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ROCK LANDFORMS THAT REFLECT DIFFERENTIAL RELIEF DEVELOPMENT IN THE NORTH-EASTERN SECTOR OF THE RYCHLEBSKÉ HORY AND THE ADJACENT AREA OF ŽULOVSKÁ PAHORKATINA (SE SUDETEN MTS, CZECH REPUBLIC)

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ABSTRACT
Rock landforms in the Sokolský hřbet (ridge) and the adjacent Žulovská pahorkatina (hilly land) have been analysed through detailed field mapping at a scale of 1:10,000; subsequently the spatial distribution of these features was analysed using a DEM within a GIS framework. Particular attention was focused upon the shape of the rock landforms, their arrangement, the aspect of their walls, and their topographic position within the two adjacent geomorphological units. Rock landforms in the Sokolský hřbet include frost-riven cliffs, isolated residual rockforms, and blockfields in metamorphic rocks. In contrast, rock landforms in the Žulovská pahorkatina include rock steps and numerous tors exposed from the basal weathering surface. The Sokolský hřbet has been interpreted as a neotectonically uplifted mountainous region; the rock landforms described here are thought to have formed under periglacial conditions during cold periods in the Pleistocene, whilst the extensive granitoid block accumulations developed on marginal fault scarps are thought to result from the exposure of intensively disintegrated rocks due to uplift. Žulovská pahorkatina has been interpreted as a remodelled stripped etch surface, which has been twice glaciated during the Middle Pleistocene. The rock landforms in both units appear to be structurally and lithologically controlled; moreover, various shapes of granite rock landforms are controlled by various types of jointing and parting. The clear differences recognised in both the rock landforms and overall morphology reflects the considerable disparity associated with relief development between two adjacent morphostructural units; such variability provides evidence for a long polygenetic history within the entire study area.

KEYWORDS: rock landforms, pre-glacial, frost-riven cliffs, cryoplanation surfaces, blockfields, etch surfaces, residual hills, tors, Bohemian Massif, Sudeten Mts.

1. INTRODUCTION

A wide-ranging study of relief development within the Sokolský hřbet (ridge) and the adjacent Žulovská pahorkatina (hilly land) has recently been undertaken (Štěpančíková, 2007a); that study integrated comprehensive geomorphological mapping at the regional scale with detailed morphostructural analyses. In order to compile the necessary geomorphological maps, landforms were classified as either structural, denudational, erosional, depositional, or rock landforms (see Štěpančíková, 2007a, for further details). This paper focuses on the latter group of landforms, as it has been recognised that these rock landforms reflect the morphostructural evolution of the study area. Thus, the aim of this paper is to demonstrate it is possible to use such landforms as circumstantial evidence able to provide considerable insight into the fundamental processes responsible for constructing the present-day relief; such insights can be gleaned because rock landforms reflect their morphogenetic history. The study area is situated in the north-eastern spur of the Bohemian Highlands, within the Bohemian Massif (Fig. 1). The area comprises the Sokolský hřbet (ridge) and the adjacent part of Žulovská pahorkatina (hilly land); the Sokolský hřbet lies within the north-eastern sector of the Rychlebské hory (mountains), themselves part of the Sudeten Mountains, whilst the Žulovská pahorkatina lies within the Sudetic Foreland.

2. GEOLOGICAL AND MORPHOLOGICAL SETTINGS

The studied part of the Žulovská pahorkatina and the north-western marginal slope of the Sokolský hřbet comprise granitoids of the Žulová granite pluton. The pluton is of Variscan age, and represents an apical part of a vast granitic body that is expressed by an extended gravity low (Cháb and Žáček, 1994). By contrast, the eastern sector of the Sokolský hřbet is composed of a Devonian metamorphic cover (Žáček et al., 1995); these crystalline rocks comprise belts of gneisses, amphibolites, quartzites, and marbles

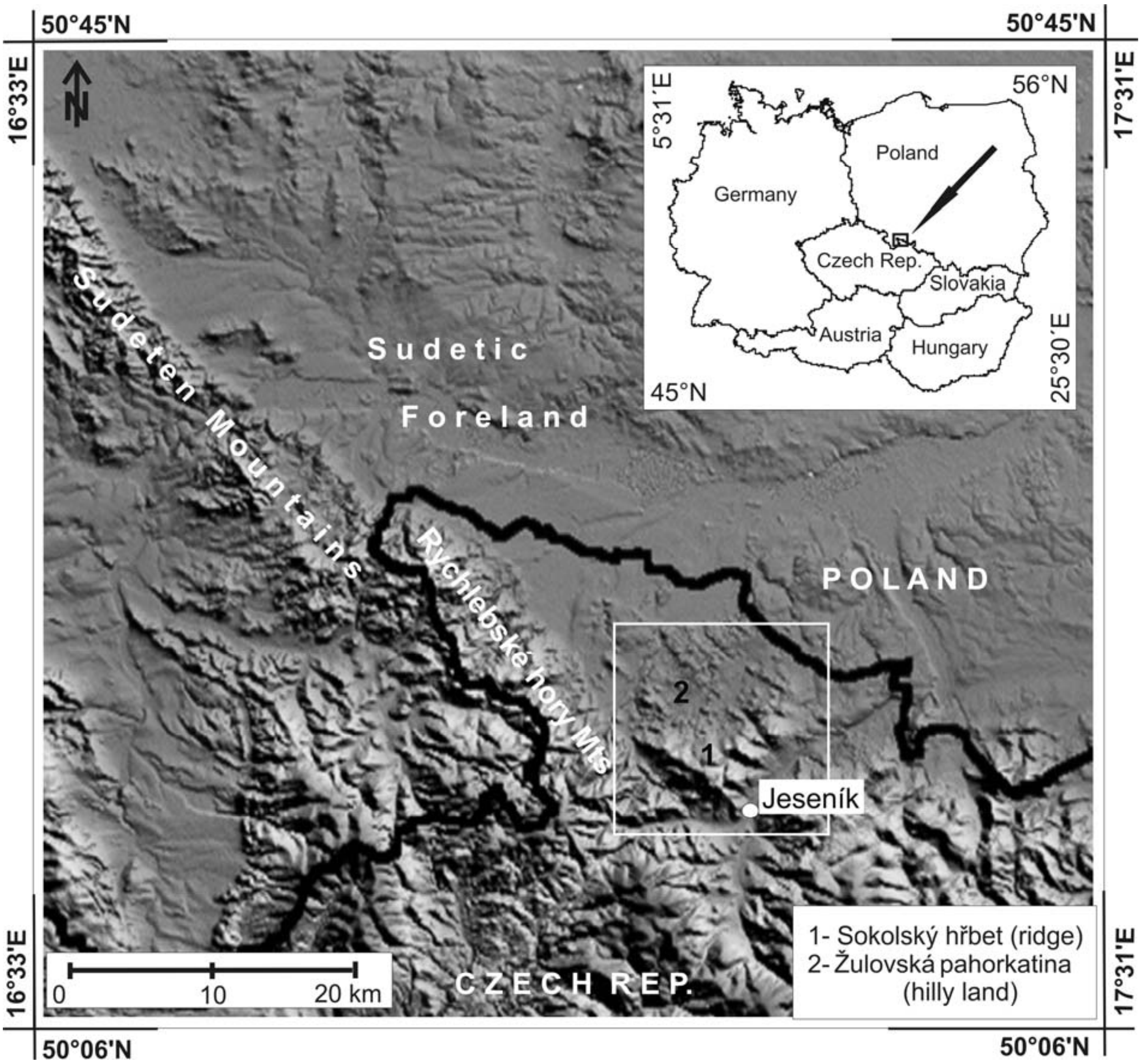

Fig. 1 The geographical location of the study area.

(Fig. 2). Neogene sediments occur intermittently in the Žulovská pahorkatina and although these sediments presently occupy uplifted positions (cf. Pecina et al., 2005), their initial deposition was associated with relative subsidence within the Fore-Sudetic block; such sediments are frequently observed in the adjacent Vidnavská nížina (lowland), where the sequence is more than 270 m thick (Gabriel et al., 1982) and covers a granitic basement kaolinised to a depth of 50 m (Ondra, 1968; Kościówko, 1982). Significant thicknesses of Quaternary sediments are only found within the Žulovská pahorkatina; these deposits include glaciogenic, alluvial, fluvial and colluvial material (Žáček et al., 2004; Pecina et al., 2005).

The wedge-shaped Sokolský hřbet is a horst-like structure, which descends in a series of steps to the NE along the parallel NW-SE striking faults (Ivan, 1997); the highest peak is Studniční vrch at 992 m asl. The prominent mountain fronts are fault-controlled and the entire horst was uplifted above the adjacent region by over 600 m (Štěpančíková, 2007a, b; Štěpančíková et al., 2008). In contrast, the adjacent Žulovská pahorkatina is thought to represent the basal weathering surface of a pre-Neogene etchplain (Štěpančíková, 2007a); this region is generally elevated at between 300-380 m asl. The basal weathering surface hosts numerous low exfoliation domes (ruwares) and isolated inselbergs with gentle convex slopes; the ruwares usually have a relative relief of between 20-30 m, and the inselbergs usually have a relative relief of between 100-150 m. Remnants of kaolinite-rich saprolite are located within those depressions that surround the hills (Demek et al., 1964; Demek, 1976, 1995; Ivan, 1983). During the Pleistocene, the surface of the Žulovská pahorkatina

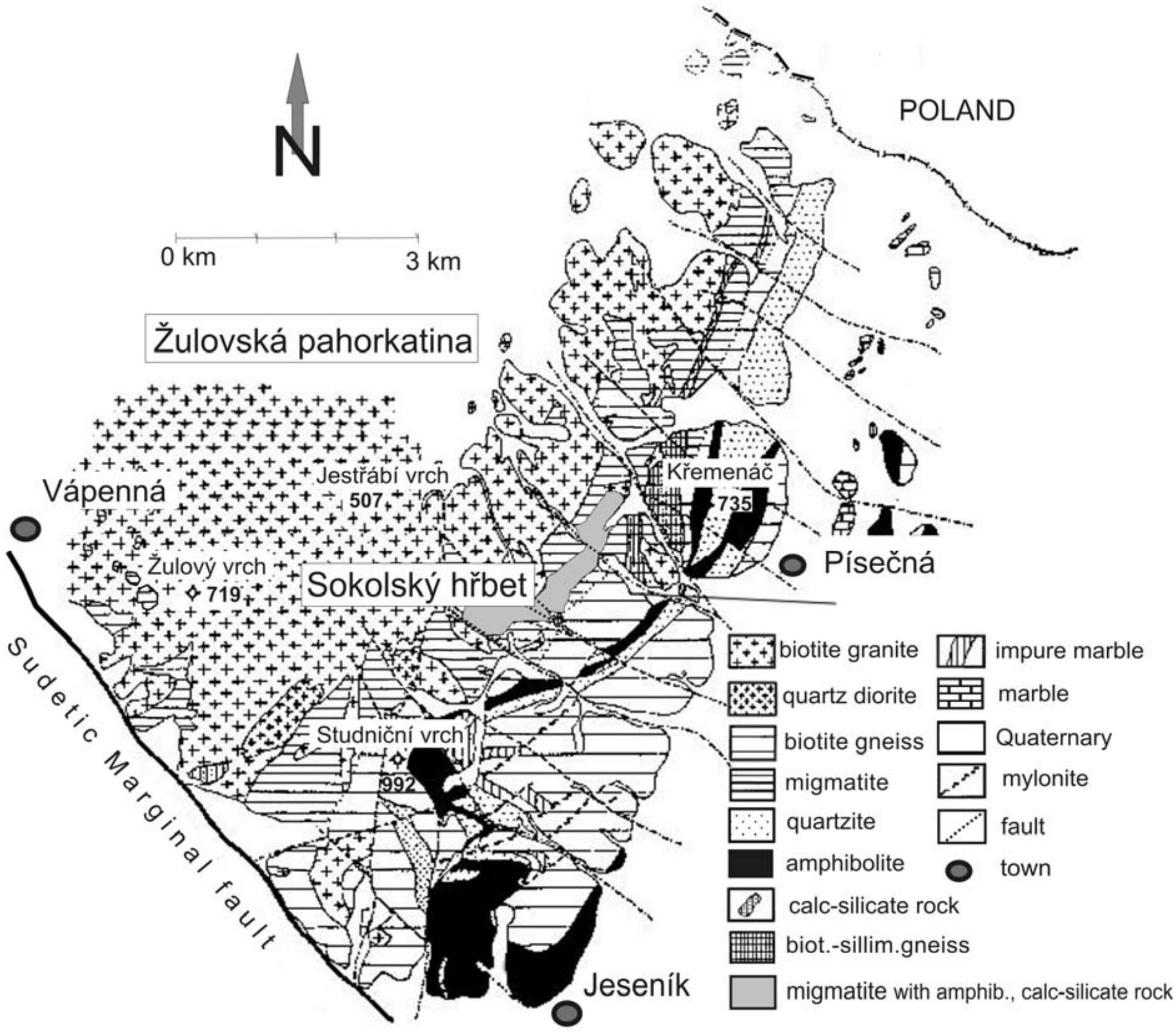

Fig. 2 A geological sketch map of the Sokolský hřbet. The studied portion of the Žulovská pahorkatina is composed by granitoids; adapted from Cháb and Žáček (1994).

was directly subjected to glaciation, as a continental ice-sheet flowed around the Sokolský hřbet (Badura and Przybylski, 1998; Cháb et al., 2004; Žáček et al., 2004; Sikorová et al., 2006). The margins of the ice-sheet reached the Žulovská pahorkatina in both Elsterian 1 (620-635 ka) and Elsterian 2 (400–460 ka); the most elevated till deposits recorded in the study area occur at an altitude of 465 m asl, on the foot of the northern flank of the Sokolský hřbet. Within the non-glaciated parts of the study area, periglacial conditions would have dominated throughout the Pleistocene. The region was strongly influenced by the continental ice-sheets of northern Europe and by the locally extensive Alpine glaciation in southern Europe (e.g. Czudek and Demek, 1971); evidence for these periglacial conditions are frequently recorded within the Bohemian Highlands.

3. METHODS

3.1. *FIELD MAPPING*

Rock landforms within the study area were geomorphologically mapped at a scale of 1:10,000, as part of a wider project that aimed to determine the morphostructural evolution of the region (Štěpančíková, 2007a); the recognised landforms consist of rock steps, blockfields and blockstreams, residual hills, and tors. Particular attention was focused upon the shape of the rockforms, their arrangement, the aspect of their walls, and their topographic position within the slope profile. Moreover, the lithology and structural setting of the rock landforms were recorded; structural measurements (strike and dip of joints) were obtained in order to examine the correlation between jointing and free-face orientation. The position of each rock landform was obtained by GPS and photo-

Table 1 Data pertaining to the rock steps identified in the Sokolský hřbet. SC - structural control of the rock step face (fracture/foliation) (Y - yes, N - no, N/Y - only side rock wall controlled), IB - inclination of benches at the base of rock steps, SA - staircase-like arrangement of rock steps and benches, N - number of rock steps in the locality, Slope origin: DS - denudational slope, ES - erosional-structural slope, DR - denudational ridge, FS - fault scarp, ED - erosional-denudational slope.

Location	Rock type	SC	Rock face height (m)	Slope inclination	IB	SA	Aspect of rock face	Topographical position	Slope origin	N
NW slope of Křemenáč	quartzite	Y	5	5-10°	5°		WNW	on the plain	DS	1
N of Jehlan	gneiss	Y	8	20-25°	5°		WNW	flanking denud. ridge	ES/DR	2
N of Jehlan	gneiss	N	4	10-15°	14°		WNW	flanking denud. ridge	ES/DR	1
SE of Studniční vrch	bitotite gneiss	N/Y	4-13	10-15°	2-8°	X	SSW-SSE	waxing slope	DS	3
SE of Studniční vrch	quartz metacongl'rate	N/Y		15-20°	8°		WSW	waxing slope	FS	1
SE of Studniční vrch	bitotite gneiss	N	3	15-20°	7°		SSE	waxing slope	FS	1
Medvědí kámen	migmatite	N	4-5	20-25°			SSW	flanking denud. ridge	ED/DR	1
Medvědí kámen	migmatite gneiss	N/Y	4-8	15-20°	10°		NW-SW	flanking denud. ridge	ED/DR	2
SW of Jasanový vrch	migmatite	Y	4-10	15-25°	9-12°	X	W	waxing slope	FS	6
W of Zelená hora	migmatite gneiss	N	12	15-25°	5-8°		WSW	waxing slope	FS	1
W of Zelená hora	migmatite gneiss	N	7	15-25°		X	SSW	waxing slope	FS	2
NW of Jehlan	erlan	Y	10-13	20-25°			WSW	valley slope	ES	1
NW of Jehlan	erlan	Y	2	20-25°			W	valley slope	ES	1
SE foot of Černá hora	silimanite gneiss	Y	6	10-15°	15°		E	waxing slope	FS	1
SE foot of Černá hora	migmatite	Y	4	10-15°	7°		SE	waxing slope	FS	1
W of Jestřabí vrch	granodiorite	Y	1-2	5-10°	6°		SSW	valley slope	ED	2
E of Křemenáč	amhibolite	Y	6	15-20°	5°		SSE	waxing slope	DS	1

Table 2 Data pertaining to the residual rock landforms identified in the Sokolský hřbet. SC - structure control of the rock step face (fracture/foliation) (Y - yes, N - no), Slope origin: RH - residual hill, ES - erosional-structural slope, DR - denudational ridge, FS - fault scarp, ED - erosional-denudational slope.

Location	Rock type	SC	Slope inclination	Slope aspect	Topographical position	Slope origin
Bílé Kameny	biotite-silimanite gneiss	Y	15-25°	S	waxing slope	RH
N of Jehlan	quartzite	Y	15-25°	ENE	waxing slope	ES
SE of Studniční vrch	gneiss	Y	5-10°	SSW	waxing slope	FS
SE of Strážný	quartz vein	Y	5-10°	S	foot	FS
Medvědí kámen	migmatite	Y	15-25°	SSW	flanking denud. ridge	FS/DR
Medvědí kámen	migmatite gneiss	Y	20-25°	S	flanking denud. ridge	FS/DR
N of Jestřabí vrch	granodiorite	Y	0-5°		top of residual hill	RH
E of Černá hora	migmatite	Y	0-5°	SE	summit plain	DR
Krajník	biotite gneiss	Y	10-15°	SSE	summit plain	DR
SSE of Jehlan	biotite gneiss/erlan	Y	20-25°	S	waxing slope	ED

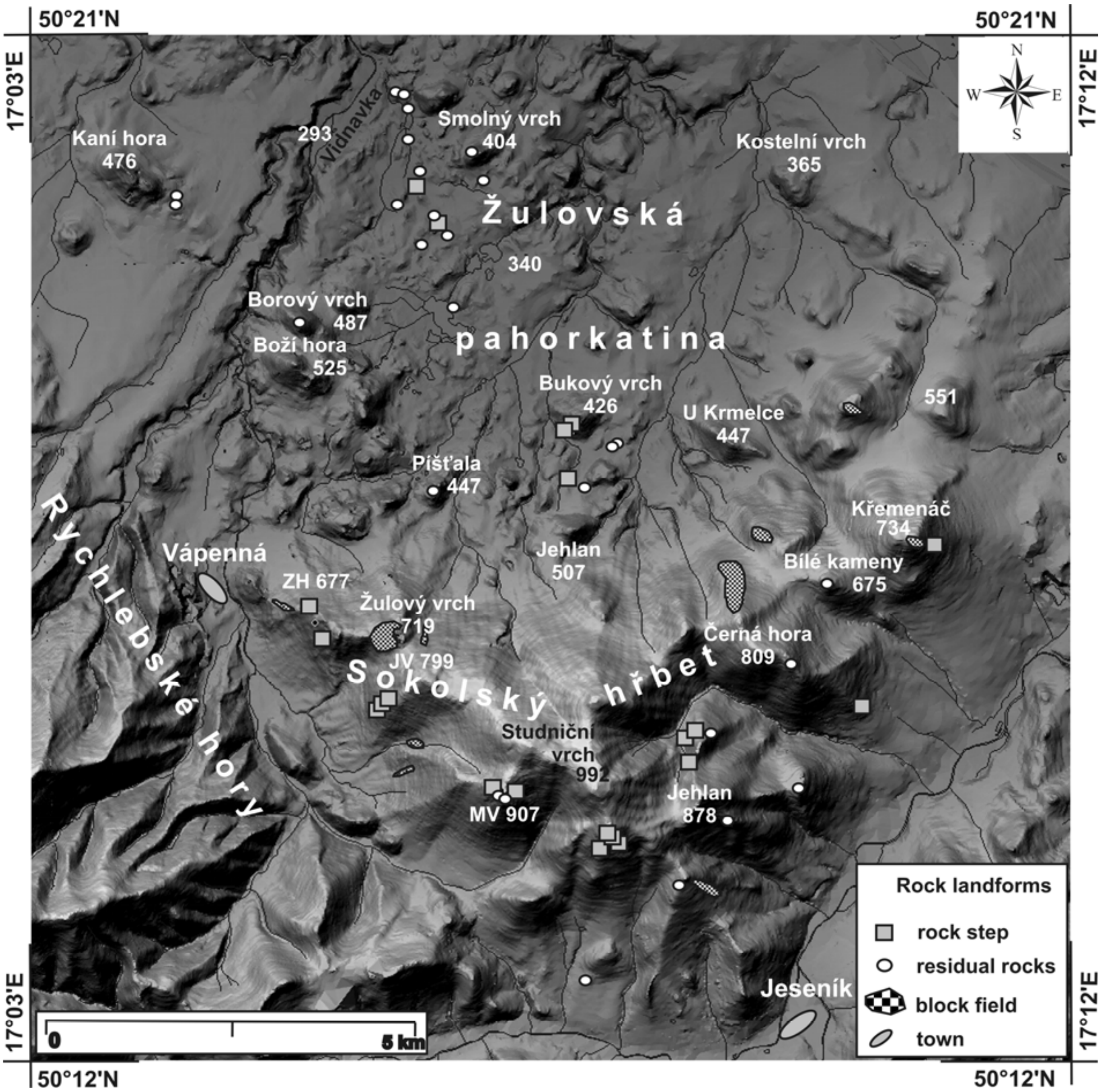

Fig. 3 The geographical distribution of the mapped rock landforms; these have been plotted onto a shaded relief map derived from the ZABAGED DEM. ZH - Zelená hora, MV - Medvědí kámen, JV - Jasanový vrch.

documented. In addition, near-surface weathering characteristics were recorded where vertical profiles could be observed, such as within the many granitoid quarries and road cuttings located in the Žulovská pahorkatina.

3.2. DEM ANALYSIS

The requisite digital elevation data were obtained through the ZABAGED project, which provides such data for the entire Czech Republic in vectorial form. The data provided by the ZABAGED project were compiled through the scanning, vectorizing, and interactive editing of base maps; such maps had a scale of 1:10,000 with a contour interval of 2 or 5 metres (Plischke, 2001). This data uses the S-JTSK (Uniform Trigonometric Cadastral Net) reference system, where positional control is based on the Bessel ellipsoid. Horizontal positional accuracy varies by between 1-10 metres, whilst the vertical accuracy varies by between 1.5-6 metres according to the relief, lucidity of territory, and the applied survey technology (Plischke, 2001).

The spatial distribution of the rock landforms were mapped and analysed in ESRI ArcMap (version 8.1) and Global Mapper (version 7), with respect to their elevation, slope aspect, slope inclination, and slope origin; the data pertaining to slope origin were adopted from Štěpančíková (2007a). The relevant morphological data are summarised in Table 1 and Table 2; the geographical distribution of the rock landforms has been mapped, and this map is presented in Figure 3.

3.3. DEFINITIONS

The assortment of genetic terms applied to both the origins and present-day morphology of rock landforms is considerable, and suffers as a result of the divergent application of such terms by different authors; therefore, it is important to clearly define those terms as they are used in the present study; these have been separated into three groups, based on the type of evidence to which they relate.

FROST-RIVEN CLIFFS AND CRYOPLANATION TERRACES

Frost-riven cliffs and cryoplanation terraces are thought to have developed as a consequence of the significant role played by cryogenic processes during the Pleistocene (e.g. Palmer and Radley, 1961; Czudek, 1964; Martini, 1969). The majority of salient research has been undertaken within central Europe and Russia (cf. Thorn and Hall, 2002), although only a limited number of these studies have been published in English (e.g. Demek, 1969; Czudek and Demek, 1971; Czudek, 1995). Frost-riven cliffs develop as a result of co-planar recession, which leads to the formation of cryoplanation terraces at their base (Smolová, 2002). Furthermore, staircase-like sequences of frost-riven cliffs and cryoplanation terraces may develop where cryogenic and morphological conditions are favourable (Czudek, 1995). Large blocks or blockfields, frost-heaving phenomena, gelifluction lobes and sometimes bedrock outcrops may occur on frost-riven cliffs (Czudek, 1995); indeed, frost weathering is believed to be at its most effective on the lowest part of the retreating frost-riven cliff. The continuing evolution of frost-riven cliffs is evidenced by accumulations of weathered material at the base of the cliff. The development of frost-riven cliffs and cryoplanation terraces has been described in a variety of geographical settings, including central Europe (e.g. Létal and Křížek, 2000; Smolová, 2002; Traczyk and Migoń, 2003; Křížek, 2003, 2007), Antarctica (Hall, 1997) and Tibet (Dian, 1995).

BLOCKFIELDS AND BLOCKSTREAMS

Blockfields, or felsenmeer, may occur over considerable areas and comprise large boulders or angular blocks that have been derived from the weathering of underlying bedrock. Blockfields are usually thought to have evolved very recently. Most commonly, it is assumed that blockfields are produced by the rapid freeze-thaw weathering of bedrock which has been exposed since the end of the last glaciation. However, it may be that blockfield formation occurred throughout the Pleistocene during phases of deglaciation (Nesje et al., 1988); again, freeze-thaw would remain the invoked formative mechanism but the greater time period allows for the production of deep weathering profiles and rounded debris. Nonetheless, it is also possible that blockfield formation pre-dates Pleistocene glaciation; thus it may be initiated under warm temperate climatic conditions, with later exposure to periglacial conditions (e.g. Roaldset et al., 1982; Dahl, 1987; Nesje, 1989). In this scheme, most deep weathering would thus be due to chemical action during pre-Pleistocene periods, when the climate was sufficiently warm and temperate (Whalley et al., 1997). Despite these long-standing controversies, examples of blockfield studies are legion within the periglacial literature (e.g. Dahl, 1966; Rapp, 1984; Rea et al., 1996; Traczyk and Migoń, 2003; Fjellanger et al., 2006).

A blockstream is a narrow linear accumulation of boulders or angular blocks (e.g. Andersson, 1906; Jennings, 1956), which extends further downslope than across slope (White, 1981); blockstreams are commonly recognised within the upper sections of ravines (Washburn, 1980). Unfortunately numerous problems are associated with the nomenclature of blockstreams within the published literature (Grab, 1996); analogous terms may also include “boulder streams” (Whittecar and Ryter, 1992), “rubble streams” (Richmond, 1962), “rock streams” (Small et al., 1970), and “rock rivers” (Costin, 1955). As with blockfields, most blockstreams within mid-latitudinal settings are thought to be formed under periglacial conditions; blockstreams have been described from a wide range of geographical settings, including southern Europe (Palacios et al., 2003), northern Europe (Rubensdotter, 2002), the United States (Clayton et al., 2001), the Tibetan Plateau (Harris et al., 1998), and the Lesotho Highlands (Grab, 1996). However, some blockstreams remain active at the present-day in Siberia (Romanovskii and Tyurin, 1974; 1983) and the Urals (Romanovskii and Tyurin, 1986).

RESIDUAL HILLS AND TORS

A residual hill is here defined as an isolated hill mass that protrudes conspicuously above a surrounding sub-horizontal surface; the morphology of such hills is often castellated. This term has purposefully been chosen in preference to the alternatives of bornhardt or monadnock as it carries no morphogenetic connotations; for example, a bornhardt is specifically a large granite-gneiss inselberg associated with the second cycle of erosion in a rejuvenated desert region (King, 1948), and a monadnock is a mountain of circumdenudation rising conspicuously above the general level of a peneplain in a temperate climate (Davis, 1893). However, the term inselberg does need to be defined; here, an inselberg is considered to be a small mountain of circumdenudation that rises abruptly from and is surrounded by an extensive sub-horizontal denudation surface (Bornhardt, 1898). Inselbergs are usually associated with humid tropical and semi-arid to arid regions at the present-day; these hills are formed through the process of etchplanation.

Tors are upstanding projections of unweathered rock that protrude conspicuously above the surrounding topographic surface; in contrast to a residual hill, such features may be located in a variety of positions within the slope profile and do not necessary occupy the most elevated point within a given locale. Tors are characteristic landforms within many European regions and have been detailed in countless papers (cf. Migoń and Lidmar-Bergström, 2001), although their age and origin continues to be debated (e.g. Hall and Sugden, 2007); three potential mechanisms for tor formation are outlined here. First, Linton (1955) proposed a two-phase origin for the tors of Dartmoor; in this scheme, a period of differential weathering was followed by a period of regolith stripping. Second, Battiau-Queney (1984; 1987) proposed a single-phase origin for the tors of southwest Wales; in this scheme, differential weathering and regolith stripping occurred simultaneously, the latter as a result of slow and prolonged regional uplift. Third, Demek (1964a) proposed a single-phase origin for the tors of the Bohemian Highlands; in this scheme, tors may be formed by frost-riven cliffs retreating in parallel as a result of the separation of blocks along joints. After a prolonged period of scarp retreat, the cliffs are denuded to such an extent that they remain only as remnant tors within the landscape.

4. RESULTS

4.1. ROCK STEPS

SOKOLSKÝ HŘBET

Rock steps in the Sokolský hřbet have been analysed in detail; these steps are recorded from a range of topographic positions within the slope profile. In the study area, such steps are formed in various rocks including migmatites, migmatite gneisses, gneisses, erlans, graphitic marbles, quartzites, and quartz metaconglomerates. These rocks often form more resistant belts or lenses when juxtaposed next to less resistant lithologies; the sole exception noted within the study area is found to the east of Křemenáč hill (735 m asl), where a rock step composed of amphibolites is surrounded by quartzites. It should also be noted that neither rock steps nor naturally outcropping bedrock composed of granitoids are exposed on any slope within the study area.

The observed rock steps occur on slopes with an inclination of between 5°-25°. Furthermore, such steps are exposed in one of three morphological settings. First, steps may be recognised on waxing slopes; most of these slopes have been identified as fault-scarps (Štěpančíková, 2007a). Steps recognised within this morphological setting include those observed to the SW of Jasanový vrch (799 m asl), and those observed to the W of Zelená hora (654 m asl). Second, steps may flank narrow sub-horizontal denudational ridges in the summit area, at the boundary between a ridge and an erosional-denudational slope; such ridges have been cut indiscriminately across all lithologies and are not presently affected slope erosion, whereas erosional-denudational slopes are unaffected by contemporary linear erosion (Štěpančíková, 2007a). Steps recognised within this morphological setting include those observed at Medvědí kámen (907 m asl), and those observed to the N and NE of Jehlan hill (878 m asl). Third, steps may occur on erosional-structural slopes; these slopes are controlled by faults that run along valley margins. Steps recognised within this morphological setting include those observed to the NNW of Jehlan hill (878 m asl) (see Fig. 3).

The exposed free-face of the steps ranges from 2-13 m in height and from a few metres to a few tens of metres in width, whilst the morphology of the steps is normally controlled by vertical joints. However, it is important to note that there are also examples of steps within the study area whose free-face orientation does not conform to any structural plane; therefore, the rock walls of these steps are not joint-controlled and cannot be simple structural features. At the base of the steps, gently inclined benches are recognised; these vary from between 2-10 metres in width, and are usually inclined by between 3°-12° (Table 1). Although such benches may have a greater inclination on steep slopes, the step morphology remains a striking form within the slope profile (Fig. 4). These benches are frequently covered by

Fig. 4 A rock step (interpreted as frost riven cliffs within the text) to the SSE of Studniční vrch in the Sokolský hřbet, which forms a striking step morphology within the slope profile.

Fig. 5 Rock steps (interpreted as frost riven cliffs within the text) formed in gneisses to the W of Zelená hora in the Sokolský hřbet; the angular blockfield contrasts sharply with the granitic boulder.

Fig. 6 The rockwall of rock step which cuts both gneisses and an included quartz vein to the SSE of Studniční vrch in the Sokolský hřbet.

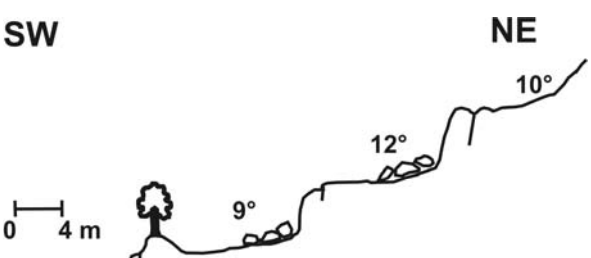

Fig. 7 A sketch of the staircase-like sequences of rock steps to the SW of Jasanový vrch in the Sokolský hřbet.

angular blocks that have been derived from the adjacent rock step.

In addition to the dominant fracture control, the lithologic predisposition of the rock steps is striking. For example, in the western part of the study area near Zelená hora (654 m asl) or Na Skalce (680 m asl), steps are only developed within the gneiss belt; these steps are up to 12 m high and surrounded by angular scree, which contrasts sharply with the rounded boulders (up to 2 m in diameter) observed in the adjacent blockfield of the Žulová granite pluton (Fig. 5).

In some places, the steps and benches are arranged in staircase-like sequences. For example, the southern slope of Studniční vrch (992 m asl) hosts such a sequence, which has developed over a downslope distance of 200 m; the individual steps are formed in both quartz metaconglomerates and gneisses. Indeed, the most elevated step is controlled by a fracture which cuts both gneisses and quartz vein inclusions along one of the exposed walls (Fig. 6). These cliffs are exposed to the SSE (i.e. downslope) and to the WSW. A further example of a staircase-like sequence is observed to the WSW of Jasanový vrch (799 m asl) (Fig. 7). Here, the sequence is formed in two parallel belts; one belt hosts two rock steps and the other belt hosts three rock steps; these are composed of migmatite and have angular blocks at the base of each step.

Aspect analysis showed that 92% of the observed steps are orientated in either westerly (SW to NW = 57 %) or southerly (SW to SE = 36 %) directions (Table 1, Fig. 8); only 7 % are orientated in either easterly or northerly directions. Thus, aspect plays an important additional role in the formation of

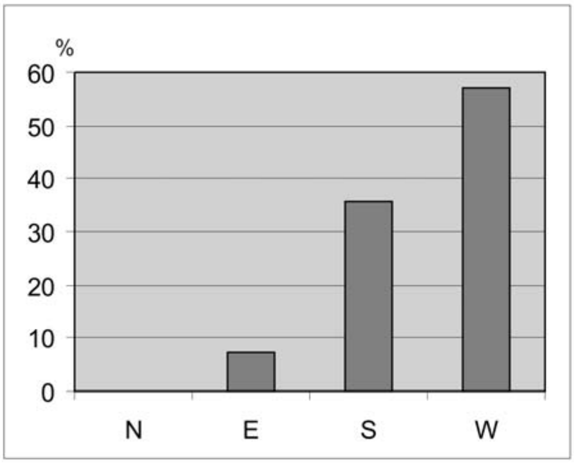

Fig. 8 A diagram showing the relationship between aspect and rock step frequency (in %).

such steps; this preference may relate to the generally greater insolation that is associated with such orientations, i.e. bigger thermal changes occur on southern and western slopes. Where the slopes are orientated thus, rocks undergo frost weathering more intensely and are subjected to faster and deeper denudation (Prosová and Sekyra, 1961); the role of differential insolation on rock landforms in the Sudeten Mts has also been described by Walczak (1963).

ŽULOVSKÁ PAHORKATINA

Rock steps formed in granitoid are completely absent from all slopes within the Sokolský hřbet. The only occurrence of such steps is at the foot of the ridge, at the boundary with the Žulovská pahorkatina. These rock steps, close to the Jestřábí vrch (507 m asl), are positioned on a denudational ridge and exposed southwards; the steps are composed of biotite granite and show platy parting (disintegration) (Fig. 9). Importantly, these steps are not surrounded by blocks derived from the adjacent free-face.

4.2. BLOCK ACCUMULATIONS

Two types of blockfield are recognised within the study area; all but one is located in the Sokolský hřbet. First, autochthonous blockfields occur in summit areas or on gentle slopes close to the source of the material; such blocks comprise bedrock weathered *in situ*. Second, allochthonous blockfields occur on slopes away from the source of the material; such blocks have been transported by solifluction, and are often stabilised by vegetation (Rubín and Balatka, et al., 1986; Goudie et al., 1991; Rea et al., 1996). In the study area, blockfields and blockstreams occur predominantly in granitoids, as well as in quartzites and gneisses; these block accumulations are generally recorded within an altitudinal range of between 500-780 m asl.

Autochthonous blockfields are the most commonly observed within the study area. A prominent example is located in the summit sector of Křemenáč hill (735 m asl), and is composed of mechanically weathered quartzite; it continues as an allochthonous blockfield on the SE downslope, which has been partially stabilised by vegetation (Fig. 10). A granitoid blockfield occurs on Žulový vrch (719 m asl), where the individual blocks may reach 5 m in diameter (Fig. 11). A further example is located on Liščí vrch (643 m asl), where rounded boulders spread from the summit. Autochthonous blockfields may continue down-slope as allochthonous blockfields (e.g. as at Křemenáč hill) or may pass into tongue-like blockstreams, which form in places where there are increased slope gradients.

Moreover, it is characteristic for block accumulations to occur along the entire length of marginal structural slopes (fault scarps) in the Sokolský hřbet; such slopes are composed of granitoids and are orientated NW and SW. These blockfields usually cover large areas, and are being stabilised at present through soil formation and vegetation encroachment. Due to their large size, their degree of stabilisation, and their occurrence within a forested area, such features are difficult to map

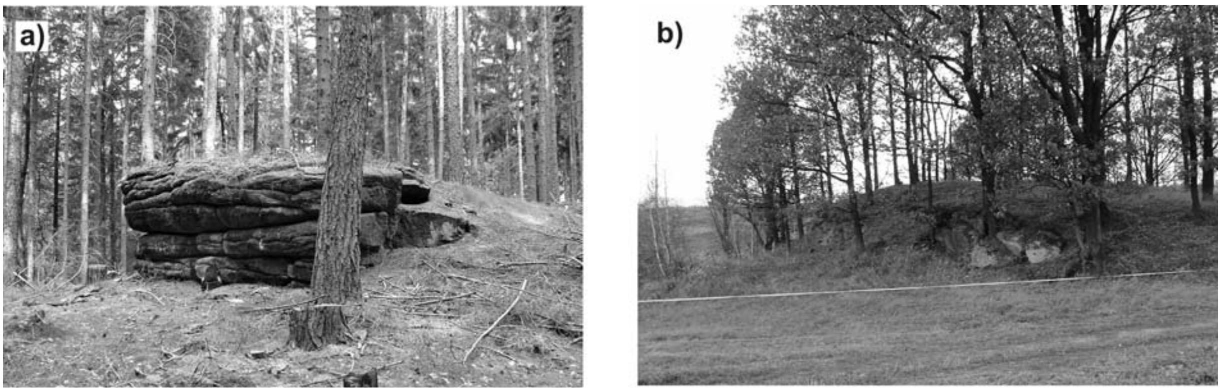

Fig. 9 Rock steps in granitoids; a) a rock step which exhibits platy parting to the NE of the Jestřábí vrch at the foot of the Sokolský hřbet, b) a rock step on the margin of basal knob in the Žulovska pahorkatina.

Fig. 10 A blockfield formed in quartzites at the summit of Křemenáč hill in the Sokolský hřbet.

precisely; therefore, only the most significant and uncovered blockfields have been recorded and mapped. Typical orthogonal primary SQL jointing and predominantly spheroidal or woolsack-like disintegration of these granitoids, with less commonly observed quadrangular disintegration, has enabled the development of these extensive block covers; such blocks are commonly 1-2 m in diameter. Locally occurring blockfields and blockstreams composed of gneisses are characterised by angular blocks, which contrast sharply with the rounded boulders characteristic of the granitoids; even within the granitoids, a wide range of block morphologies are observed as a result of the various types of parting (Fig. 12). Although the rounded shape of such blocks was previously considered to only result from long-term sub-surface chemical weathering (e.g. Twidale, 1971), several examples observed from quarries within the study area demonstrate that primary spheroidal jointing of granite occurs in places unaffected by chemical weathering (Fig. 12). In addition, rock disintegration and the formation of blockfields may be accelerated as a result of the role assumed by vegetation (Fig. 12).

Furthermore, there are also several instances of slopes within the Sokolský hřbet that are covered by blocks transported by solifluction, recorded from vertical sections exposed in road cuttings; these blocks are seen to be "floating" in the uppermost part of the sandy-loam colluvium, which has been derived from stripped grus (Fig. 13).

In contrast, blockfields are rarely observed in the Žulovská pahorkatina; however, one example is recorded on the SW slope of the residual Smolný vrch (404 m asl).

4.3. RESIDUAL ROCK LANDFORMS
SOKOLSKÝ HŘBET

In the Sokolský hřbet, the isolated residual rock landforms include castellated hills, rockwalls, and tors. These rock landforms occur mainly in the summit areas on denudational ridges, on the denudational slopes of residual hills, on the waxing slopes of fault scarps, on erosional-structural slopes, and on erosional-denudational slopes. The inclination of these slopes generally ranges from 5°-25°, except in the case of a denudational ridge which is inclined between 0°-5°; the preferred aspect of these rock landforms is within the southern sector (Table 2). Residual rock landforms recognised on denudational ridges include those observed to the SE of Černá hora (809 m asl), and those observed on Krajník hill

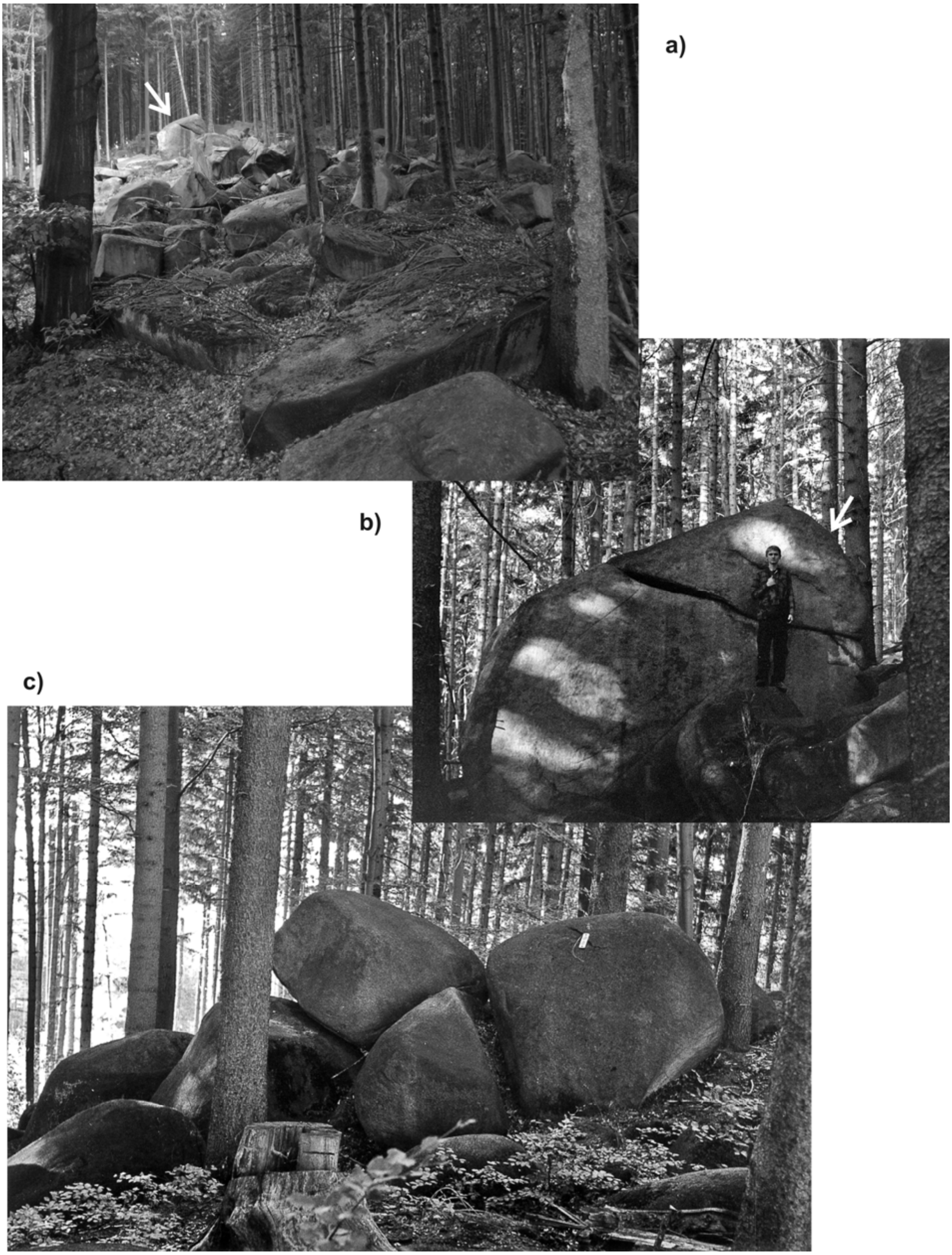

Fig. 11 An autochthonous blockfield composed of granitoids at the summit of Žulový vrch in the Sokolský hřbet; a) the blockfield to the W of the summit, b) a boulder within the aforementioned blockfield (person for scale), c) spheroidal parting of granitoids at the summit surface to the W of Žulový vrch.

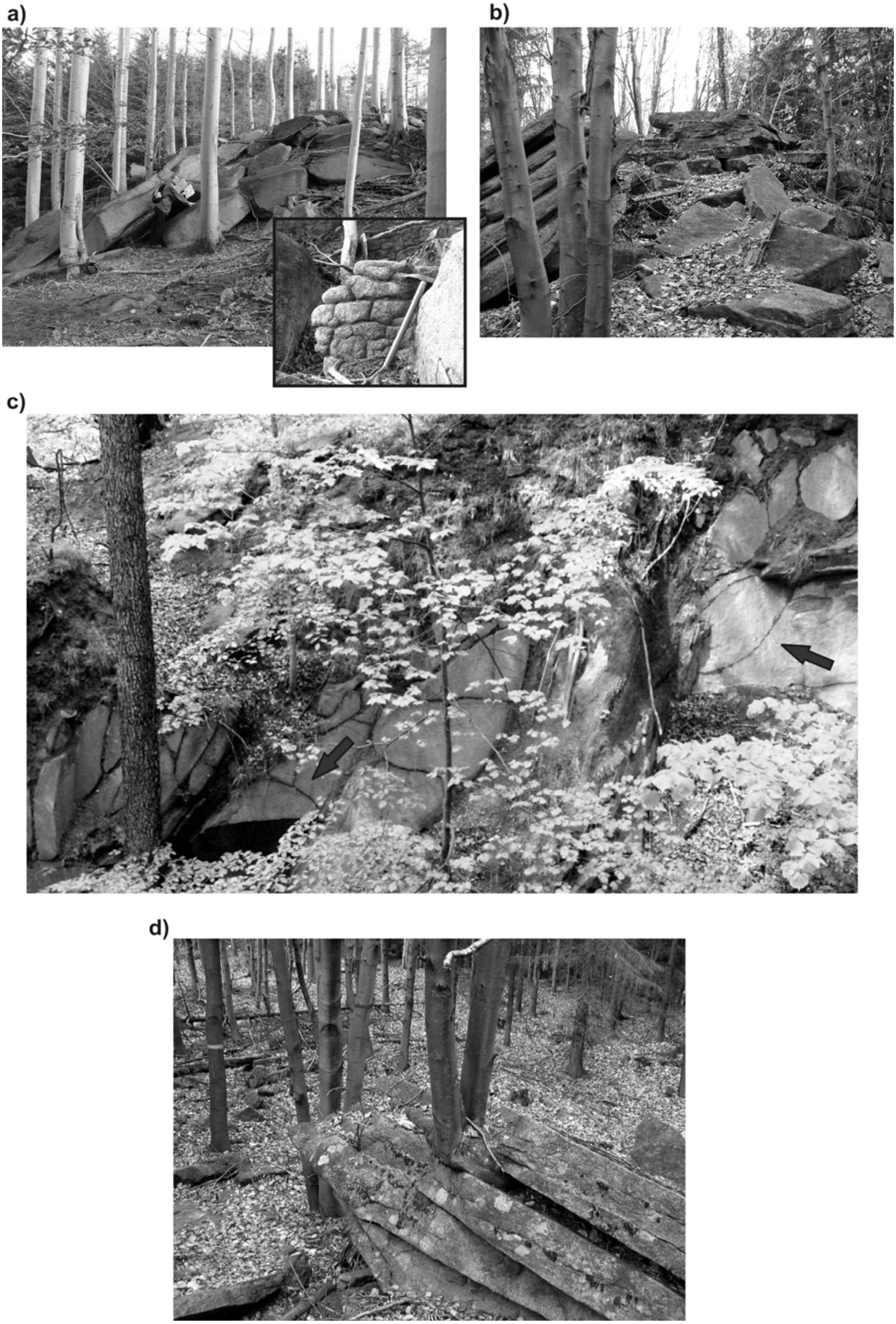

Fig. 12 Examples of various types of parting within biotite granites and granodiorites; a) platy parting exhibited on the western slope of Jestřábí vrch in the Sokolský hřbet; note the detail with polygonal cracks, b) slab-like parting on the summit of U Krmelce hill in the Sokolský hřbet, c) primary spheroidal parting in quarry near Boží hora in the Žulovská pahorkatina, d) an example of the destructive action of roots at the summit of U Krmelce in the Sokolský hřbet, which is contributing to mechanical rock disintegration.

Fig. 13 A granite block “floating” in the uppermost part of a sandy-loam colluvium that has been derived from grus-like regolith located on the upper part of a marginal slope; this block is exposed in road cutting to the S of Sokolí vrch in the Sokolský hřbet.

(658 m asl). Furthermore, at Medvědí kámen (907 m asl) rock landforms flank the sub-horizontal denudational ridge within the summit area, where they coexist with rock steps. Residual rock landforms recognised on the denudational slopes of residual hills include those observed on Bílé Kameny hill (675 m asl); this residual hill has been identified as probably representing an uplifted inselberg (Štěpančíková, 2007a). Residual rock landforms recognised on erosional-structural slopes include those observed to the NE of Jehlan hill (878 m asl). Residual rock landforms recognised on the waxing slopes of fault scarps include those observed to the SE of Studniční vrch (992 m), and those observed on the boundary between the fault-scarp and the erosional-denudational slope SE of Jehlan hill.

Residual rock landforms have formed in gneisses, quartzites, veiny quartz, and migmatites. An example of a rockwall, developed in a resistant belt of quartzites, lies N of Jehlan hill (878 m asl) (Fig. 14); this rockwall forms the summit sector of a small structural ridge that is elongated downslope for 100 m and is over 10 m high, whilst its walls are controlled by joints that have three perpendicular orientations. Another significant site is the Bílé Kameny (675 m asl); the rockforms here are formed within 4-5 belts of more resistant biotite-sillimanite gneisses with garnet, and are spaced at intervals of between 5-20 m. These rock landforms include both castellated rocks and tors; in all mapped cases, the shape of the residual rock form is controlled by a fracture system that borders their walls.

ŽULOVSKÁ PAHORKATINA

Residual rock forms composed of granitoids could be found only in the transitional area between the Sokolský hřbet and the Žulovská pahorkatina. These rock forms occur at the SW foot of the ridge on top of a residual hill (398 m asl), 0.5 km NNE from Jestřábí vrch (507 m asl); the residual hill is elevated only few metres above the surrounding sub-horizontal denudation surface. Here, the rock landforms comprise a group of castellated rocks, rock walls, and tors in medium-grained biotite granodiorite (Fig. 15). The individual forms are rather isolated and well-rounded even where there is platy parting, and microforms can also be found on their surfaces. The absence of modern debris or more extensive blockfields under these rock landforms suggests that frost-shattering has not been a significant geomorphological agent in recent times.

Fig. 14 A rockwall developed in a resistant belt of quartzites to the N of Jehlan hill in the Sokolský hřbet.

In those other parts of the Žulovská pahorkatina that are composed of fine- to medium-grained biotite granodiorites of Žulová granite pluton, castellated rocks and tors of various shape and size occur. These rock landforms are always located on summits or to a lesser extent on the waxing slopes of residual hills, which have been identified as inselbergs and low exfoliation domes (Demek et al., 1964; Demek, 1976; Ivan, 1983; Migoń, 1997). Examples of surficial forms developed on inselbergs include those recognised at Píšťala hill (447 m asl), where microforms such as weathering pits and tafoni are recognised; at Borový vrch (487 m asl) weathering pits, tafoni, and honeycombs have developed on tors and bedrock surfaces; and at Smolný vrch (404 m asl) weathering pits and tafoni have also developed (Fig. 15). Tors are also recognised on small residual hills and low exfoliation domes to the S of Smolný vrch (Demek 1976). Moreover, smaller individual tors (1-6 m high) were mapped in an area to the S of Smolný vrch (404 m asl); these conspicuously protrude above the surrounding sub-horizontal surface (Fig. 16). The surfaces of these tors host both weathering microforms and a limonite crust (Fig. 16). Open joints allow advanced weathering to be observed within a group of tors to the SE of Kaní hora (475 m asl) in fine-grained biotite granodiorite, at an altitude of about 395 m; these open joints control the shape of the tors (Fig. 16). However, rock fragments with differing lithologies are found deep inside these joints; they include metagabbro, quartz, and quartz diorite. It is suggested that these fragments have been deposited by a continental glacier, and thus that the tors are of pre-glacial origin.

5. DISCUSSION

5.1. ROCK STEPS

The identification of a striking rock step within the slope profile, with a bench at its base implies parallel backslope retreat; such morphological evidence is further enhanced where the bench is covered by blocks derived from the adjacent step. The main process considered responsible for the formation of such steps and benches within the mountainous environment of the study area is frost shattering (congelifraction), which is particularly effective in well-jointed rocks. Thus, the mapped rock steps are identified as frost-riven cliffs (Section 3.3); such cliffs have been described from many localities within the Sudeten Mts (cf. Panoš, 1961; Ivan, 1966; Traczyk

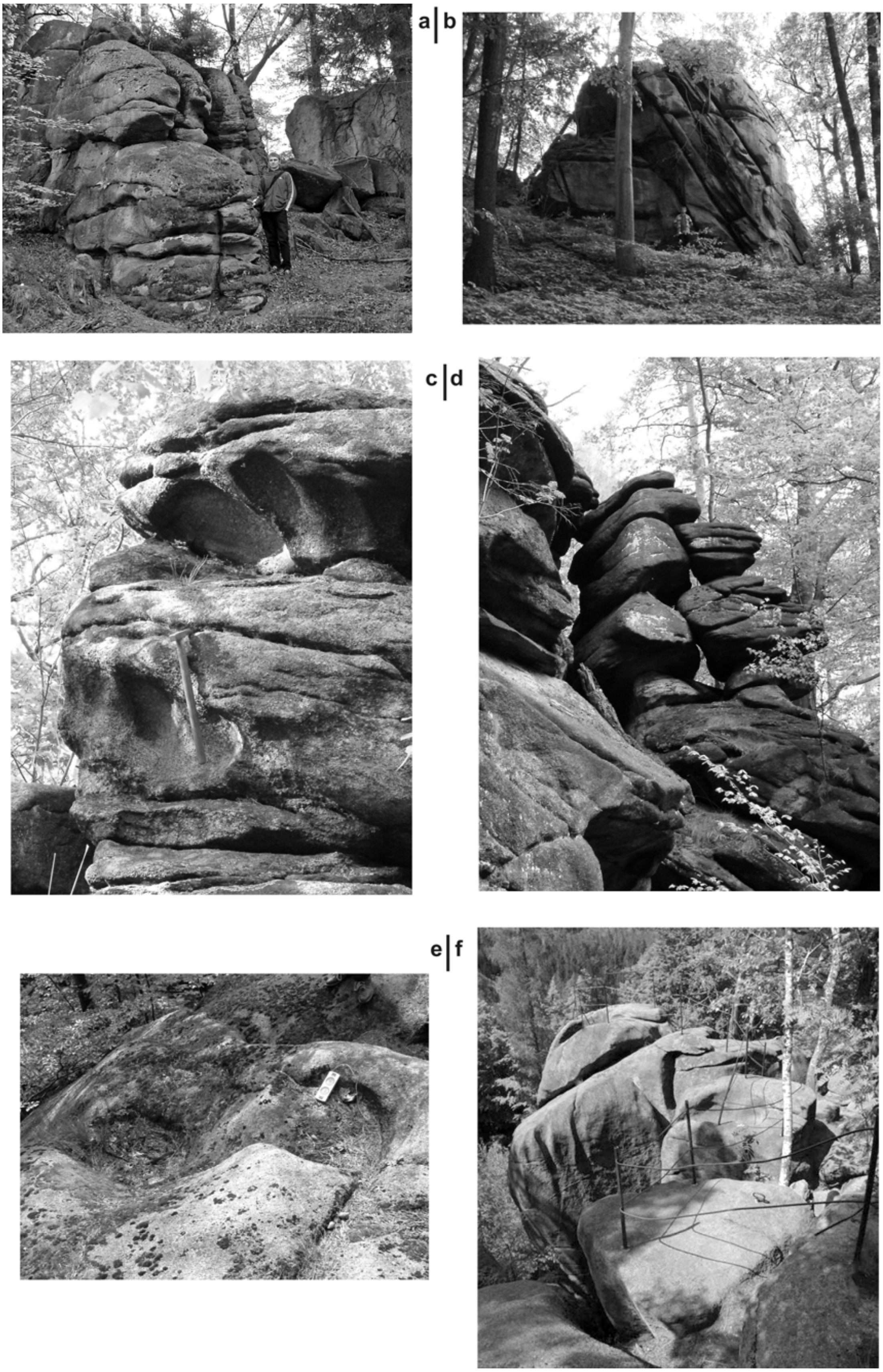

Fig. 15 Residual rock landforms composed of biotite granodiorites; a) isolated rock landforms (tors, rock walls) with weathering microforms to the N of Jestřábí vrch at the foot of the Sokolský hřbet, b) a tor at the top of the inselberg of Píšťala in the Žulovská pahorkatina, c) weathering pits and tafoni located on the tor noted in (b), d-e) various rockforms located on the top of the inselberg of Borový vrch in the Žulovská pahorkatina, f) rockwalls with weathering pits at the top of the inselberg of Smolný vrch in the Žulovská pahorkatina.

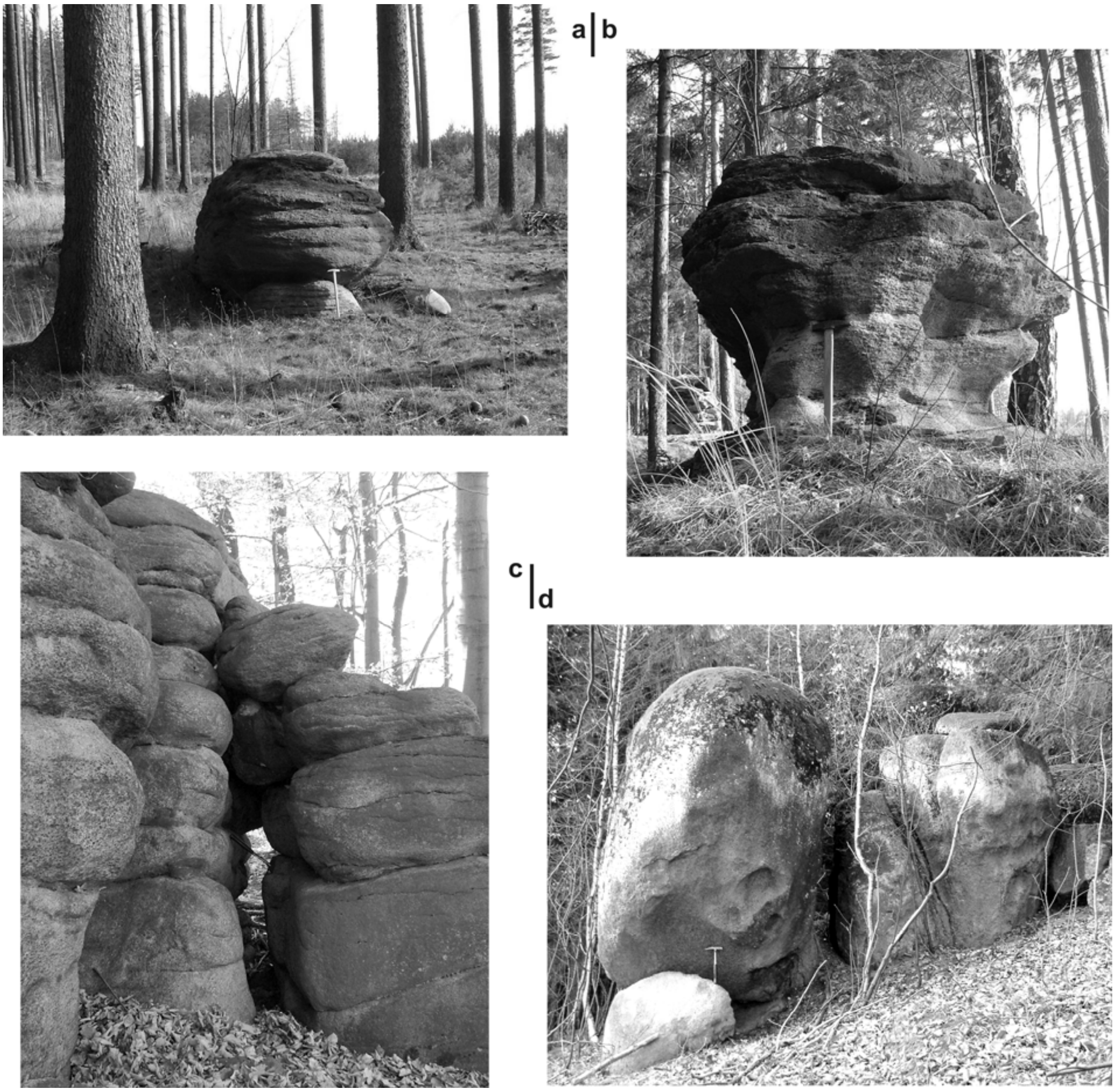

Fig. 16 Tors formed composed of granite in the Žulovská pahorkatina; a) tor conspicuously protruding above the surrounding sub-horizontal surface, to the S of Smolný vrch, b) mushroom rocks and tors to the S of Smolný vrch, c) tors to the SE of Kaní hora where eratics between joints were found, d) tors with a limonite crust, to the SW of Bukový vrch.

and Migoń, 2003; Křížek, 2007; Křížek et al., 2007). Moreover, clear evidence of climatic control is thought to be demonstrated where a frost-riven cliff diagonally cuts a lithological boundary (Traczyk and Migoń, 2003); such a scenario was described from the southern slope of Studniční vrch (992 m asl) in Section 4.1 (Fig. 6).

If the mapped rock steps are regarded as frost-riven cliffs, it follows that the benches at the base of cliffs are regarded as cryoplanation features; such terraces are generally considered to be fossilised features in central Europe and North America, which developed during Pleistocene glacial periods (e.g. Czudek, 1964; Hall, 1997). The cryoplanation terraces recognised within this study area are quite narrow and not fully developed in comparison with those presently developing in periglacial regions. Furthermore, the aspect control of the mapped steps does not correspond to the frequently observed preferred orientation of cryoplanation terraces in such regions, which usually abound north-facing slopes; this preferred orientation has been ascribed to the spatial pattern of snow accumulation and ablation, whereupon localised erosion initiates the formation of cryoplanation terraces (Hall, 1997; Nelson, 1998; Křížek, 2007). Nonetheless, the retreat of frost-riven cliffs in this area is still considered to be the result of congelifraction. Moreover, the rate at which such cliffs retreat is highest under periglacial conditions as a result of frost shattering (e.g. Hinchliffe and

Ballantyne, 1999; Matsuoka and Sakai, 1999); it is therefore most probable that these cliffs primarily developed during the cold periods of Pleistocene as the width of the cryogenic benches reaches a maximum of only 10 m. This figure cannot be accounted for during the Holocene alone, although the development of the benches may have continued to a lesser extent during this period.

In contrast, the rock steps in the Žulovská pahorkatina occur within a formerly glaciated area and in different morphological positions to those observed on the Sokolský hřbet (e.g. at the base of residual hills); it is therefore probable that the steps have divergent origins. In the Žulovská pahorkatina, fine-grained weathered material was removed and this process exposed the rock face; steps in this area are not surrounded by blocks derived from the adjacent rock (Fig. 9); initially some of these rock steps were considered to have formed the lee-side of roche moutonnée, but this was later disproved (Vídeňský et al., 2007).

5.2. BLOCKFIELDS AND WEATHERING

There is considerable controversy regarding the origins of blockfields (Section 3.3). The blockfields in quartzites (SE from Křemenáč hill and S from Jehlan hill), and in gneisses (WNW from Zelená hora) are composed of angular blocks. These are presently situated below the alpine timberline, and therefore probably originated during cold periods in the Pleistocene as a consequence of mechanical periglacial weathering processes such as frost shattering (cf. Rea et al., 1996); these forms are inactive under present climatic conditions (cf. Křížek, 2007). It should be noted that quartzites and gneisses have a markedly different parting to granitoids.

The autochthonous blockfields situated in granitoid summit areas are composed of rounded boulders which have evidently been stripped of their associated grus; the fine-grained grus material has been deposited downslope, and is commonly observed in road-cuttings. The overall position of these block accumulations corresponds with the typical granite slope evolution described by Demek (1964b); i.e. the biggest blocks occur on the summits and upper convex parts of the slopes, whereas in the lower parts rather fine-grained, washed-out material can be found. Thus, by far the most plausible origin of the described granitoid autochthonous blockfields is as a result of exhumation from beneath the weathering mantle. The grus in the Sudeten Mts is considered to be no more than of Plio-Pleistocene age (Migoń, 1999; Migoń and Lidmar-Bergström, 2001); therefore these blockfields must be coeval with, or younger than, the Plio-Pleistocene. The age range associated with these blockfields is reflected by the different stages in their stabilisation - from deep accumulations that have an open void system through to accumulations that are covered by vegetation and soil. The initial stage of grus removal can be observed in, for example, the granite quarry on the NW slope of the Sokolský hřbet (Fig. 17); other quarries located on the granitoid slopes of the Sokolský hřbet show that vertical grus-weathering proceeds to a maximum depth of 1 m, but is usually much less (Fig. 18).

In contrast, in the Žulovská pahorkatina the granitoids are weathered to a much greater depth, and this grus-weathering can be observed in many of the quarries situated on slopes of residual hills (inselbergs); typical corestones are exposed, for example, north of Vycpálek hill (500 m) (Fig. 18). Kaolinite-rich saprolite was stripped, with remnants only recorded from a small number of localities in the Žulovská pahorkatina. Examples include the basal remnants of kaolinite-rich saprolite that has been recovered from boreholes that were sunk in depressions between residual hills (e.g. Demek et al., 1964) and residual kaolin that is presently exposed within a pit in the town of Vidnava; here the kaolin is up to 90 m thick and avoided stripping because of its position, as it rests upon a tectonically subsided block (e.g. Milický et al., 1985). Moreover, the granite morphology of the Žulovská pahorkatina has also facilitated the formation of sheeting joints; thus numerous exfoliation domes are found in this area. These sheeting joints are observed in those quarries located in low exfoliation domes or on the surface of inselbergs; such joints produce forms that are notably different to those forms required to initiate the formation of blockfields (Fig. 18).

5.3. RESIDUAL ROCK LANDFORMS

Residual rock forms that occur on summit plains or along their edges in the Sokolský hřbet confirm that their origin is due to denudational processes and slope recession. Regardless of the type of rock landforms mapped in the Sokolský hřbet (castellated rocks, rock walls, or tors) the forms are always surrounded by rather angular blocks of various sizes that have been derived from the free-face. Thus, the origin of these rock landforms would correspond with the single-phase model proposed by Demek (1964a). In that scheme, tors are considered to have formed as a result of parallel slope retreat due to the separation of blocks along their joints; the principle process required for this separation was thought to be frost weathering (see Section 3.3).

In contrast, the tors observed at the foot of the Sokolský hřbet and in the Žulovská pahorkatina occur in very different morphological positions (i.e. at the summits of residual hills or at very low elevations on the sub-horizontal surface). These tors are not surrounded by extensive blockfields; thus they are probably of etched origin and could have been subjected to a two-stage evolution. In that scheme, the tors are considered to have been exposed as corestones as a result of the removal of weathered material thereabouts; this weathered material was either characteristically sandy or possibly rich in kaolinite, if such weathering occurred prior to the

Fig. 17 The initial phase of exposure associated with the woolsack-like to spheroidal disintegration of granites; the rounded shapes contrast sharply with the paragneisses overlaying the granite (top right hand-side). The quarry is located near the Zelená hora in the Sokolský hřbet.

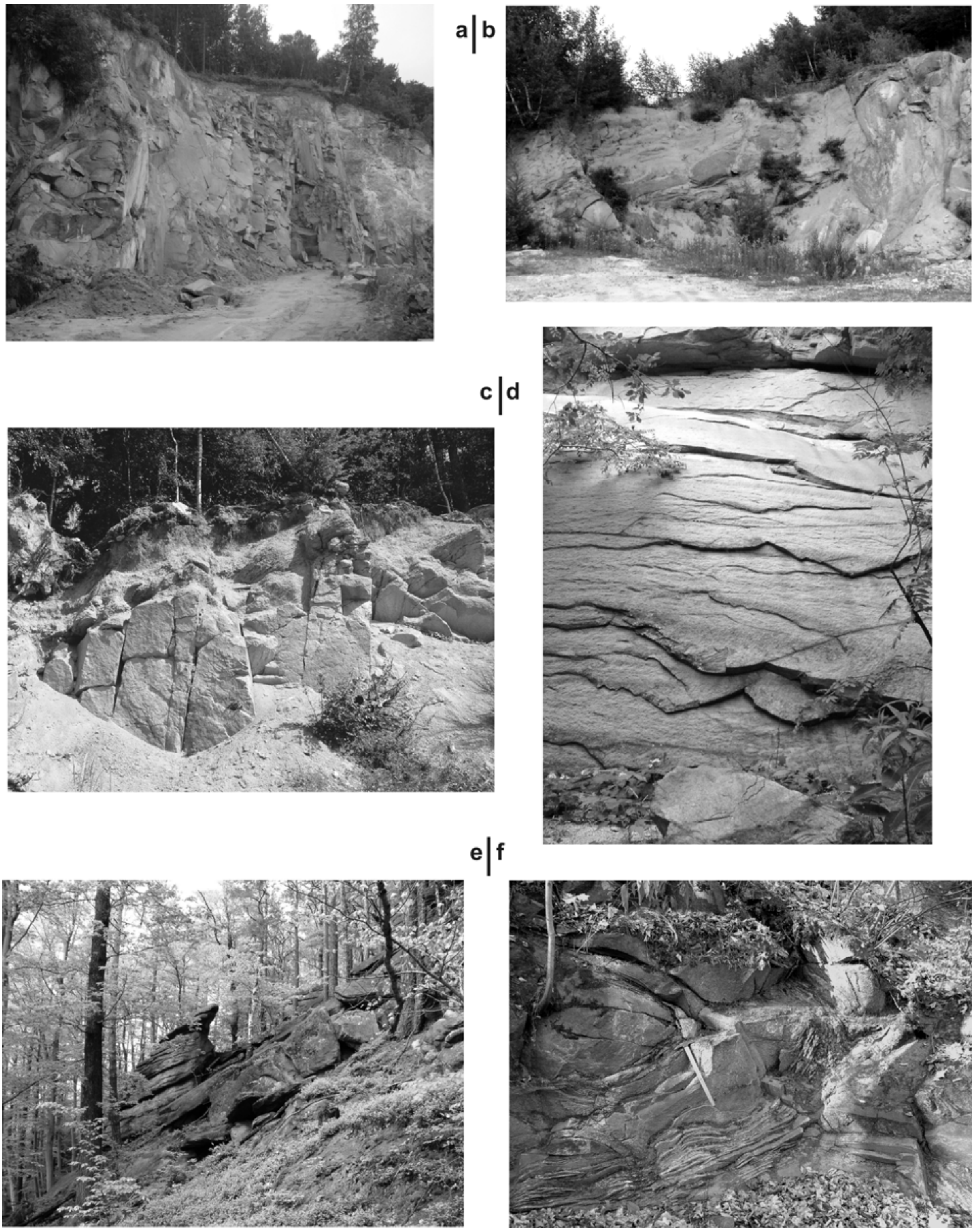

Fig. 18 The weathering characteristics of granitoids observed mainly from quarry sections; a) a vertical rock face exposed in a quarry to the N of Zelená hora in the Sokolský hřbet. Note the very limited development of grus at the top of the profile, which is typical for slopes in the Sokolský hřbet, b) corestones in grus exposed in a quarry located on the northern slope of the inselberg Vycpálek in the Žulovská pahorkatina, c) grus-like weathering observed on the foot of a low exfoliation dome to the N of Bukový vrch in the Žulovská pahorkatina, d) sheeting joints observed in quarry on the inselberg of Vycpálek in the Žulovská pahorkatina, e) sheeting joints forming the surface at the top of the inselberg Borový vrch in the Žulovská pahorkatina, f) onion weathering exposed on a valley slope of the Vidnavka river in the Žulovská pahorkatina.

Pliocene (Migoń and Lidmar-Bergström, 2001). As some of the tors were most probably covered by a continental ice-sheet, they are of pre-glacial origin; this glacial cover is evidenced by those eratics found within open joints (see Section 4.3). Tor preservation under glacial ice is widely recognised in regions where cold-based glacial processes dominate (e.g. André, 2004; Hall and Sugden, 2007 and references therein), even during periods of repeated advance and retreat. However, it is probable that warm-based glacial processes predominately operated here because the dynamic margins of the continental ice-sheet reached the Žulovská pahorkatina. Nevertheless, sub-glacial erosion, which is controlled by ice-sheet movement dynamics, could have locally decreased. Such a scenario is particularly likely when the ice-sheet encounters an area of elevated relief; for example, it is known that less sub-glacial erosion occurs on the lee-side of nunataks because the relief on that side is sheltered from the most rapidly moving part of the glacier. This type of sheltering is postulated to have occurred with regard to the tors near Kaní hora (475 m asl); these tors are positioned on the SE lee-side of the Kaní hora, whilst the principal glacial advance has been shown to be from the NW towards the SE (Sikorová et al., 2006). As the lee-side was not overridden by the frontal, rapidly moving part of the glacier, the pre-glacial relief could have survived in these sheltered positions (D. Nývlt, pers. comm.).

5.4. DIFFERENTIAL RELIEF EVOLUTION REFLECTED BY ROCK LANDFORMS

The morphology and spatial distribution of both the rock steps and blocks observed within the granitoid blockfields described in this paper is controlled by the petrography of the granite and the type of jointing and parting with which it is associated (Demek et al., 1964; Migoń 1997, 2004). Twidale (1971) deemed that the nature and closeness of the fracture pattern were the most significant factors in determining the development of bedrock landforms in granite; only secondary significance was attached to mineralogy, which was thought to control minor details within granite landforms. However, grain size provides a fundamental control with regard to the dominent type of mechanical weathering. For example, coarse granite tends to experience frost weathering along grain-to-grain boundaries and this does not produce blockfields, whereas fine-grained granite yields more easily to frost-shattering, especially if densely jointed (Handley, 1954; pp. 207 in Demek et al., 1964; Migoń, 2007). Here it is shown that despite the similar fracture pattern, the divergent petrography and homogeneous texture (grain size) of the granitoids within the Sokolský hřbet and the Žulovská pahorkatina has lead to each area hosting different types of rock landform in markedly different topographic positions. Sokolský hřbet is characterised by numerous frost-riven cliffs and cryoplanation benches, extensive blockfields developed on granitoid fault scarps, the limited depths attained by granitic grus-weathering, and the complete absence of rock steps and natural rock outcrops on any marginal slope composed of granitoids. Žulovská pahorkatina is characterised by the absence of frost-riven cliffs, the presence of numerous rock steps and tors that have been uncovered as a result of the exposure of basal weathering surface, deeper grus-weathering profiles on residual hills, and the limited extent of blockfields.

These divergent rock landform characteristics are due to these adjacent regions recording two unique evolutionary histories, as a consequence of morphostructural variations. The Sokolský hřbet was uplifted during the Miocene rather than during the Pliocene; the timing of this uplift is reflected in adjacent parts of the Rychlebské hory Mts (Walczak, 1954; Ivan, 1966; Štěpančíková, 2007a,b); this uplift probably resulted in an enhanced rate of disintegration within the granitoids, which was intensified as a result of their exposure (cf. also Twidale 1971, pp. 37). This disintegration is probably reflected in the extensive blockfields that cover the marginal slopes of the Sokolský hřbet. Following uplift, the Sokolský hřbet has been a mountainous region; during the Pleistocene it has been repeatedly flanked by continental ice-sheets, whilst periglacial processes have formed the rock landforms, such as frost-riven-cliffs, blockfields, and residual rocks, which occur within the summit areas. In contrast, the Žulovská pahorkatina is a remodelled etchplain that has been subjected to a long period of sub-aerial evolution. This etchplain was initiated in, or prior to, the Paleogene; kaolinitic weathering was either accompanied or followed by subsequent stripping (cf. Kužvart, 1965; Jahn, 1980; Ivan, 1983; Migoń, 1999). Etching continued during the Plio-Pleistocene, which resulted in the formation of grus saprolite (Ivan, 1983; Migoń, 1999; Migoń and Lidmar-Bergström, 2001). The result of this evolution is a characteristic morphology that includes inselbergs and low exfoliation domes. The observed rock landforms, such as tors and castellated rocks on residual hills, probably formed during Cenozoic during phases of etching and stripping. During the Middle Pleistocene, the Žulovská pahorkatina was twice covered by a continental ice-sheet (Elsterian 1 and Elsterian 2), which slightly remodelled the surface and stripped any remnants of the kaolinite-rich saprolite found within the oldest tills (Gába, 1992; Žáček et al., 2004). Stripping also continued after deglaciation, probably as a result of the uplift of the Žulovská pahorkatina; this uplift has been ascribed to glacio-isostatic rebound (Štěpančíková et al., 2008). Furthermore, glaciogenic deposits (till and glacio-fluvial sediments) have largely been removed (Žáček et al., 2004; Pecina et al., 2005).

6. CONCLUSIONS

In this paper, the systemic disparity between those rock landforms described from the Sokolský hřbet (ridge) and those rock landforms described from the Žulovská pahorkatina (hilly land) reflects differential relief development within two adjacent morphostructural units. In particular, the rock landforms are demonstrated to vary markedly in terms of their shape, their arrangement, the aspect of their walls, and their topographic position within in the slope profile. Despite these differences, it has also been shown that the rock landforms in both units appear to be structurally and lithologically controlled; moreover, the various shapes associated with the granitic rock landforms are controlled by various types of jointing and parting (disintegration).

The development of relief within the Sokolský hřbet is reflected through a number of morphological characteristics associated with those rock landforms observed in that area. Sokolský hřbet is characterised by numerous frost-riven cliffs and cryoplanation benches, extensive blockfields developed on granitoid fault scarps, the limited depths attained by granitic grus-weathering, and the complete absence of rock steps and natural rock outcrops on any marginal slope composed of granitoids. The Sokolský hřbet has been interpreted as a neotectonically uplifted mountainous region; the rock landforms are thought to have formed under periglacial conditions during Pleistocene cold periods, whilst the extensive granitoid block accumulations developed on marginal fault scarps are thought to result from intensive rock disintegration due to uplift. Likewise, the development of relief within the Žulovská pahorkatina is reflected through a number of morphological characteristics associated with those rock landforms observed in that area. Žulovská pahorkatina is characterised by the absence of frost-riven cliffs, numerous rock steps and tors that have been uncovered as a result of the exposure of basal weathering surface, deeper grus-weathering profiles on residual hills, and the limited extent of blockfields. Žulovská pahorkatina has been interpreted as a remodelled stripped etch surface, which has been twice glaciated during the Middle Pleistocene.

This paper has demonstrated that it is possible to use rock landforms as circumstantial evidence with regard to the fundamental processes responsible for constructing the present-day relief; it is here demonstrated that these insights can be gleaned because rock landforms reflect the morphogenetic history of the area in which they are situated. Of course, the evidence provided by rock landforms is difficult to substantiate fully unless it is compiled as part of a study that integrates detailed geomorphological mapping and morphostructural analyses. Nonetheless, the morphological characteristics of the rock landforms described in this study provide further evidence for a long polygenetic history between two adjacent morphostructural units.

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