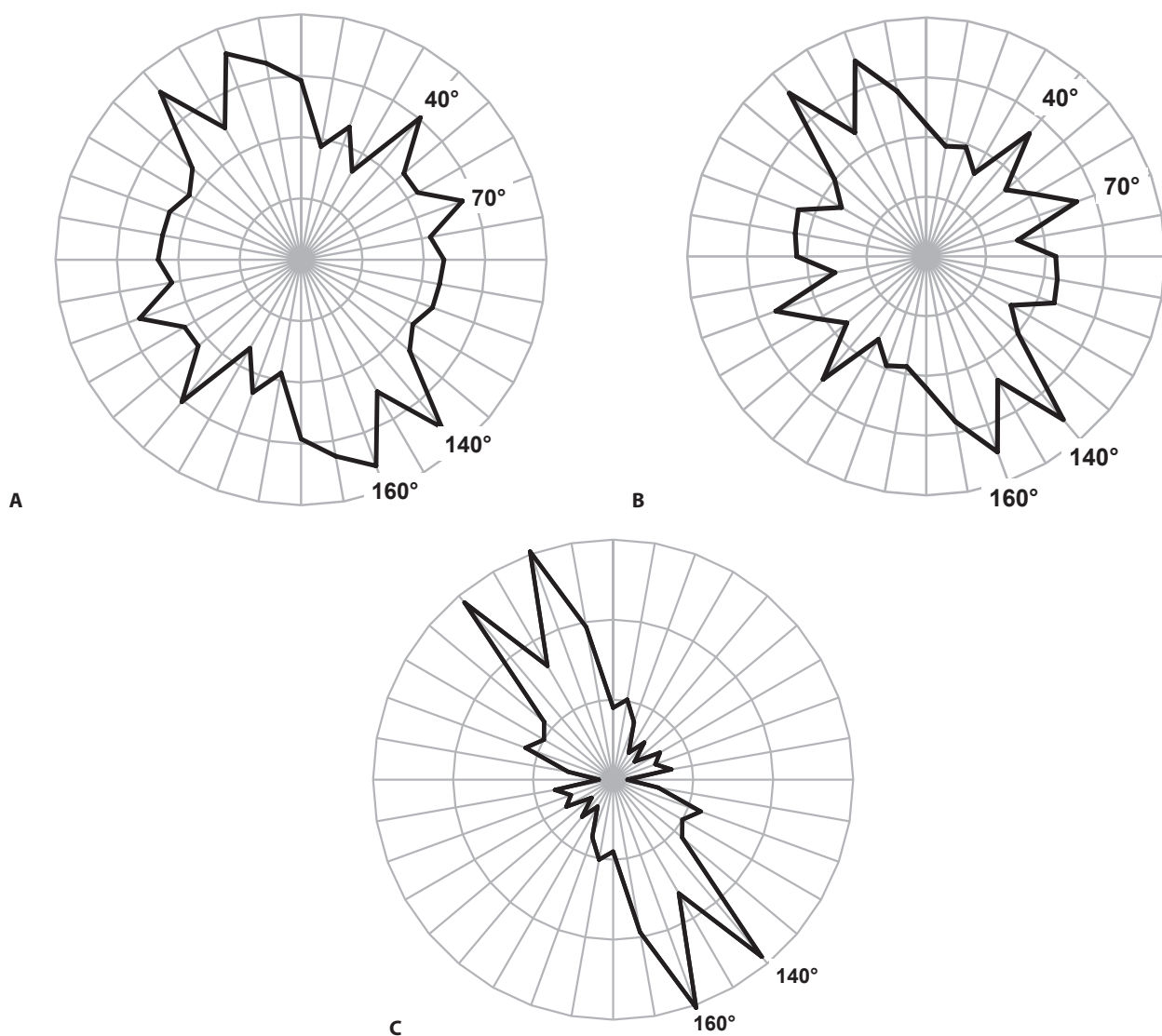
**Fig. 4** Orientation of tectonic faults in Polická vrchovina (A) and Jestřebí hory (B). In total, 64 km were analyzed in Polická vrchovina and 88 km in Jestřebí hory

morpholineaments are more concentrated into the NW-SE quadrants. The dominance of NW-SE directions is typical, primarily, for topographic morpholineaments, where the concentration in NW-SE quadrants reaches 70% in the Upper Cretaceous and 96% in the Permo-Carboniferous sediments. In order to explain

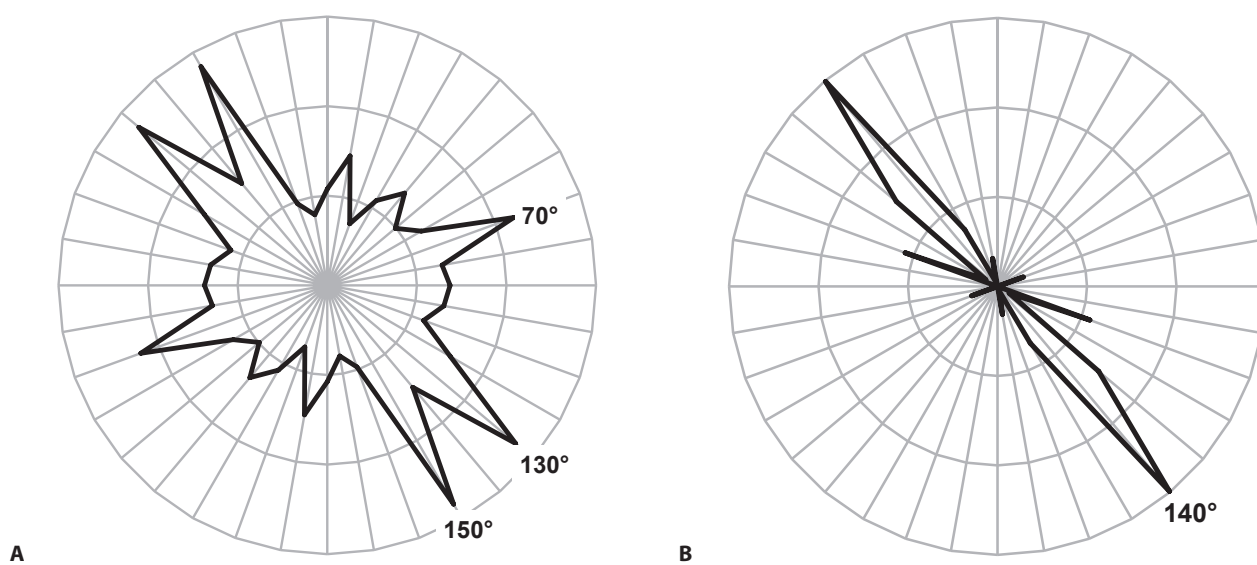
the prevailing NW-SE orientation of morpholineaments we carried out a shallow seismic survey in the middle part of Polická vrchovina. Our objective was to detect the mechanical properties of tectonic joints that would be favourable for erosion processes concentrated along one particular direction of tectonic joints.



**Fig. 5** Map of morpholineaments of both types delineated in the studied area of Polická vrchovina and Jestřebí hory



**Fig. 6** Morpholineaments in Upper-Cretaceous sediments of Polická vrchovina. A – valley type morpholineaments with all river valleys included. B – valley type morpholineaments excluding the Metuje valley. C – topographic morpholineaments



**Fig. 7** Morpholineaments in Permo-Carboniferous sediments of Jestřebí hory. A – valley type morpholineaments. B – topographic morpholineaments

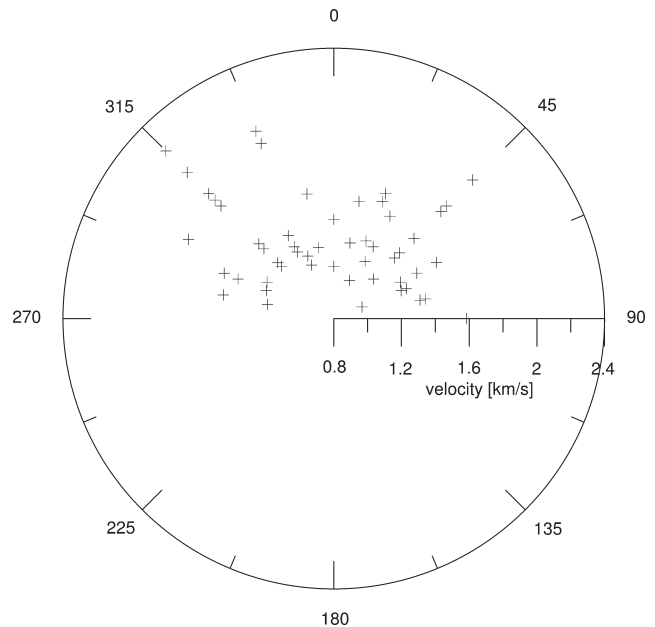


### 4.3 Tectonic joint detection using 3D seismic tomography

We expected the orientation of fracture systems to reveal itself in the form of elongated lower-velocity zones of seismic waves in the direction of fractures. In contrast, regarding the measurements of azimuthal changes in velocity, the orientation of fracture systems is indicated by an azimuth with increased values of seismic wave velocity. The seismic tomography computes velocities for a large portion of the model: in areas where the ray coverage is sufficient. Hence, lateral and vertical changes in the “fracture zones” can be tracked, i.e. tendencies to fade out or change direction. Cross-sections from the computed model are shown in Fig. 8. The low velocity anomalies depict zones weakened by fracturing. The profiles clearly illustrate vertical changes in the fracture systems. Both fracture systems are sub-vertical. The NE-SW fracture system is shallow and prevalent in the near-surface zone but fades out quickly with increasing depth. It is apparent down to a depth of approximately 9 metres. In deeper parts of the model, it is overridden by the Sudetic NW-SE fracture system. To test the correctness of these results we can utilise a previously mentioned method of measurement along profiles with different orientations and look for the seismic anisotropy as further proof of the presence of fracture systems. We can benefit from the fact that the refractor was found to be sub-horizontal at a depth of three metres. Therefore the values of apparent velocities are only significantly affected by changes in the seismic velocity of the media and not by changes in the slope of interfaces. Thus we can use the azimuthal change in apparent velocities as an indicator of seismic anisotropy, similarly to measurements along profiles with different orientations. We selected source-receiver pairs for which source-receiver distance ranges between 20 and 30 metres. Such pairs are plotted in Fig. 8. The rays connecting source-receiver pairs in the latter figure are affected by structures in roughly the same depths and, therefore, any corresponding velocities should be comparable. The azimuthal differences in velocities clearly depict two directions with increased values of apparent velocity – 45° (NE-SE) and 315° (NW-SE).

Our interpretation of the results of 3D seismic tomography is consistent with direct joint measurements. We identified two perpendicular, sub-vertical joint systems with NW-SE and NE-SW orientations. Joints in the NE-SW direction were not detected deeper than nine metres below the surface, indicating that they close relatively quickly with increasing depth. On the other hand, joints in the NW-SE direction were still quite apparent even at a depth of 15 m. This finding is very important, especially when studying the dependencies between morpholineaments and joint tectonics. In the previous section we concluded that, from the entire studied area, morpholineaments with a NW-SE orientation are more frequent than those with a NE-SW orientation. Based on the results of the 3D seismic

tomography, this can be attributed to the differing mechanical properties of both joint systems. The more opened joints aligned in a NW-SE direction are more favourable for weathering and erosion processes, which subsequently lead to a higher concentration of landforms into these directions.



**Fig. 8** Azimuthal distribution of apparent velocities for source-receiver pairs with a distance between 20 and 30 metres. The graph shows two directions of increased velocities – 45° (NE-SE) and 315° (NW-SE)

## 5. Conclusions

Direct measurements of tectonic joints in Upper Cretaceous and Permo-Carboniferous sediments revealed two different prevailing directions of perpendicular joint systems. Two prevailing directions – N-S and E-W – were identified west of the Hronov-Poříčí fault zone (HPFZ), while east of the HPFZ, in Jestřebí hory and Polická vrchovina, NE-SW and NW-SE directions prevail. The different orientation of tectonic joints east and west of the HPFZ can be explained by different orientations of stress fields at the time when the joints originated. Compared to the orientation of local tectonic faults, the dominant directions of joints are slightly shifted to the north (i.e. in a counter-clockwise direction). 3D seismic tomography confirmed the joint directions detected by field measurements. In addition, by using this indirect method, we identified different mechanical properties of the NE-SW and NW-SE striking joints, i.e. the latter joint system is more opened and penetrates to greater depths.

The orientation of linear topographic features (morpholineaments), as identified from 1 : 10,000 topographic

maps, shows clear dependency on the orientation of tectonic joints as identified by the two above-mentioned methods. However, morpholineaments with a NW-SE orientation are more apparent in surface topography and exhibit a higher frequency of occurrence. This can be attributed to the mechanical properties of the NW-SE striking joints which are more susceptible to denudation and erosion processes.

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## RÉSUMÉ

### Využití geomorfologického a geofyzikálního výzkumu při studiu vztahů mezi tvary reliéfu a puklinovou tektonikou v Broumovské vrchovině (Česko)

V článku byl analyzován vztah mezi zlomovou tektonikou, systémy puklin a povrchovými tvary reliéfu, a to v jz. části Broumovské vrchoviny, kde se v reliéfu výrazně projevuje tektonická a litologická predispozice sedimentárních souvrství pocházejících z období permo-karbonského a ze svrchní křídly. Systémy puklin byly zjištěny při terénních měřeních a z 3D seismické tomografie. Směry lineárních topografických prvků (morfolineamentů) vykazují závislost na systému vzájemně kolmých směrů puklin (JZ-SV a SZ-JV). Morfolineamenty směru SZ-JV se v reliéfu projevují výrazněji a frekvence jejich výskytu je také četnější. Toto může být přisouzeno jejich mechanickým vlastnostem, jelikož jsou více rozvětvené a pronikají do větší hloubky. Těto skutečnosti využívají jak zvětrávací, tak i erozní procesy a vede to k častějšímu zastoupení erozních forem reliéfu.

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