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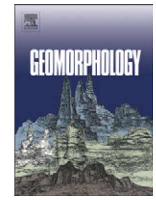

Neotectonic development of drainage networks in the East Sudeten Mountains and monitoring of recent fault displacements (Czech Republic)

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ABSTRACT

This paper presents results of morphotectonic research carried out in order to determine the neotectonic development of the drainage network in the NE spur of the Bohemian Massif (central Europe). The area studied comprises the north-eastern sector of the Rychlebské Mts, belonging to the Sudeten Mountains and the adjacent part of the Žulovská Hilly Land in the Sudetic Foreland (Czech Republic). Analysis of drainage network characteristics such as cross-sections, erosion rate, longitudinal river profiles, stream length-gradient index (SL) and investigation of alluvial fans/terraces was performed using detailed geomorphological mapping and field examination, and DEM data. Moreover, a reconstructed neotectonic evolution was compared with present-day fault movements obtained by fault monitoring using the TM71 deformeter. The deformeter was installed directly across faults in two karst caves in the study area within the NW–SE striking Sudetic Marginal Fault (SMF) zone. This zone is one of the morphologically most prominent neotectonic structures in central Europe, separating the Sudeten Mountains from the Sudetic Foreland. Morphotectonic research reveals that segments of enhanced erosion correspond well with increased SL indices, changes in valley cross-sections and anomalies in the longitudinal profiles. The beginnings of the stretches of increased headward erosion/rejuvenated erosional phase are concentrated at the foot of marginal slopes of the mountainous sector of the study area, which supports the hypothesis that uplift of the mountainous sector is still expressed in its relief. Alluvial fans/terraces of three levels recognized in the adjacent Žulovská Hilly Land are of Middle to Late Pleistocene age: Saalian 1 (240–280 ka), Saalian 2 (130–180 ka) and Weichselian (10–80 ka), respectively. They postdate the retreat of the last continental ice-sheet, which reached the study area in Elsterian 2 (400–460 ka). Their relative heights above the river channel are greater than terrace levels of the same age along the main Nysa Kłodzka River. The height differences attain 20 m at the highest level 1, at least 8 m at level 2, and up to 2–3 m at level 3. These discrepancies imply post-Saalian 1 uplift of the Žulovská Hilly Land relative to the topographically lower Nysa Kłodzka valley.

Monitoring of present-day tectonic movements in the studied area revealed slow micro-displacements (hundredths to tenths of millimetres per year). The displacements have an aseismic character and the vertical component always prevails over the horizontal one. The inferred compressive stress comes generally from the southern sector, which would imply dextral transpression in the studied portion of the SMF, where the northern part is thrusting over the southern one. The trend of these present-day movements corresponds well with uplift of the studied area north of the SMF, which is also indicated by analysis of the drainage network. It is concluded that in areas of low tectonic activity the detailed study of individual characteristics of the drainage network, particularly their spatial relationships, as well as monitoring of fault micro-displacements can reveal rates and kinematics of ongoing tectonism.

1. Introduction

There is a wide range of definitions for the term neotectonic (see e. g. Vita-Finzi, 1986; Becker, 1993; Zuchiewicz, 1995). The majority of authors define neotectonics as crustal movements starting after the youngest orogenic phase or related to the youngest stress field occurring in the late Neogene and Quaternary. Opinions on the onset of the neotectonic period in central Europe, particularly in the Bohemian Massif, underwent an evolution, which closely followed the gathering of more data. Kopecký (1972) considered neotectonics in the Bohemian Massif to begin in the Oligocene, because neotectonic movements have formed the main features of present-day relief. Dyjor (1983) put the onset of neotectonics within the Sudetic region, in the NE part of the Bohemian Massif, as late Paleogene, later to Neogene (Dyjor, 1993).

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According to Becker (1993), characteristic changes in the tectonic evolution of central and northern Europe occurred for the last time in the early late Miocene, therefore the onset of neotectonic activity should be associated with this period, approximately 10 Ma BP. Zuchiewicz (1995) suggested that the neotectonic stage should be confined solely to the Pliocene and Quaternary. In this paper, however, we deal mainly with younger tectonic movements occurring during the Quaternary.

As the Bohemian Massif is a part of the Epihercynian platform (pre-Alpinian), for decades it was considered rather stable during the Quaternary (see e.g. references in Kopecký, 1972). However, morphotectonic research carried out in Czech and Polish parts of the Bohemian Massif during the last two decades has revealed areas of at least Middle-Pleistocene tectonic activity (e.g. Kalvoda and Stemberk, 1993; Vilímek and Stemberk 1994; Vilímek, 1995; Krzyszkowski and Pijet, 1993; Krzyszkowski et al., 1995, 2000; Badura et al., 2003). Moreover, in addition to seismic activity, results gained from geophysical and geodetic surveys (precise levelling), monitoring of micro-displacements directly on fault planes, and GPS measurements have revealed recent tectonic activity in the Bohemian Massif, although of low intensity compared to areas of active mountain building (Cacoń and Dyjor, 1995; Kalvoda, 1995; Košťák, 1998, 2000; Schenk et al., 2003; Kontny, 2004; Cacoń et al., 2005).

The aim of this paper is to assess how active tectonics in the northeastern spur of the Bohemian Massif is expressed in the development of the drainage network. The area belongs to the Fore–Sudetic block separated from the Sudeten Mountains by one of the most clearly marked tectonic zones in Central Europe; the 300 km long, NW–SE striking Sudetic Marginal Fault (SMF). The SMF underwent various types of movements during its evolution (Oberc and Dyjor, 1969; Skácel 1989; Mastalerz and Wojewoda, 1993; Krzyszkowski et al., 1995; Badura et al., 2003, 2004). Apart from the prominent mountain-front fault scarp of the Sudeten Mountains, the trace of the SMF and other parallel faults within the zone is marked by mineral springs and Neogene to Quaternary volcanic rocks (Buday et al., 1995; Badura and Przybylski, 2000a; Birkenmajer et al., 2002; Badura et al., 2005 and references therein). Moreover, historical seismicity has been documented within this region along the trend of the SMF and connecting splays (Kárník et al., 1958; Pagaczewski, 1972; Guterch and Lewandowska-Marciniak, 2002).

Because drainage patterns may contain useful information about the past and present tectonic regime (see e.g. Seeber and Gornitz, 1983; Audemard, 1999; Burbank and Anderson, 2001; Keller and Pinter, 2002), the drainage basin of the study area was analysed to assess its neotectonic development. In addition, a comparison of the fracture system and the arrangement of landforms, which can have a causal relationships (cf. e.g. Ericson et al., 2005), was performed. Monitoring of micro-displacements directly on fault planes was carried out in order to assess present-day movements. Subsequently,

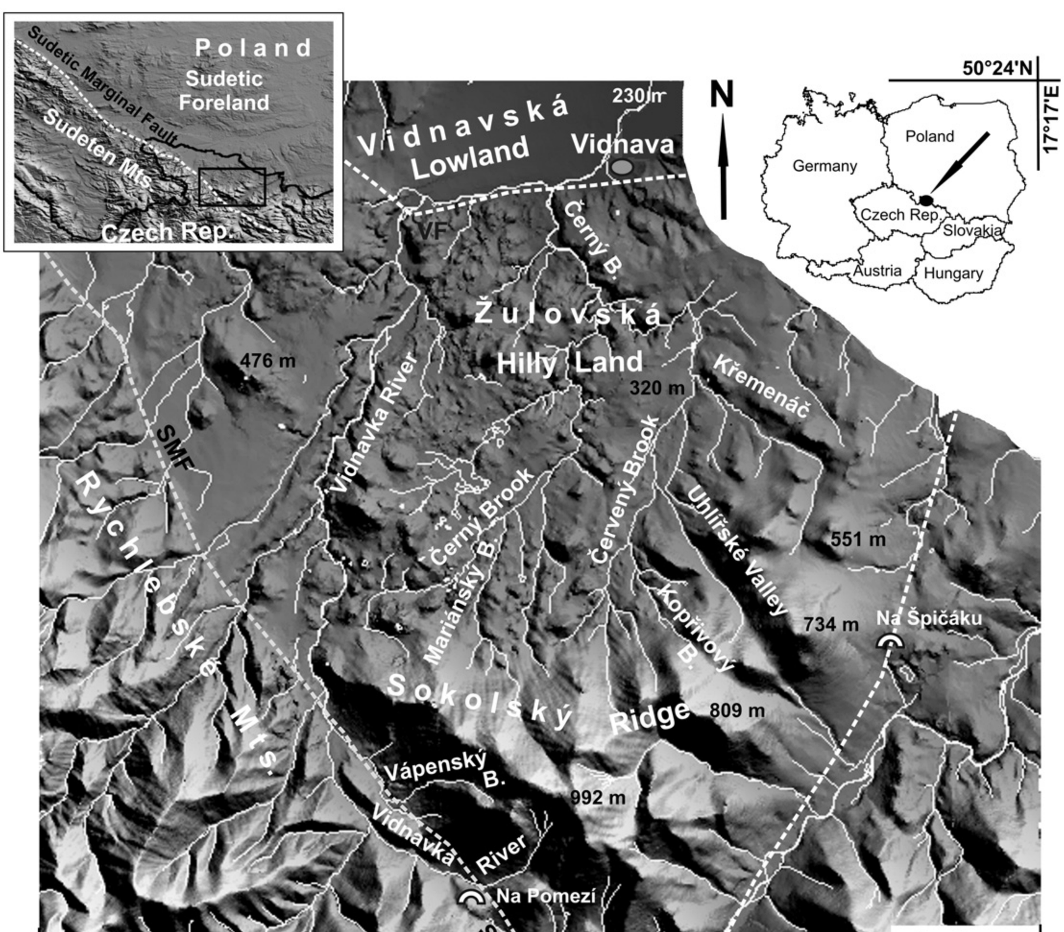

Fig. 1. Topography and morphology of the area under study. SMF — Sudetic Marginal Fault, VF — Vidnava Fault.

the present-day trend of movements obtained by the monitoring was compared with the general neotectonic evolution of the study area.

2. Morphological and geological settings

The studied area (100 km^2) is located in the north of the Czech Republic and includes the north-eastern part of the Rychlebské Mts, called the Sokolský Ridge, and the adjacent part of the Žulovská Hilly Land (Fig. 1).

The wedge-shaped Sokolský Ridge (highest peak: Studniční Mt. 992 m a. s. l.) is a horst-like structure descending stepwise to the NE along the parallel NW–SE striking faults, similarly to the entire Rychlebské Mts (Ivan, 1997). The marked marginal slopes of the Sokolský Ridge are probably bound by faults along which the entire structure was elevated above its surroundings by over 600 m. The highest part involves round isolated hills separated by wide flat valley heads.

The adjacent part of the Žulovská Hilly Land is a slightly lowered basal surface of weathering of the pre-Neogene planation surface (etchplain). The basal surface contains numerous inselbergs and also several remnants of kaolin-rich saprolites (Demek, 1976; Ivan, 1983; Demek, 1995). Additionally, this undulated basal surface was reworked by a Pleistocene continental ice-sheet, which reached the area probably in the latest Elsterian 2 (400–460 ka). (Žáček et al., 2004). In the north, towards the lower-situated Vidnavská Lowland, the Žulovská Hilly Land is delimited by fault scarps, which are 30 to 40 m high. The Vidnavská Lowland is a part of the Paczków Graben, one of the Fore–Sudetic Neogene grabens, filled with Miocene deposits up to 680 m thick (see e.g. Frejková, 1968; Ondra, 1968; Cwojdziński and Jodłowski, 1978; Badura et al., 2004 and references therein).

The study area comprises the Variscan Žulová granite pluton, which is the apical part of a vast granitic body marked by an extended gravity low (Cháb and Žáček, 1994), and its Devonian metamorphic cover including a belt of predominantly gneisses, amphibolites, quartzites, and marble. The entire studied part of the Žulovská Hilly Land and the north-western marginal slope of the Sokolský Ridge is composed of granitoids of the Žulová pluton, whereas the eastern part of the Sokolský Ridge is built up of the metamorphic cover (Fig. 2). Neogene sediments linking to relative subsidence of the Fore–Sudetic block occur in the adjacent part of the Vidnavská Lowland and are more than 270 m thick there (Gabriel et al., 1982). They cover a kaolinised (to a depth of 50 m) granitic basement (Ondra, 1968; Kościówko, 1982), which was dislocated and placed to different altitudinal levels. Quaternary sediments occur mostly only in the Žulovská Hilly Land. They include glacigenic, alluvial, fluvial and colluvial deposits (Žáček et al., 2004; Pecina et al., in press).

3. Methods

3.1. Analysis of drainage network

A systematic geomorphological analysis of the drainage network was carried out by means of field mapping and survey of anomalous features of individual valleys. These are particularly related to anomalies in their longitudinal profiles and cross-sections (knick-points, changes in intensity of rejuvenated/modern erosion).

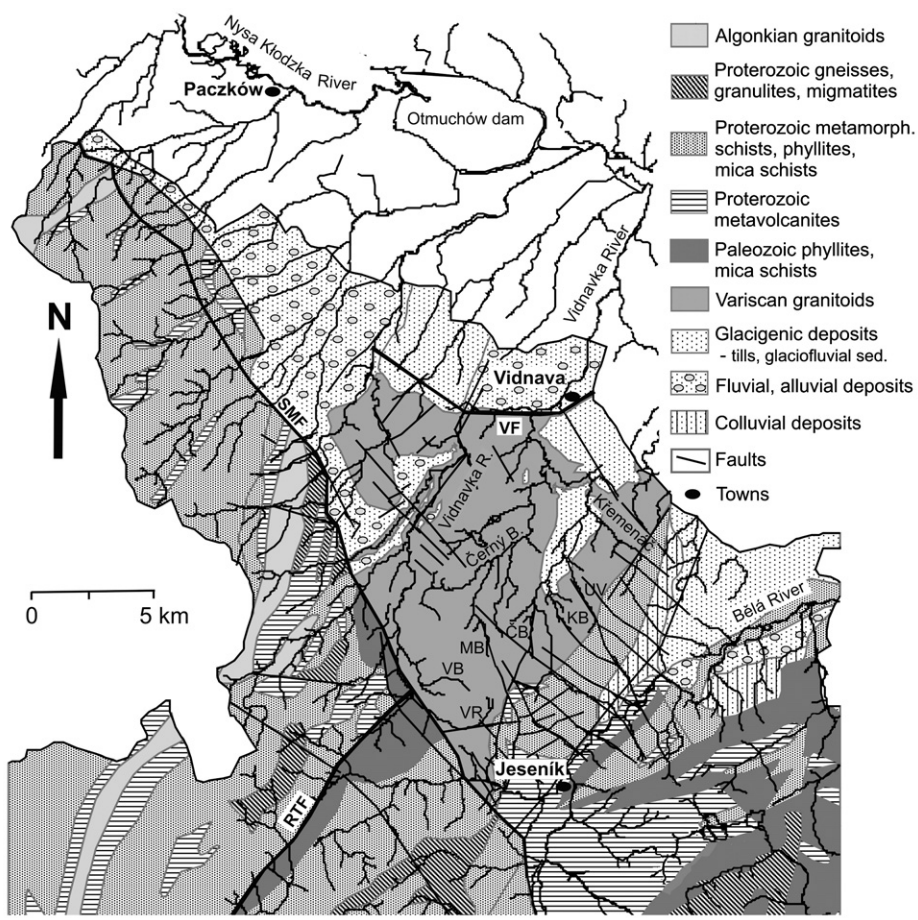

Fig. 2. Geological sketch of the studied area. SMF — Sudetic Marginal Fault, VF — Vidnava Fault, RTF — Ramzová Thrust Fault separating Lugicum and Silesicum, VR — Vidnavka River, VB — Vápenský Brook, ČB — Červený Brook, MB — Mariánský Brook, KB — Kopřivový Brook, UV — Uhlířské Valley Brook (compiled with the basic geological map by the Czech Geological Survey, 1998).

Longitudinal profiles were constructed basing on 1: 10 000 topographic maps, with a contour interval of 2 or 5 m. Cross-sections of the valleys were also based on 1:10 000 topographic maps. However, where the incision is young, results of a laser rangefinder, which was used directly in the field, were applied. Valley segments of recent incision or erosion were mapped in the field, and headcuts were positioned by the GPS.

The stream length-gradient index SL (Hack, 1973) was calculated for successive 100-m-long segments along the stream using the formula: $SL=(\Delta H/\Delta L)L$, where $\Delta H/\Delta L$ is the gradient of the studied segment, and L denotes the total upstream length. The sensitivity of the SL index to changes in the channel slope makes it possible to evaluate the relationships among tectonic activity, rock resistance and topography (Keller and Pinter, 2002). Moreover, SL indices were compared with stream gradients (m/km) computed for 100-m-long segments.

A geomorphological sketch of selected fluvial features, such as segments of enhanced erosion, fluvial terraces and alluvial fans, was created. Besides 1:10 000 and 1:25 000 topographic maps, the digital elevation model (DEM) based on these maps, and aerial photographs was also used during geomorphological mapping and analysis.

3.2. Analysis of morpholineaments and fractures

Morpholineaments are represented by linear elements of the relief, such as the foot or trace of rectilinear slopes or landforms related to the drainage network (thalwegs, etc.). They can be associated with tectonic dislocations or geological (lithostratigraphic) boundaries (see Ostaficzuk, 1981; Badura et al., 2003). In this study, they were identified based on 1: 10 000 and 1: 25 000 topographic maps, DEM, our own geomorphological and geological maps, and were processed within the GIS. The method of condensed contour lines were also used (cf. Ostaficzuk, 1975; Badura and Przybylski, 1999). Additionally, thematic maps displaying water springs and waterlogged areas were used as their linear arrangement frequently corresponds with morpholineaments. During the analysis, the length of morpholineaments was considered with respect for their trends. Only significant morpholineaments, longer than 500 m, were taken into account.

Furthermore, the orientation of morpholineaments was compared to that of fault and joint systems in order to assess their possible causal relationships, such as the influence of the structure on the drainage pattern or the impact of neotectonics on landforms. A fault system analysis was performed on the basis of geological, geophysical, and geomorphological maps, and on measurements in quarries (no fresh fault planes are exposed in the area). Joint strikes were measured both in quarries and natural rock-outcrops. As the quarries are widespread all over the area, we considered these measurements to be representative of the fracture pattern of the area and took the frequency of the orientations into account.

3.3. Methodology of fault displacement monitoring

Displacements occurring on faults are monitored using a TM71 deformeter, which is usually installed directly across a fissure or a fault plane. Suitable sites for monitoring are selected within important fault zones displaying recent or active tectonics. The TM71 device is based on a mechanical optical principle (Moiré technique) and has been successfully used in several regions with different levels of tectonic activity (for details see Košťák, 1991; Dobrev and Košťák, 2000; Stemberk et al., 2003). The movements are recorded three-dimensionally. Horizontal displacements perpendicular to the fissure are recorded along the x axis, lateral displacements along the y axis, and the z axis reflects vertical displacements. The rotations along the planes xy and xz, which may not be displayed in charts of individual displacements, are also recorded. Under conditions of minimum interference by exogenous processes, the gauge is capable of demonstrating relative spatial movements between two adjacent crack faces as small as 0.01 mm/year and relative angular deviations of up to 0.00032 rad. All the obtained data were corrected for the influence of temperature.

In the studied area, four TM71 deformeters were installed in two fault-controlled karstic cave systems (in 2001 and 2002), since there is no suitable clear fault scarp on the surface (Stemberk and Štěpančíková, 2003). The cave Na Pomezí is situated directly in the zone of the SMF and generally follows the NW–SE direction (Fig. 1). For that reason, this cave was selected within the framework of EU COST Action 625 "3-D monitoring of active tectonic structures" as an appropriate site to monitor the SMF fault displacements. Since there is no suitable fissure in the SMF direction, two fissures oblique to this direction were straddled by the TM71 devices. This oblique system of fissures (NNW–SSE/WSW–ENE) also defines most of the cave corridor directions. The second cave, Na Špičáku, is situated a few kilometres north of the SMF on the foot of the fault scarp, which is presumably controlled by a NE–SW trending fault (Fig. 1). The cave also follows fissures of this direction in addition to the NW–SE trend (see later Section 4.3). Two fissures striking NW–SE and E–W were straddled by the TM71 devices here.

All the monitored sites in the studied area are situated deep enough to eliminate the influence of superficial slope processes as well as seasonal climatic variations. Micro-displacements obtained from the monitored caves were recorded regularly once or twice a month. Final values of micro-displacements along each axis were obtained as the sum of individual movements of the same orientation (Košťák, 1993).

4. Results

4.1. Characteristics of streams and drainage basin

The study area drains to the north-east into the Nysa Kłodzka River. The drainage network analysed in detail comprises the main stream — the Vidnavka River (of fourth stream order) — and its right-side catchment area, which includes streams of first to third order. All these streams originate in the Sokolský Ridge and then flow through the Žulovská Hilly Land to the Vidnavská Lowland, thus through the same geomorphological units. Based on this fact, it can be assumed that their evolution was similar, unlike in the case of the left-side catchment area of the Vidnavka River, where the streams running from the Rychlebské Mts cross their prominent marginal fault scarp controlled by the SMF.

The drainage network is predominantly of a dendritic pattern, in particular in the mountain area it follows the prevailing slope. In the lower part of the study area, in the Žulovská Hilly Land, a rectangular drainage pattern occurs, commonly reflecting the joint and fault systems as discussed later in this paper.

Apart from the very upper parts of several valleys crossing the belt of metamorphic rocks, the stream network flows through the granitoids of the Žulová granite pluton. This uniform lithology simplifies recognition of tectonic influences on longitudinal stream profiles. Furthermore, according to Burbank and Anderson (2001), such anomalies in river profiles not correlated to lithologic contrasts may be interpreted as reflecting ongoing tectonism. However, all potential factors that could influence river channel morphologies should be taken into account.

4.1.1. Longitudinal profiles, stream length-gradient index and headward erosion

Longitudinal profiles, stream gradients and stream length-gradient indices (SL) were constructed for the most important streams within the study area in order to assess the influence of tectonic movements on the evolution of the drainage basins. Since these streams are of different orders, the anomalies of both the stream gradients and SL indices rather than their real values were taken into account. Moreover, the extent of the newest erosional phase was investigated in the field.

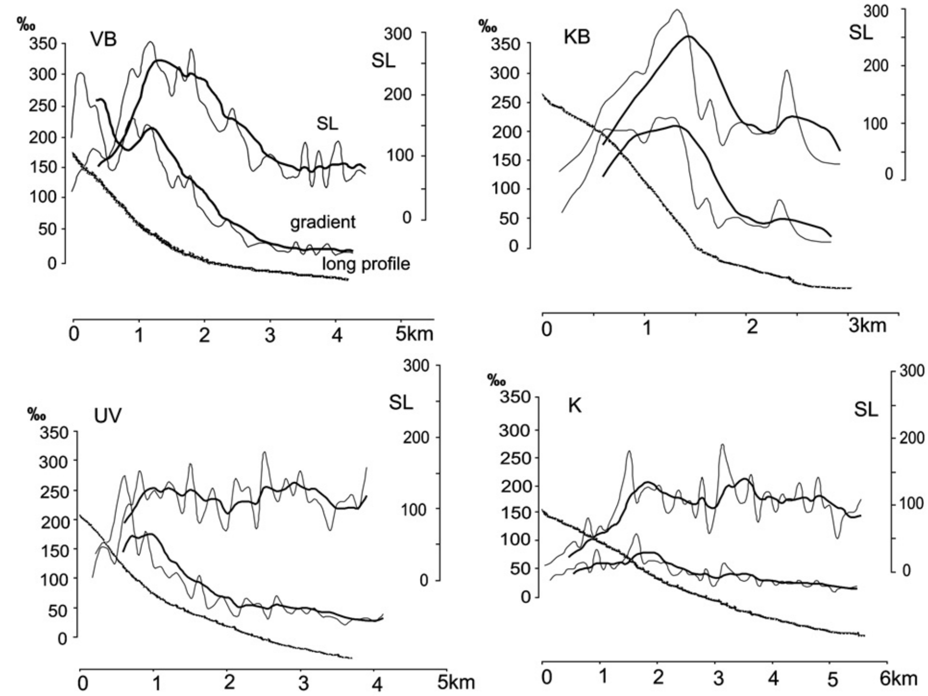

Fig. 3. SL indices and stream gradient distributions of the Vápenský (VB), Kopřivový (KB), Uhlířské Valley (UV) and Křemenáč Brook (K) channel beds. Five-term simple moving average curves represents a mean trend at a length of 500 m.

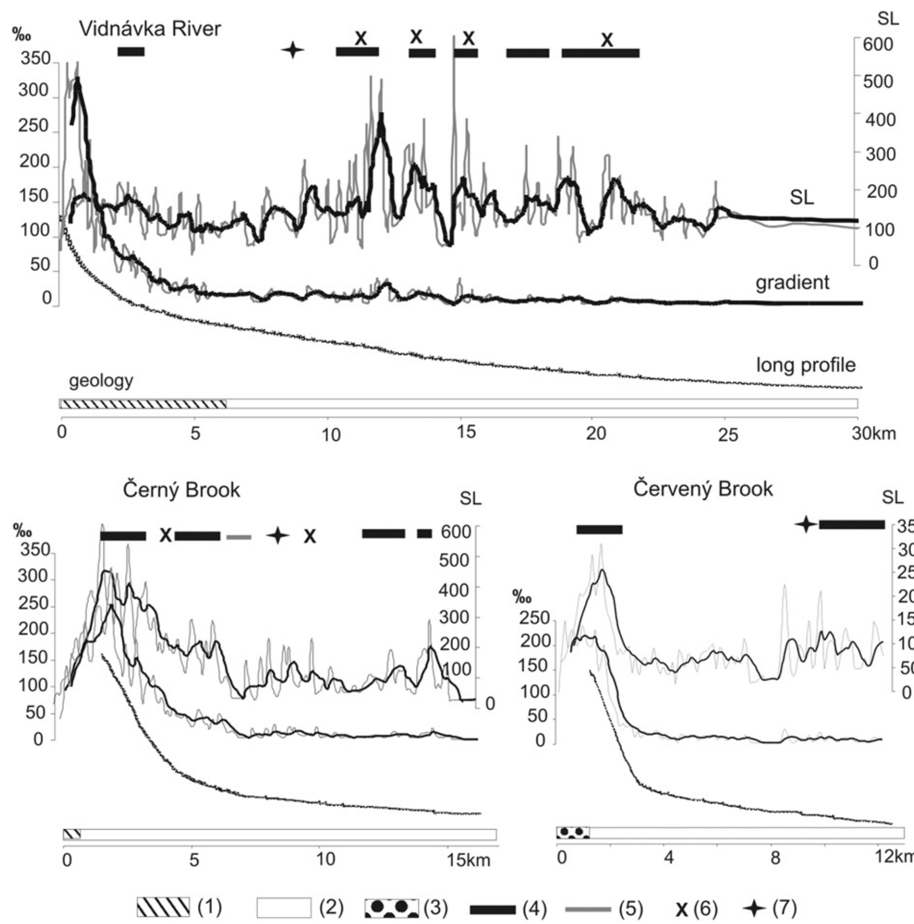

Fig. 4. SL indices and gradients distribution of the Vidnavka River, Černý (Mariánský Brook = upper reach) and Červený Brook channel beds. Lithology: (1) — metamorphic rocks (gneisses, marbles, phyllites, amphibolites), (2) — granitoids, (3) — segment of stream flowing along the lithological boundary; (4) — stream follows a morpholineament/fault, (6) — river crosses a morpholineament/fault, (7) — beginning of the deepened valley, (5) — river flows into the planation surface (etchplain).

All streams within the Sokolský Ridge have non-rejuvenated wide valley heads with much lower SL indices than in lower situated segments (Figs. 3, 4; Černý, Červený and Kopřivový Brooks). Downstream, in the middle reaches, where the Sokolský Ridge is rather steep, the streams have almost undeveloped valleys lacking apparent drainage divides between them. They also manifest themselves through the linear shape of their longitudinal profiles with rather higher gradients with the SL indices of 240–320 m/km and SL 260–620, respectively. It suggests that these segments and the slopes are young. Approaching the foothills, the valleys deepen and widen in response to headward erosion dissecting the margins of the Sokolský Ridge from its foot.

The Uhlířské Valley, Křemenáč Brook, and partially the Vidnavka River, differ from the above-mentioned valley types. They created deep valleys directly below their wide valley heads, which is reflected also by more concave longitudinal profiles, and lower SL indices and gradients (Figs. 3, 4). These three streams follow marked faults, which probably influenced their more advanced morphological development.

Along the SW foot of the Sokolský Ridge, which is controlled by the SMF, the Vidnavka River flows through various metamorphic rocks, which is reflected by changes in both the gradients and SL indices. However, these changes are not so significant when compared to those on the subsequent stretch of the river and its tributaries situated exclusively within the Žulová granite pluton (Fig. 4).

Within the transition area towards the Žulovská Hilly Land in the NW, as well as in the hilly land itself, the longitudinal profiles of the streams analysed are far from being smooth. They most frequently reflect tectonic and structural controls, which are probably emphasised owing to the already stripped etchsurfaces and to the advance of headward erosion (Fig. 4). Several knickpoints within the step-like arranged foothills correspond with the bases of these steps or the foot of the marginal slope of the Sokolský Ridge. The foothill steps are reflected also by higher SL indices. The knickpoints have retreated due to headward erosion by 40 m to 70 m. The closer the knickpoints are to the marginal slope of the ridge, the lower the value of the retreat. Different values of knickpoint retreat may suggest different levels of

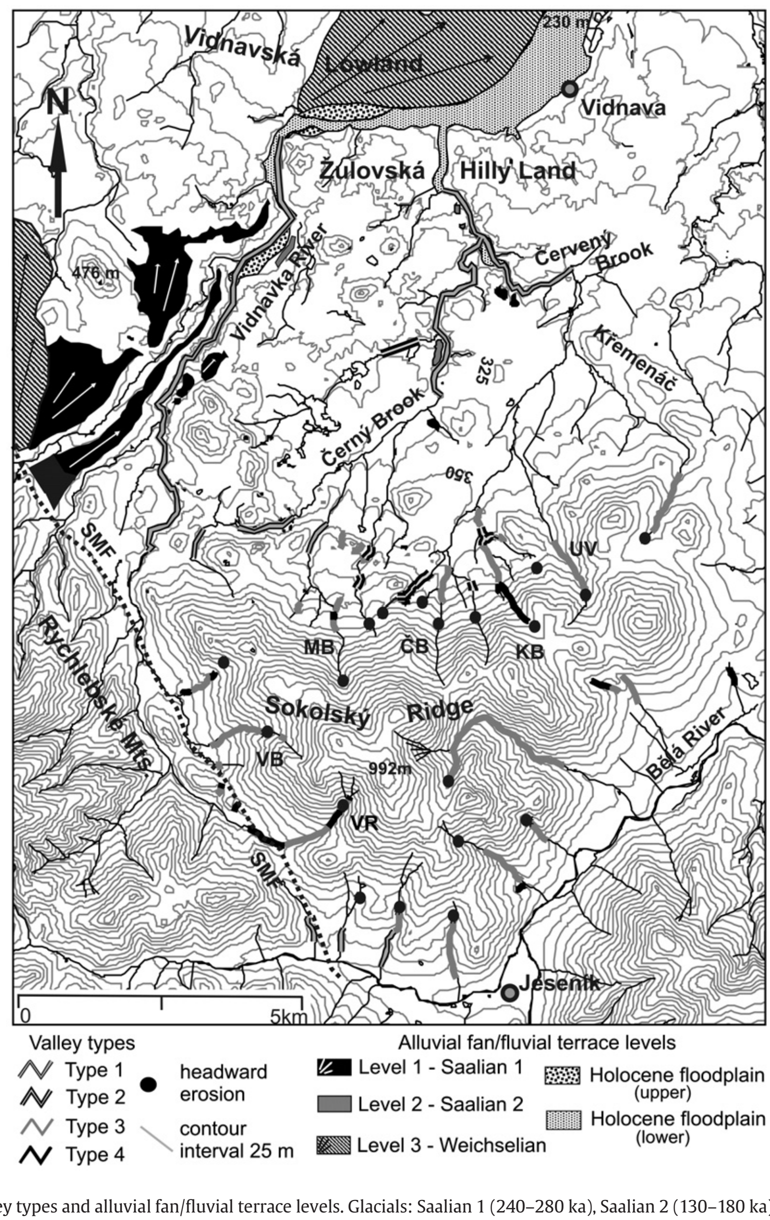

Fig. 5. Geomorphological sketch of valley types and alluvial fan/fluvial terrace levels. Glacials: Saalian 1 (240–280 ka), Saalian 2 (130–180 ka), Weichselian (10–80 ka). Valley types — see for explanation Section 4.1.2; headward erosion — the farthest reach of the youngest erosional phase; arrows — alluvial fans or fan-shaped fluvial terraces; VR — Vidnavka River, VB — Vápenský Brook, MB — Mariánský Brook, ČB — Červený Brook, KB — Kopřivový Brook, UV — Uhlířské Valley.

fault activity bordering these steps. In addition, the increased SL indices and stream-gradients of the analysed streams coincide frequently with rectilinear and/or narrow valley segments, which also follow or cross morpholineaments or even mapped faults. These facts may suggest a tectonic control of these morpholineaments, although the inferred faults have not been recognised so far.

Moreover, an analysis of headward erosion showed that the streams displaying the longest and highest reach of the youngest erosional phase are all in the SW part of Sokolský Ridge. This sector involves the most prominent and highest marginal fault scarp, which is controlled by the SMF (Fig. 5). The occurrence of the most intensive erosion in this part may correspond with the supposed differential uplift of the ridge, which is also highest exactly in this SW part. On the marginal slope facing the Žulovská Hilly Land, modern headward erosion has advanced to a similar extent as that in the SW marginal slope in the case of two streams, the Mariánský and Kopřivový Brooks. Their courses are both controlled by faults and also display distinct anomalies in SL indices and gradients, which may suggest their recent activity (see Figs. 2–4).

4.1.2. Cross-sections

Anomalies in longitudinal profiles frequently correspond with changes in the cross-section morphology of the valleys. In the study area, several types of valley have been distinguished based on their cross-sections. These individual types reflect different erosional phases and intensity of erosion, frequently controlled by tectonic activity as well as structural and lithological factors.

The valley types showing enhanced erosion were identified based on their cross-sections and are as follows (Fig. 6): 1) a deep valley with a rather wide valley floor, 2) a deep narrow valley, 3) a valley with a remnant of an older valley floor cut by younger erosion, 4) a valley with enhanced recent erosion.

Type 1 (Fig. 6) is characterised by a deep incision of up to 50 m (the Vidnavka River, the Černý Brook) and is typical for the fringe of the Žulovská Hilly Land. It contains long valley segments with a well-marked upper-valley edge. The main control on valley development was played by headward erosion from the Vidnavská Lowland and dissecting older Quaternary deposits or the planation surface. Additionally, this type occurs in the transition area towards the Sokolský Ridge. The valleys here are usually rectilinear since most of them probably follow fractures and flow around more or less isolated granite inselbergs. The segments of type 1 generally have graded longitudinal profiles with some small local knickpoints.

Type 2 represents a deep valley with a narrow or missing floodplain, resulting from recent incision, deepening the valley (Fig. 6). These stretches of valley in the study area are strictly limited to rectilinear segments, which probably follow fault and/or fracture systems.

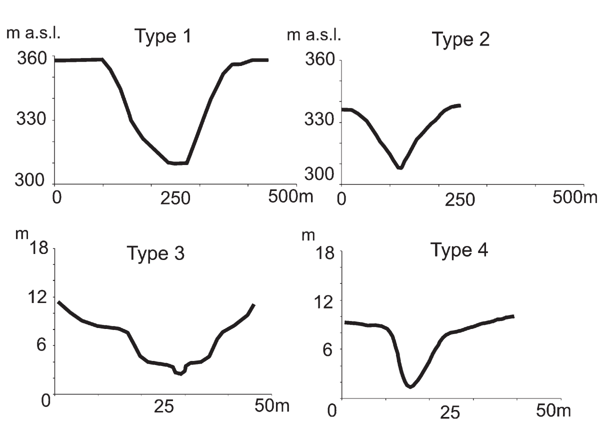

Fig. 6. Valley types based on their cross-sections. See for explanation Section 4.1.2.

Type 3 (Fig. 6) comprises valleys with an older, wider valley floor situated only a few metres (2–7 m) above the present-day valley bottom, which implies a renewed incision. They occur almost exclusively in the mountainous sector of the study area, the Sokolský Ridge. As shown in Fig. 5, Type 3 is confined to deep and developed valleys occurring within the Sokolský Ridge, which are clearly controlled by marked fault lines. In addition, such valley segments begin approximately at the foot of the Sokolský Ridge; therefore, they correspond with the base of an uplifted area (e.g. the Vidnavka River, the Vápenský Brook, etc.; see Fig. 5). The position of the segments of Type 3 may suggest a causal relationship with the uplift, as will be discussed later.

Type 4 (Fig. 6) involves stretches of enhanced recent erosion, including up to 8 m modern incision of the streams. These segments are limited to the very beginning at the foot of the Sokolský Ridge, which follows the trace of the marginal faults, and/or they follow transverse faults (Fig. 5). These spatial relationships suggest recent uplifting in the Sokolský Ridge and some degree of activity on the transverse faults crossing the ridge.

4.1.3. Depositional features

Three levels of Middle to Late Pleistocene fluvial terraces (predominantly sandy gravel deposits) were identified in the study area (Fig. 5). Within the valley cross-sections, the oldest, upper terrace has lower relative heights above the channels than the adjacent youngest glaciation till occurring in the study area, which has an Elsterian 2 age (OIS 12/400–460 ka). It implies that the terraces postdate the till and would belong to the Saalian 1 (OIS 8/240–280 ka), Saalian 2 (OIS 6/130–180 ka) and Weichselian (OIS 4-2/10–80 ka) (Žáček et al., 2004). The upper level 1 is located 35–40 m above the valley bottom of the Červený Brook with a thickness of up to 2 m and 20 m above the Černý Brook. The different relative heights above the brooks are caused by differences in headward erosion. This first level can be correlated with the Upper Terrace of the main river, the Nysa Kłodzka River, into which the Vidnavka River flows (Przybylski, 1998a; Badura and Przybylski, 2000b). The second level (correlated with the Middle Terrace) occurs only locally 13 to 22 m above the present stream channels and displays a thickness of less than 2 m. The surface of the only occurrence of the third level, correlated with the upper Lower Terrace of the Nysa Kłodzka River (cf. Przybylski, 1998a), is situated in the Vidnavská Lowland, 4–8 m above the river channel. It is fan-shaped and made of 5–7 m thick materials.

In addition, three generations of alluvial fans have been described in this region (Pecina et al., in press). These three fan generations correspond with the aforementioned fluvial terraces. The oldest alluvial fan overlie glaciofluvial deposits resting on the till of Elsterian 2 so that it was classified as of the Saalian 1 age (OIS 8/240–280 ka). This alluvial fan can be found along the Vidnavka River continuously at a distance of 5 km, around 38–48 m above the valley bottom (Fig. 5).

As already mentioned, the fluvial terraces and alluvial fans, based on their character and morphostratigraphic position (35–48 m, 13–22 m, and 4–8 m above the present river channel), probably correspond with the Upper, Middle and Lower Terraces of the Nysa Kłodzka River, (20–30 m, 10–17 m, 2–5 m, respectively), into which the Vidnavka River flows (cf. Przybylski 1998a,b; Badura and Przybylski, 2000b). Yet the heights of two upper levels above the Vidnavka River are larger than heights of corresponding levels above the Nysa Kłodzka River. This fact would imply a convergence of the terrace levels of the Vidnavka River downstream (Fig. 7). In the confluence area, the Vidnavka River incises into the Upper and Middle Terraces of the Nysa Kłodzka River, which lie on Miocene sediments, to depths of 15 m and 10 m, respectively. In contrast, in the area of the Žulovská Hilly Land situated upstream, incision of the same age marked by fluvial terraces reaches 35–48 m and 20 m, respectively. This convergence of the terrace levels downstream suggests a relative uplift of the Žulovská Hilly Land.

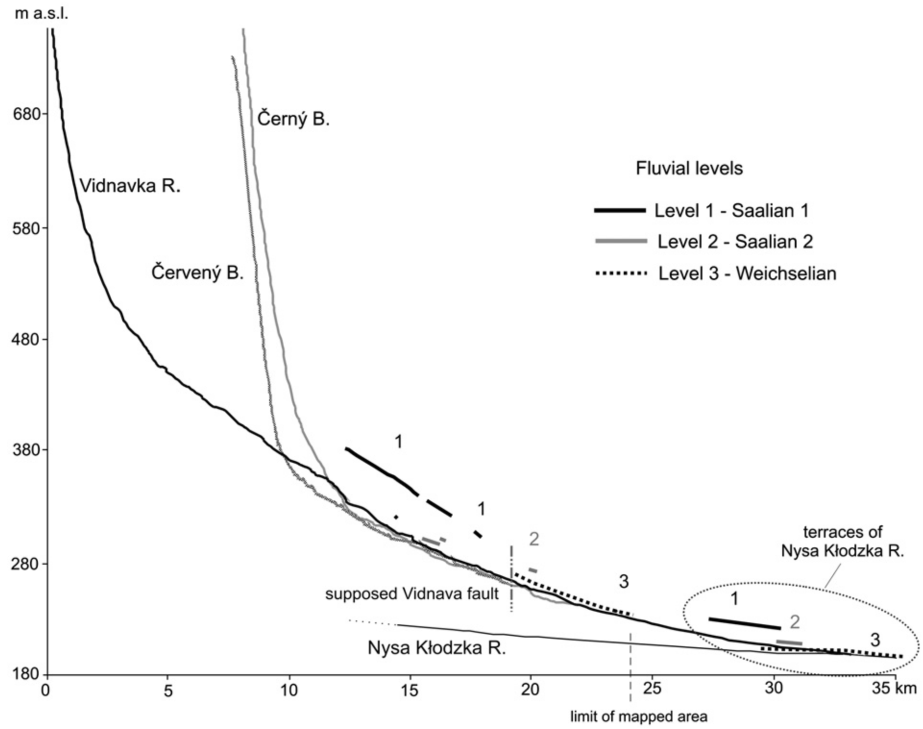

Fig. 7. Longitudinal profiles with fluvial levels of the Vidnavka River, the Černý and Červený brooks and the Nysa Kłodzka River at the confluence area. Terraces/alluvial fans: 1 — Saalian 1 (240–280 ka), 2 — Saalian 2 (130–180 ka), 3 — Weichselian (10–80 ka).

4.2. Morpholineaments and fractures

4.2.1. Morpholineaments

The morpholineaments in the study area are expressed in the landscape mainly as the foot zones of rectilinear slopes, and as landforms related to the drainage network (thalwegs, etc.). Most morpholineaments are related to fault and/or joint patterns in the area, although not all of the faults are geologically proven.

Morpholineaments in the study area follow two prominent, more or less orthogonal directions: NE–SW (30–50°) and NW–SE (130–150°; Fig. 8). The NE–SW orientation is displayed in the relief more conspicuously. Some segments of the Vidnavka River, and the Skorošický, Černý, and Červený Brooks are examples of this orientation. The foot of the SE marginal fault scarp of the Sokolský Ridge is another distinct morpholineament of this orientation (Fig. 1). Although the morpholineaments of the NE–SW orientation are shorter in length, they are more frequent. In contrast, the morpholineaments of the Sudetic direction (NW–SE) are not so frequent, but are expressed in the relief over longer distances. The longest morpholineaments within the analysed area that maintain a constant direction reach approximately 6 km. The SW marginal fault scarp of the Sokolský Ridge, as well as the entire NE border of the Rychlebské Mts, follows the SMF and is a typical example of the Sudetic morpholineament trend. Moreover, these two main directions control perpendicular corridors of karst dissolution occurring in the study area.

4.2.2. Joint and faults orientations

The data on fracture systems were collected using several kinds of maps and field measurements (see Section 3.2). The joint and fault strikes were measured in quarries and natural outcrops of various Palaeozoic crystalline rocks, mostly granitoids (Štěpančíková, 2005). As shown in Fig. 8, rose diagrams constructed for joints and faults also display two dominant directions: NE–SW and NW–SE. However, the Sudetic NW–SE direction, the youngest trend in the Bohemian Massif, prevails. It is necessary to highlight that these joint and fault systems differ in their directions by around 20°. The typical strikes for the joint system are 10–30° and 110–130°, whereas those of the fault system are

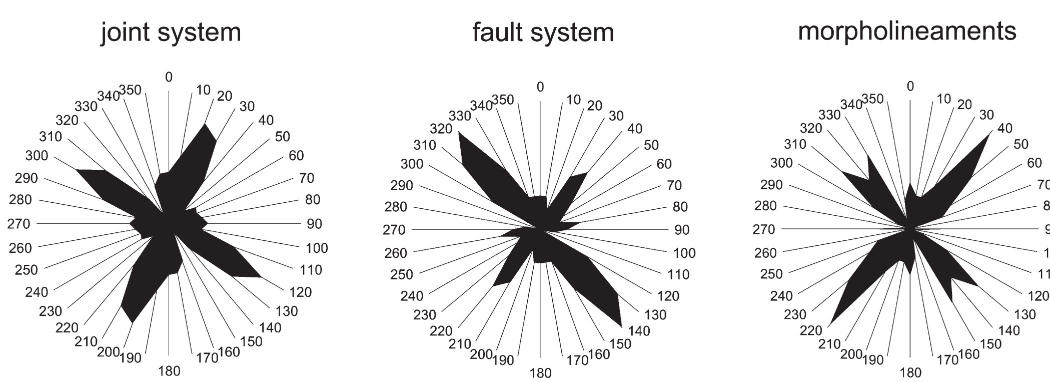

Fig. 8. Rose diagrams of joint (1002 readings) and fault (120 readings) system strikes compared to the morpholineament orientations (total length approximately 223 km).

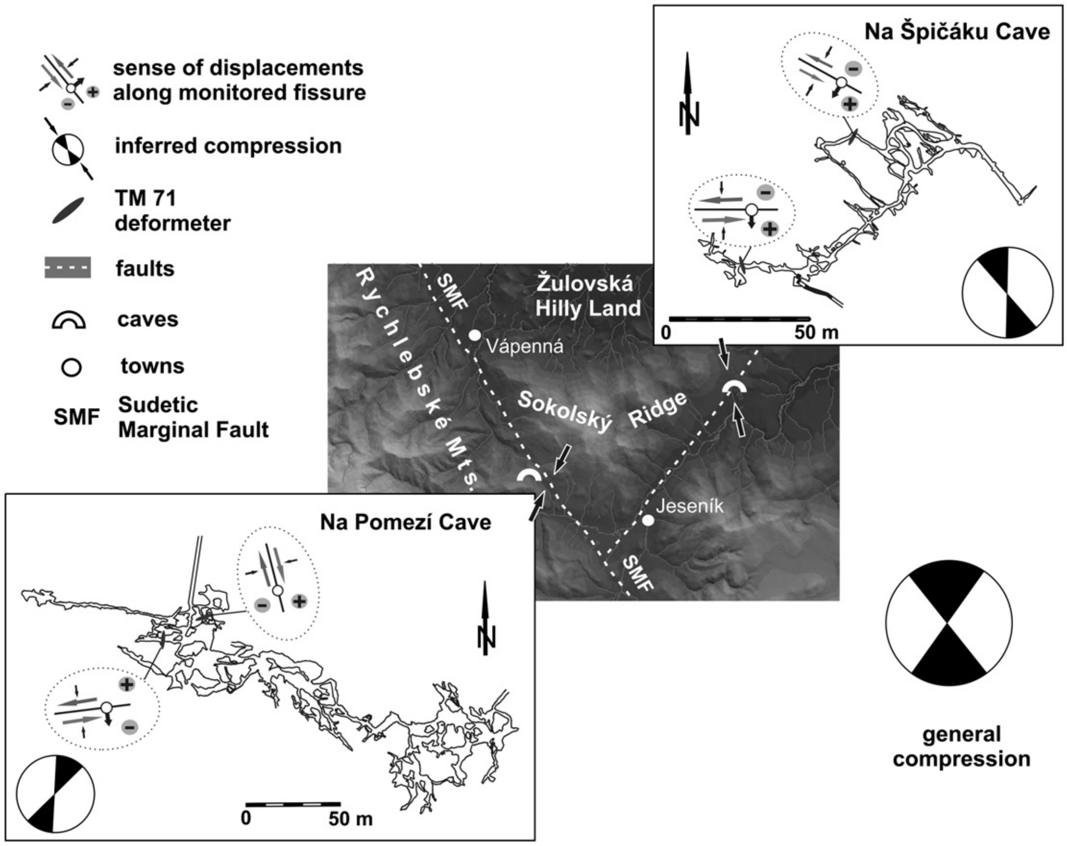

Fig. 9. Sketch of the monitored caves with locations of the TM71 deformeters, the sense of recorded displacements, and the inferred compression orientations.

30–50° and 130–150°. Thus, there is a strong correlation in morpholineament and fault trends because the main morpholineament trends are also 30–50° and 130–150° (Fig. 8). It suggests strongly that the morpholineaments in the study area are more controlled by younger secondary faults than the primary joint system (Fig. 8).

4.3. Analysis of the data obtained by 3-D monitoring of micro-displacements

Both monitored sites in the Na Pomezí Cave and the Na Špičáku Cave consist of tectonically controlled dissolution corridors. The Na Pomezí Cave is located on the left bank of the Vidnavka River, directly in the zone of the SMF, 5 km NW of the town of Jeseník (Fig. 9). Two TM71 deformeters were installed across the NNW–SSE and WSW–ENE striking fissures, located about 30 m and 40 m below the surface, respectively. The fissures display crushed rocks, which suggests recent movement along them (Fig. 10). The Na Špičáku Cave is situated 7 km NE of the town of Jeseník, at the foot of the eastern marginal slope of the Sokolský Ridge, which follows an inferred NE–SW fault. The E–W and NW–SE striking fissures were monitored with two TM71 deformeters about 20 m and 40 m below the surface, respectively (Fig. 9).

4.3.1. The Na Pomezí 1 site (P1: NNW–SSE fissure — 350°/90°)

The cumulative values of micro-displacements along each axis recorded since 2001 are as follows: *x*: +0.02 mm (average displacement rate +0.005 mm/year), *y*: −0.125 mm (average displacement rate −0.03 mm/year), *z*: +0.1 mm (average displacement rate +0.025 mm/year) (Fig. 11). The registered displacements have a right-lateral component (along the *y* axis) with the vertical component (the *z* axis) due to the uplift of the eastern side of the monitored fissure. The displacements registered along the *x* axis thus represent horizontal compression across the monitored fissure. As a result, the obtained data reflect an oblique (transverse) uplift of the eastern side relative to the western side. The right-lateral component may be due to the Sokolský Ridge being thrust over the southern block of the Rychlebské Mts due to north-eastwards compression (Fig. 9).

4.3.2. The Na Pomezí 2 site (P2: WSW–ENE fissure — 260°/76°N)

The cumulative values of micro-displacements along each axis that have been recorded since 2001 are: *x:* +0.04 mm (average

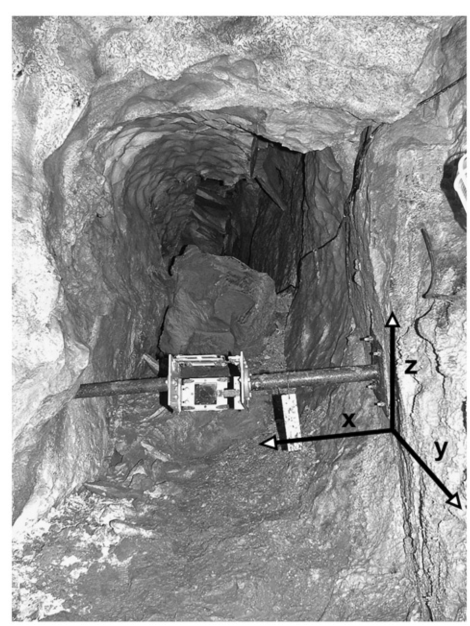

Fig. 10. The TM71 deformeter installed across the monitored fissure in the cave Na Pomezí (site P1).

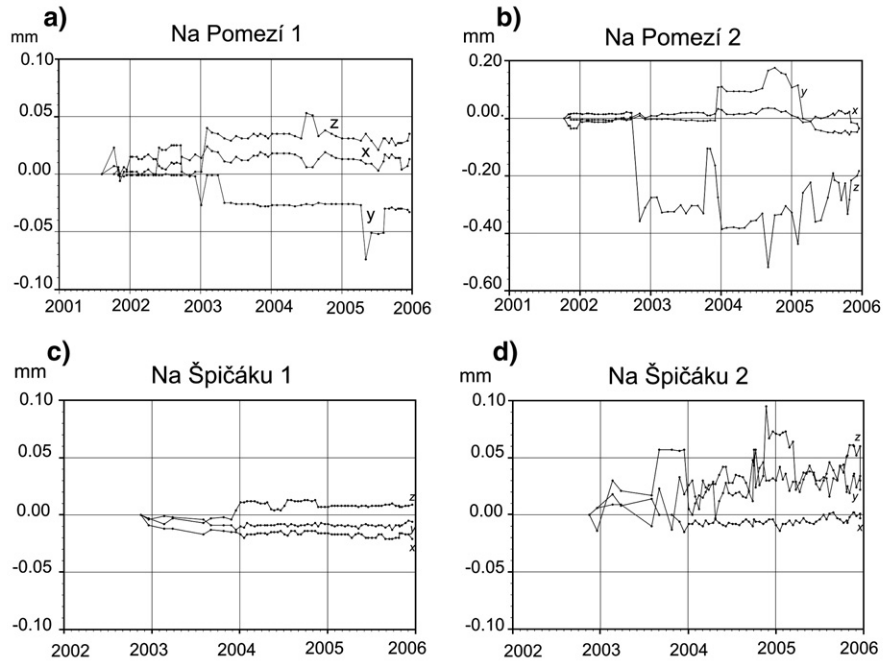

Fig. 11. Displacements registered: x, y - horizontal movements; z - vertical movements; a) in the Na Pomezí Cave, site Na Pomezí 1, b) in the Na Pomezí Cave, site Na Pomezí 2, c) in the Na Špičáku cave, site Na Špičáku 1, d) in the Na Špičáku cave, site Na Špičáku 2.

displacement rate +0.01 mm/year), *y:* +0.2 mm (average displacement rate +0.05 mm/year), *z*: −1.34 mm (average displacement rate −0.33 mm/year) (Fig. 11). The recorded displacements show mostly left-lateral components (along the *y* axis), and vertical components (the *z* axis) which are about seven times greater than the horizontal component. Oblique vertical displacements are produced by the uplift of the northern side of the fissure as a result of the southern block being pushed under the northern block. The displacements registered along the *x* axis represent a slight compression across the monitored fissure.

Generally, the results from both sites at Na Pomezí are interpreted as showing the displacements resulting from approximately SSW–NNE to SW–NE-oriented compression associated with thrusting of the northern sector (Sokolský Ridge) over the southern one (Rychlebské Mts) (Fig. 9).

4.3.3. The Na Špičáku 1 site (Š1: E–W fissure — 90°/82°S)

The cumulative values of micro-displacements along each axis which have been recorded since 2002 are: *x:* −0.02 mm (average displacement rate −0.007 mm/year), *y:* −0.015 mm (average displacement rate −0.005 mm/year), *z*: +0.03 mm (average displacement rate +0.01 mm/year) (Fig. 11). The registered displacements have a right-lateral component (along the *y* axis), and the vertical component (the *z* axis), which is about two times greater than the horizontal component. Vertical displacements are produced by a relative uplift of the southern side of the fissure. The displacements registered along the *x* axis represent extension across the fissure.

4.3.4. The Na Špičáku 2 site (Š2: NW–SE fissure — 124°/80°SW)

The cumulative values of micro-displacements along each axis which have been recorded since 2002 are: *x:* 0.0 mm, *y:* +0.04 mm (average displacement rate +0.013 mm/year), *z*: +0.05 mm (average displacement rate +0.017 mm/year) (Fig. 11). The registered displacements have a left-lateral component (along the *y* axis), with the vertical component (the *z* axis) of about the same value as the horizontal component. Vertical displacements result from the uplift of the southern side of the fissure.

In summary, the observed displacements in the Na Špičáku Cave show NNW–SSE to N–S-oriented compression resulting in thrusting of southern blocks over northern blocks (Fig. 9).

5. Discussion

The neotectonic origin of the prominent fault scarp, controlled by the Sudetic Marginal Fault, which forms the border between the Sudeten Mountains and the Sudetic Foreland, has been broadly discussed and documented by several authors (e.g. Oberc and Dyjor, 1969; Ivan, 1997; Badura et al., 2003 and references therein). The Sokolský Ridge is the SE sector of the Rychlebské Mts which belong to the Sudeten Mts. Yet the ridge itself is situated beyond the SMF on the hanging wall so it tends to be regarded as a part of the Fore–Sudetic block. The main features of the Sokolský Ridge, as well as the entire Sudeten Mts, are supposed to have formed since the Neogene (e.g. Ivan, 1997; Badura et al., 2003). However, neither the Sokolský Ridge nor the adjacent Žulovská Hilly Land have been hitherto studied in detail from a neotectonic point of view.

Anders (1939) mentioned the step-like character of the relief of the study area, where the steps from SE to NW are as follows: the Sokolský Ridge, the Žulovská Hilly Land and the Vidnavská Lowland. He discussed the presumable fault origin of the marginal slope of the Sokolský Ridge, by which the latter was uplifted by over 600 m towards the Žulovská Hilly Land. Anders (1939) excluded any flexure, since the given zone is composed of massive granitoids. However, he concluded that owing to uniform bedrock, the presumable fault, in particular its trace, would be very difficult to prove geologically.

5.1. Drainage analysis

The hypothesis of uplift of the study area is supported by the presented geomorphological data based on a detailed analysis of the drainage network, particularly the nature of individual stream valleys and their cross-sections, incision, anomalies in longitudinal profiles, SL indices, and in stream gradients.

The stream stretches displaying significant incision or rejuvenated erosion start to develop from the base of the marginal slope of the

Sokolský Ridge, controlled in the SW by the SMF. Similarly, they start to develop at the base of obvious morphological steps in the adjacent part of the Žulovská Hilly Land or along its northern fringe. Moreover, the longitudinal profiles, SL indices, and stream gradients reflect these prominent valley segments by distinctive knickpoints. Several of these knickpoints display a linear arrangement corresponding with the lower edge of the Sokolský Ridge, as well as with the bases of the above-mentioned morphological steps within the Žulovská Hilly Land, even if some of the knickpoints have already slightly retreated. All these valley characteristics could be regarded as a response to the uplift of the Sokolský Ridge and of the stepped terrain of the foothills belonging to the Žulovská Hilly Land. Furthermore, in several places, the stretches of those streams which display rejuvenated erosion and enhanced incision as well as the highest and longest reach of headward erosion coincide with transverse faults. This correlation may suggest a reactivation of these transverse faults.

The fact that the entire Sokolský Ridge as a horst-like structure is descending stepwise to the NE (from the altitude of approximately 1000 m to 400 m a.s.l.; Fig. 1) implies that the ridge was subjected to differential uplift, with the highest rate in its S–SW sector. This uplift very likely developed during the main period of its formation in the Neogene, analogous to the adjacent mountain ranges (e.g. Ivan, 1997). The asymmetric drainage network of the Vidnavka River seems to be a result of this tilting. The general trend of streams within the Sudeten Mts to flow north- or north-eastwards (already in the Neogene), inferred from sedimentary evidence in the Sudetic Foreland, is also displayed in the Rychlebské Mts. However, this north-eastwards tendency in the studied right-side catchment of the Vidnavka River was disturbed in response to the uplift of the Sokolský Ridge. As a result, a new stream network originated, draining the ridge. The hypothesis of a younger age for this drainage is supported by modern morphological analysis of most streams within the ridge (see Section 4.1.1) — they lack developed valleys, have unclear divides, and their longitudinal profiles are rectilinear. Moreover, these relatively young valleys are in sharp contrast to wide, shallow valley heads, surrounding the inselberg-like summits of the ridge; landforms probably inherited from the Neogene. In addition, the interpretation of differential uplift is supported by stream features on the highest and steepest marginal slope of the Sokolský Ridge situated in the SW. There, the stretches of rejuvenated and enhanced modern stream erosion, beginning on the SMF trace (in case of the Vidnavka River even following the SMF), extend the longest distance and greatest elevational difference. Therefore, it is most likely that the greatest magnitude of uplift occurred exactly in this SW part of the ridge. In addition, the intensity of modern erosion generally diminishes from SW to NE through the entire Sokolský Ridge.

Concerning the drainage basins of the Žulovská Hilly Land, in places where the main trunks of the Černý and Červený Brooks flow through the slightly undulated etchsurface, they display only slightly developed, wide shallow valleys reflected by their smooth longitudinal profiles and very low stream gradients (3–14 m/km). Nonetheless, headward erosion propagating from the northern edge of the hilly land due to relative subsidence of the Vidnavská Lowland has already dissected the etchsurface as well as the Middle to Lower Pleistocene deposits within the marginal part of the Žulovská Hilly Land. It has resulted in the creation of the deep and rather narrow valleys of the Vidnavka River, and Černý and Červený brooks (Fig. 1). As already described in Section 4.1.3, the Quaternary development of these three main streams in the study area can be inferred from fluvial levels. Fluvial terraces in central Europe are considered to result from the combination of climatic changes and tectonic movements (e.g. Starkel, 2003, Tyráček et al., 2004). Since the relative elevation of alluvial fans and terraces in the study area attain much higher values when compared to the terraces of the same age on the contiguous main river Nysa Kłodzka (the difference being up to 20 m at level 1, at least 8 m at level 2, and up to 2–3 m at level 3), a tectonic control can be considered. It implies a relative uplift of the Žulovská Hilly Land, probably along the approximately W–E striking presumable Vidnava (Vidnava–Głucholazy?) fault (schematically delineated by Dyjor, 1993; Ivan, 1997; Badura and Przybylski, 2000a). This fault is supposed to define the prominent northern edge of the Žulovská Hilly Land by a 30 to 40 m high fault scarp (Ondra 1968; Ivan 1983, 1997). Moreover, the lowest Pleistocene terrace of the Vidnavka River level 3 (Weichselian — OIS 4-2/10–80 ka), situated in the Vidnavská Lowland, is rather thick (7 m) compared to terraces of the same age within valleys of equivalently small streams in the Bohemian Massif (up to 2 m). In addition, the modern channel of the Černý Brook is situated below the level of the Vidnavka River channel at the length of 10 km upstream from its mouth (see Fig. 7). Because the Černý Brook is a tributary of the Vidnavka River with a confluence at the boundary of the Žulovská Hilly Land and Vidnavská Lowland, the lower position of its channel may also support the hypothesis of subsidence of the Vidnavská Lowland, and may be a result of minor tilting of the Vidnavská Lowland to the NE, probably also along the presumable Vidnava fault, combined with differential movements within the Žulovská Hilly Land.

However, the valley of the main Nysa Kłodzka River does not display any evidence for significant subsidence which would be connected with the supposed subsidence of the adjacent Vidnavská Lowland or which would be the cause of headward erosion penetrating into the Žulovská Hilly Land (Przybylski 1998a,in press). Therefore, tectonic movements affecting the Žulovská Hilly Land and the adjacent part of the Vidnavská Lowland probably result from a combination of uplift of the hilly land and subsidence of the lowland. Nevertheless, the Žulovská Hilly Land appears to be an “interpositioned block” (Ivan, 1983), because besides the subsidence of the adjacent Vidnavská Lowland there is also the uplift of the adjacent Sokolský Ridge, in the SE.

5.2. 3-D monitoring

Furthermore, the geomorphological data, resulting from the detailed analysis of the drainage network are consistent with those obtained by 3-D monitoring of micro-displacements carried out on tectonic structures in two karst caves by means of the TM71 deformeters.

Analysis of the value and orientation of the recorded displacements on both devices in the Na Pomezí Cave suggests a tectonic origin, controlled by present-day SSW–NNE to SW–NE compressive stress field (Fig. 9) (Stemberk and Štěpančíková, 2005). The curves of the observed micro-displacements comprise individual sudden aseismic impulses (Fig. 11). This type of displacement is well-known from studies of rock behaviour under pressure (see e.g. Erismann and Abele, 2001). The observed displacements suggest thrusting of the Sokolský Ridge, situated north of the SMF, over the Rychlebské Mts, the southern sector of the SMF zone. As a result, the highest uplift of the Sokolský Ridge is close to the SMF. It should be emphasized that these movements are relative. Therefore, general uplift of the Rychlebské Mts also south of the SMF is not excluded as it was documented farther to the NW for the entire Sudeten Mts (e.g. Dyjor, 1993, 1995; Badura et al., 2003, 2004). Within the analysed portion of the SMF, the vertical movements prevail but the inferred stress implies also minor dextral movements along the SMF. Due to the variable orientation of the entire SMF (WNW–ESE to NNW–SSE) relative to the inferred maximum stress direction, the sense of lateral movement may vary depending on the orientation of the individual segments. This fact could probably explain the different movements within the SMF zone (Badura and Przybylski, 2000a).

The inferred stress in the studied portion of the SMF is consistent with the results of borehole breakout analysis performed within adjacent areas (present-day maximum horizontal stress within Fore–Sudetic Monocline SSW–NNE; see Jarosiński, 2005, 2006) as well as with the GPS measurements (maximum compression within Sudeten and Fore–Sudetic Block SW–NE; Kontny, 2003, 2004). This north-eastward-directed stress generally corresponds with that of the Alpine foreland (e.g. Reinecker et al., 2005). Rather different directions of present-day compression (NW–SE), based on the results of focal mechanisms computed for seismic events, was concluded by some authors (Havíř, 2004; Špaček et al., 2006) within the Sudeten Mts farther to the SE (Jeseníky region). The Jeseníky region is, however, situated in a different geological unit and lies closer to the Outer Western Carpathians, where a similar stress field (NW–SE maximum horizontal stress) is interpreted based on borehole breakouts (Peška, 1992; Jarosiński, 2005).

A different type of displacement was observed in the second cave, Na Špičáku. Here, the trend of displacements is more or less linear. The observed displacements also result from the approximately NNW–SSE to N–S-oriented compression. It leads to a thrusting of the southern blocks over the northern block. Despite the compression-induced thrusting, we observed relaxation (extension). This relaxation can probably be ascribed to the high morphological position of the site Na Špičáku, since the locality represents an isolated block situated around 100 m above the valley bottom.

6. Conclusions

This study examines drainage basins in an area showing differential neotectonic uplift. The streams within the zone of the Sokolský Ridge, show rejuvenated erosion and/or enhanced modern incision (also reflected by increased SL indices) starting at its foot as a plausible result of the uplift of the ridge. The general topography of the ridge is characterised by a stepwise inclination to the NE as a result of differential uplift. As the intensity of rejuvenated modern incision is highest in the most uplifted part of the Sokolský Ridge and diminishes north-eastwards in correspondence with decreasing topography, a continuation of the differential uplift may be suggested. The hypothesis of this uplift is also supported by the data obtained by 3-D monitoring of tectonic displacements using a TM71 deformeters, installed in two karst caves. The recorded micro-displacements have an aseismic character with a rate in the range of hundredths to tenths of a millimetre per year. Moreover, it can be concluded that at all observed sites, the vertical component of displacement prevails over the horizontal one. It implies oblique thrusting (dextral transpression in the studied portion of the SMF) due to north–north-eastward-oriented compression, which results in thrusting of the Sokolský Ridge over the southern sector of the Rychlebské Mts probably along the SMF, steeply dipping to the NE.

Furthermore, the neotectonic development of the studied drainage basin within the adjacent Žulovská Hilly Land can be reconstructed based on the distribution of Quaternary sediments. Three levels of fluvial terraces/alluvial fans of the Middle to Late Pleistocene age are distinguished. As their relative elevation above the stream channels have higher values when compared to the terraces of the same age along the main Nysa Kłodzka River, a tectonically induced down-cutting is inferred. These height differences suggest the greatest relative uplift of the Žulovská Hilly Land postdating the Saalian 1 (Drenthe/240–280 ka) and diminishing towards the Late Pleistocene. This is in accordance with the results of neotectonic research carried out in the Polish part of the Sudetic region (see references in Zuchiewicz, 1995; Przybylski, 1998a). The last ice-sheet (Elsterian 2/ 400–460 ka) covered the Žulovská Hilly Land only by its distal part, so the role of isostatic rebound in the above discussed uplift postdating the retreat of ice-sheet in the area remains disputable, particularly when taking into consideration the uplift of the adjacent non-glaciated Sokolský Ridge.

In addition, comparison of the morpholineaments with fracture patterns shows that many of lineaments are fault-controlled. They include, for example, the bases of fault scarps or long rectilinear courses of valleys, which are locally narrowed and may display anomalies in their longitudinal profiles and SL indices. Therefore, it is likely that some faults have recently influenced the development of the study area, because they are still pronounced in the relief, and expressed as morpholineaments.

Thus, detailed field investigations of stream valley characteristics (cross-sections, intensity of erosion), alluvial features, longitudinal profiles and SL-index values, and in particular, examination of their spatial relationships appears to be a useful method in neotectonic investigation of areas of low-rate tectonic uplift. Moreover, instrumental monitoring of faults, capable of recording micro-displacements, may reveal the rates and kinematics of ongoing tectonism.

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